Tenth Quarterly Progress Report

April 1, 2004, through June 30, 2004

Speech Processors for Auditory Prostheses

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submitted by

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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 efforts were directed at five main areas that include:

1) binaural psychophysical testing of two additional subjects who have used a monolateral implant for at least 6 months and recently underwent implantation of their unimplanted ear. The psychophysical measures include relative interaural pitch, fusion, interaural timing differences (ITD-JND), speech reception, localization and binaural interactions in electrically-evoked brain stem responses as a function of time in the three bilaterally-implanted subjects described in earlier QPRs. These data, together with results from current testing designed to determine the cues these subjects use in localization tasks, will be reported in future QPRs.
2) evaluation of split-spectrum processors using asynchronous sound processors.
3) development of techniques for using measures of electrical artifact potentials on the scalp to evaluate implant device function and integrity. Progress in this area includes development of advanced analysis tools to identify and examine aberrant stimulus artifact events from a large pool of otherwise normal stimulus events and development of a new electrode probe that facilitates rapid recording of artifact potentials on the scalp in order to examine the topology of potentials across the scalp.
4) continued measurement and analysis of intracochlear evoked potentials (IEPs) to characterize the quality, magnitude and variability of this measure across a pool of subjects as well as sources of variability that may be introduced by the measurement system integrated into the implanted device, and
5) investigations of channel interaction using the IEP measures. Presently we are focused on understanding the nature of these responses and evaluating whether the results may be reasonably interpreted in the context of present knowledge of stimulation mechanisms in the cochlea. We are also evaluating various metrics so that relative degrees of interaction may be meaningfully compared across subjects and test conditions. Such metrics will allow us to compare

psychophysical measures of interaction with those obtained using of intracochlear evoked potentials (IEPs).

In this QPR, we concentrate on further progress in the measurement and analysis of channel interactions using the IEP in which we extend our examination of interactions from group behavior across subjects to examine specific situations occurring in individual subjects. We will also describe efforts to perform control studies on test devices to rule out the possibility that trends in the data might be introduced by systematic changes and/or non-ideal behavior in the stimulation and recording characteristics of the implanted hardware.

2.0 IEP Measures of Channel Interaction

As reported in the eighth quarterly report (QPR8) of this project (Herrmann et al., 2003), we are developing a method of measuring channel interaction by comparing intracochlear evoked responses (IEPs) collected using various combinations of masker and probe stimuli presented *simultaneously*. Subjects (six) are postlingually-deafened, monolaterally-implanted Clarion CII\HiFocus patients with moderately good speech-reception performance (62% to 82% CNC word scores). The growth of IEP amplitude (aIEP) as a function of stimulus level using single-channel stimulation was described for these and other subjects in QPR4 (Finley et al., 2002). These results showed a wide range of variability in aIEP growth across subjects and across electrodes within a subject.

In the present report we briefly describe the general method for measuring channel interaction and summarize the group results across subjects. Both are described in more detail in QPR8 (Herrmann et al., 2003). Next, we present interaction data for two individual subjects in the group. These results are discussed in the context of the group findings (QPR8) and with respect to instrumentation characteristics that could potentially produce similar findings. Efforts to rule out the latter instrumentation issues are also reported.

2.1 Summary of IEP Interaction Procedure

Channel interaction was explored using the IEP by examining the change in the aIEP to a single-electrode *probe* stimulus when additional *masker* current is applied to *masker* electrode. The aIEP was defined as the absolute amplitude difference between the N1 and P2 components of the IEP response (QPR8). In order to simplify our initial exploration of IEP interaction, we used masker levels well below those eliciting an IEP when applied to the masker electrode alone (i.e. below IEP threshold). By using these low masker levels, we did not need to account for the effects of the "masker alone" condition in interpreting our results. By presenting the masker and probe signals simultaneously we also maximized the likelihood of observing interaction. Finally, we investigated the effect of phase by using biphasic pulsatile maskers that are both in-phase and 180 degrees out-of-phase with the biphasic pulse applied to the probe electrode. All

stimuli were 32 μsec/phase biphasic pulses presented in alternating polarity in order to minimize residual electric artifact in the averaged waveforms. Averaged response waveforms for 256 stimulus presentations were obtained for each test condition.

As summarized in Table 1, IEPs are recorded for four experimental conditions for each probe-masker combination (Conditions A,B,C,D) and for the probe electrode stimulated alone at base level (Condition E).

Condition	Probe-Electrode Stimulus	Masker-Electrode Stimulus
A	Base μA + ΔμA (in-phase)	0
B	Base μA – ΔμA (out-of-phase)	0
C	Base μA	ΔμA (in-phase)
D	Base μA	ΔμA (out-of-phase)
E	Base μA	0

Table 1. Summary of probe- and masker-electrode stimulus levels for each stimulus test condition.

The base stimulus level (Base μA) is selected to correspond to the steepest position on the probe electrode's IEP growth function. In condition A, the ΔμA stimulus is added in-phase to the base stimulus (Base μA) on the probe itself resulting in an increase in the probe stimulus level. Consequently, the aIEP for condition A ($aIEP_A$) is greater than for condition E (i.e., $aIEP_A > aIEP_E$). The ΔμA stimulus is added out-of-phase to the base stimulus on the probe in condition B, decreasing the current magnitude on the probe electrode and resulting in $aIEP_B < aIEP_E$. In condition C, the base stimulus is applied to the probe electrode and the ΔμA stimulus applied to a masker electrode in-phase with the probe's base stimulus. In the case of condition D, the base stimulus is applied to the probe electrode and ΔμA is applied to a masker electrode out-of-phase with the probe stimulus. The degree to which $aIEP_C$ and $aIEP_D$ differ from $aIEP_E$ depends on the degree of interaction between the probe and masker electrodes. The comparison of $aIEP_C$ to $aIEP_A$ and $aIEP_D$ to $aIEP_B$ contrasts the interaction between the probe and the masker to the simple increase of current on the probe. For each condition, 95% confidence intervals for aIEP are calculated based on a statistical resampling procedure described in detail in QPR8.

Figure 1 below (previously presented as Figure 5 in QPR8), graphically summarizes the relationships for one set of measures (Conditions A-E) collected in subject C120. The probe stimulus amplitude (Base μA) is 648 μA_{peak} applied to electrode E7. The masker stimulus amplitude (ΔμA) is 96 μA_{peak} applied to electrode E13. IEP responses are recorded from electrode E5. When ΔμA was added in-phase to the probe stimulus on E7, the aIEP recorded from E5 increased as expected ($aIEP_A > aIEP_E$). Similarly, when ΔμA

was added out-of-phase to the probe stimulus, the aIEP decreased as expected ($aIEP_B<aIEP_E$). However when ΔμA was delivered to the masker electrode (E13) in- or out-of-phase, no significant impact was measured for the aIEP. This indicates no interaction between electrodes E7 and E13.

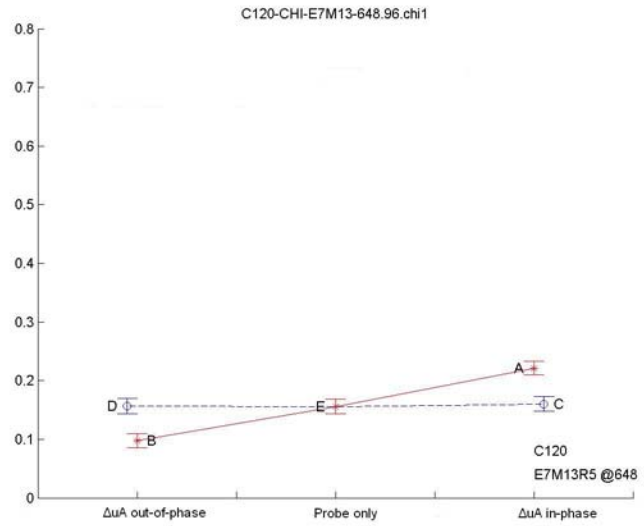


Figure 1. Plot of IEP amplitude (mV) and corresponding 95% confidence intervals for the five conditions defined in Table 1 .The masker/probe/recording configuration was: probe E7, masker E13 and recording E5.

IEP interaction data like those shown in Figure 1 (Conditions A-E) have been collected for three probe electrodes (E3,E7,E13) each in combination with 9 masker electrodes in six subjects. Masker electrodes for each probe include the two electrodes adjacent to the probe plus the odd-numbered electrodes on either side of the probe electrode. For example, for probe E7, masker electrodes were E1, E3, E5, E6, E8, E9, E11, E13 and E15. The recording electrode for the IEP was spaced either two electrodes apical or two electrodes basal to the probe electrode depending upon whether the masker was apical or basal to the probe electrode. If the masker electrode was basal to the probe, the recording electrode apical to the probe was used and vice versa. This selection of recording electrode was made (1) to further simplify interpretation of the recorded IEP data by avoiding potentially complex response summations occurring in the region between the probe and masker electrodes and (2) to allow uniform recording electrode conditions over a wide range of probe-masker electrode distances, but especially when the masker is near the probe electrode. Because the aIEP was observed to vary depending upon the recording electrode in several subjects, the aIEP for the probe alone at the base stimulus level (Condition E) was recorded for both recording electrode conditions and matched to that used for the measurements of Conditions A–D for each probe-masker combination.

Figure 2 (below) plots aIEP as a function of makser electrode for probe electrode E7 in subject C120. The left panel of Figure 2 shows data for Conditions A and C (masker and probe stimuli in-phase), whereas the right panel shows data for Conditions B and D (masker and probe stimuli out-of-phase). Both panels contain the probe-alone condition (Condition E) in blue. Confidence intervals (±95%) are shown for all data. The data for masker electrode E13 depicted in Figure 1 above are included in Figure 2 and marked by the vertical dashed lines at the masker electrode E13 positions. The large difference in the aIEP levels for the masker electrodes apical or basal to the probe electrode is due to

the different recording electrode used. The recording electrode was selected so it was never positioned between the probe and masker electrode positions. The recording electrode used for each masker electrode is indicated only in the left panel of Figure 2 but is the same for both in-phase and out-of-phase stimuli.

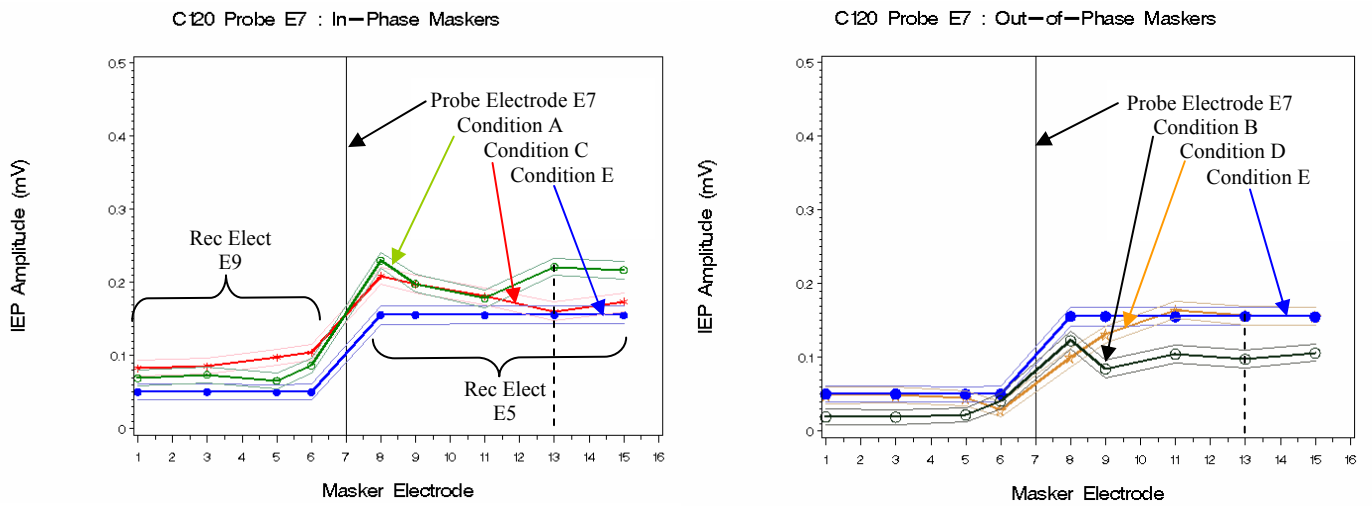


Figure 2. Complete aIEP data sets for probe electrode E7 in subject C120. The left panel shows data for in-phase masker and probe stimuli (Conditions A and C). The right panel shows data for out-of-phase masker and probe stimuli (Conditions B and D). The probe alone aIEP data (Condition E) are generally collected only once for each recording electrode utilized and are then used as a reference values for each masker-probe condition. See text for further explanation.

2.2 Analysis of Electrode Interactions Based on IEP Measures – Group Data Summary

As described in QPR8, IEP interaction was defined as the change in the aIEP to a probe-alone, base-level signal (Condition E) when a subthreshold current was placed simultaneously on a different masker electrode (Conditions C and/or D). The aIEPs measured when the subthreshold current (ΔμA) was added directly to the base-level stimulus on the probe itself ($aIEP_A$ for Condition A and $aIEP_B$ for Condition B) are considered reference aIEPs representing conditions of total interaction as if the probe and masker electrodes occupy the same physical position.

In our previous analysis, we observed three effects of the subthreshold masker:

1) *No interaction* - where statistically no effect of applying the masker was observed, as illustrated in Figure 1,
2) *Interaction* - where a statistically significant change in aIEP that was in the same direction but either less than or equal to the reference aIEP change seen when ΔμA was added directly to the probe, and
3) *Hyperinteraction* - where a change in aIEP that was significantly greater than the reference aIEP change expected for full interaction.

We also observed that both *interaction* and *hyperinteraction* were at times present for both masker phase conditions and sometimes only for one masker phase (primarily in-phase). We have summarized the types of interaction effects observed in Table 2 for discussion purposes. The selection of these classifications is based on the observed occurrence of these combinations and does not at this point imply any mechanistic interpretation.

Interaction State		In-Phase Masker and Probe		Out-of-Phase Masker and Probe
No Interaction ○		$aIEP_C = aIEP_E$	AND	$aIEP_D = aIEP_E$
Interaction ◆	for both phase conditions	$aIEP_A \geq aIEP_C > aIEP_E$	AND	$aIEP_B \leq aIEP_D < aIEP_E$
Interaction ◆	for one phase condition	$aIEP_A \geq aIEP_C > aIEP_E$	OR	$aIEP_B \leq aIEP_D < aIEP_E$
Hyperinteraction ■		$aIEP_C > aIEP_E$ and $aIEP_C > aIEP_A$	AND/OR	$aIEP_D < aIEP_B$ and $aIEP_D < aIEP_E$

Table 2. Summary of the masker-probe interaction types most frequently observed in the group data across all subjects and test conditions. This table summarizes results presented in detail in QPR8. The colored symbols correspond to symbols used in Figures 3 and 4 to designated types of interaction.

The frequency of occurrence of these interaction types across all subjects are described in QPR8 as a function of probe electrode selection, the electrode spacing distance between the masker and probe electrodes, and the phase relationship between masker and probe stimuli. In general, interactions are more likely to occur with in-phase maskers and probes with 66% of all in-phase conditions showing interaction as compared with only 22% of out-of-phase conditions. Hyperinteractions are also more likely with in-phase stimuli. Thirty-seven percent of in-phase stimuli producing interactions (37% of the 66% described above) were of the hyperinteraction type compared with only 5% of the out-of phase interactions. Furthermore, it appears that the likelihood of IEP interaction changes with the position of the probe electrode and with the phase of the masker stimulus. Probes E3 and E7 are the most similar having a greater frequency of interaction and hyperinteraction than probe E13. For both in-phase and out-of-phase maskers, interaction is more likely if the masker electrode is closer to the probe electrode. For in-phase maskers, the likelihood of interaction and hyperinteraction is greater for maskers apical to the probe. Interaction is less likely for masker signals that are out-of-phase with the probe signal and least likely for the most basal probe, E13. In general, there are distinct asymmetries in the frequency of occurrence of IEP measured interactions with regard to 1) the phase relationship of masker and probe and 2) the apical-basal selection of the probe electrode.

2.3 Analysis of Electrode Interactions Based on IEP Measures – Individual Subjects.

We are currently exploring methods to quantify interaction in individual subjects that allow for meaningful comparison of IEP interaction measures across subjects and with psychophysical measures. One encouraging observation is that the general trends summarized above for the frequency of interaction types for the group data are also well represented in the individual data of each subject. We illustrate this point by presenting the individual data for two subjects.

Figure 3 (below) shows the individual data for Subject C97, who is selected for the relatively high incidence of interactions observed with the IEP measures. The data follow the general format for the in-phase and out-of-phase maskers previously described in Figure 2. Figure 3 includes data for all three probe electrodes studied (E3, E7 and E13). Across the top of each panel colored symbols have been added which indicate the type of interaction observed for each masker position. The interaction types follow the definitions in the previous table and include *No Interaction* (open circle), *Interaction* either with both phases of stimulation (split blue diamond) or with only one phase of stimulation (green diamond), and *Hyperinteraction* (red square).
Several group trends are immediately obvious in these individual data for Subject C97:

- Interactions are more likely when the masker electrode is closer to the probe electrode.
- In-phase masker-probe conditions are more likely to produce interactions.
- Interactions are more likely and are larger for more apical probe electrode positions.
- Hyperinteractions are more likely to occur when the masker electrode is close to the probe. Hyperinteractions are more likely to occur in response to in-phase masker and probe stimuli. Hyperinteractions are more likely when the masker electrode is apical to the probe electrode.

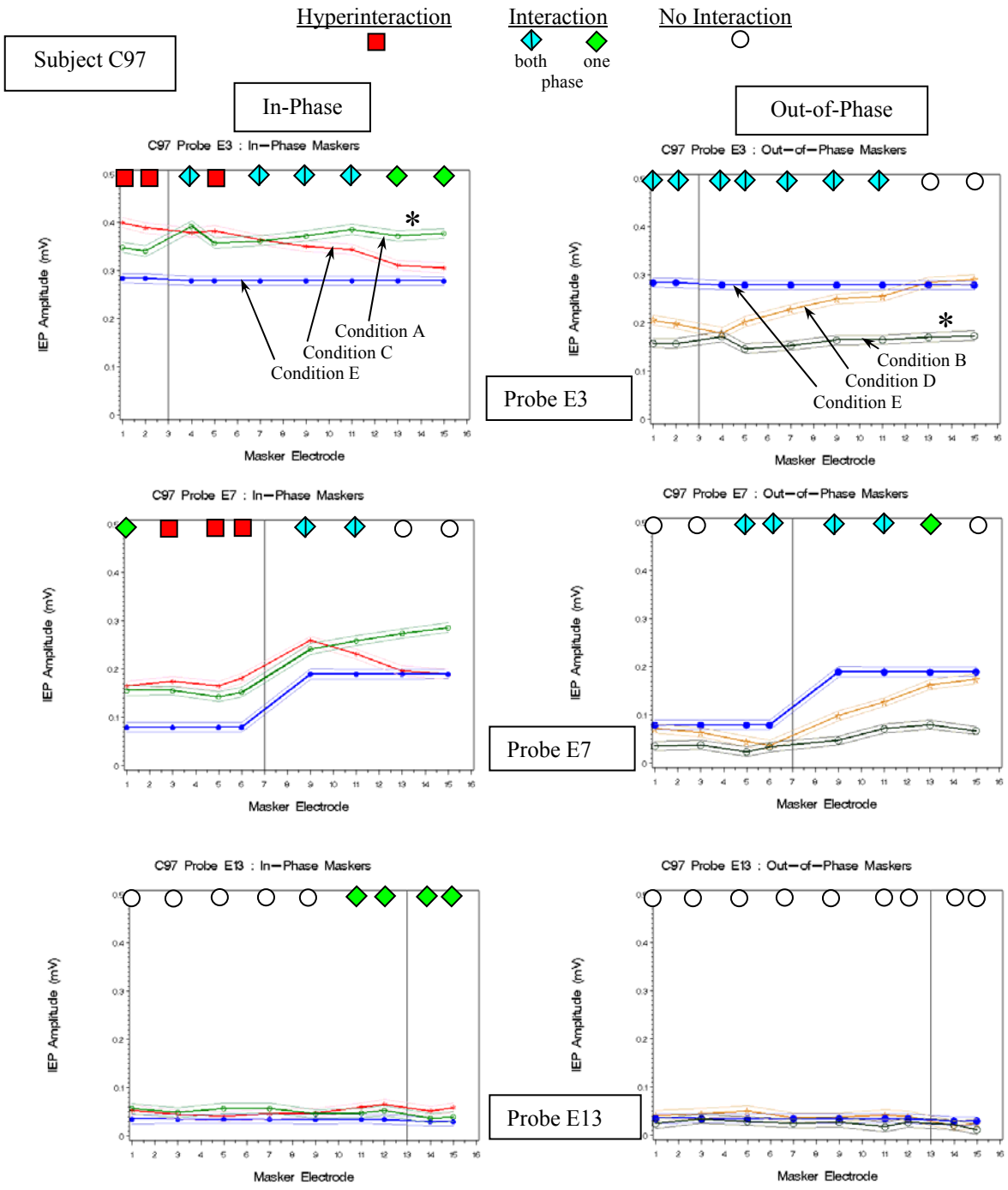


Figure 3. Complete data set of IEP channel interaction measures for subject C97. Left and right columns are for in-phase and out-of-phase masker probe stimulus conditions. Each row represents apical, middle and basal probe electrode positions from top to bottom. Each in-phase panel contains aIEP data values as a function of masker electrode position for test Conditions A, C, and E, whereas each out-of-phase panel contains data for Conditions B, D, and E. Across the top of each panel are symbols representing the type of interaction observed for the masker electrode positions studied. See text for further explanation.

Figure 4 shows the individual data for Subject C114 in the same format as Figure 3. Although this subject has a smaller incidence of interaction, there are many similarities to the interaction patterns observed in C97 and for the overall group data. In particular,

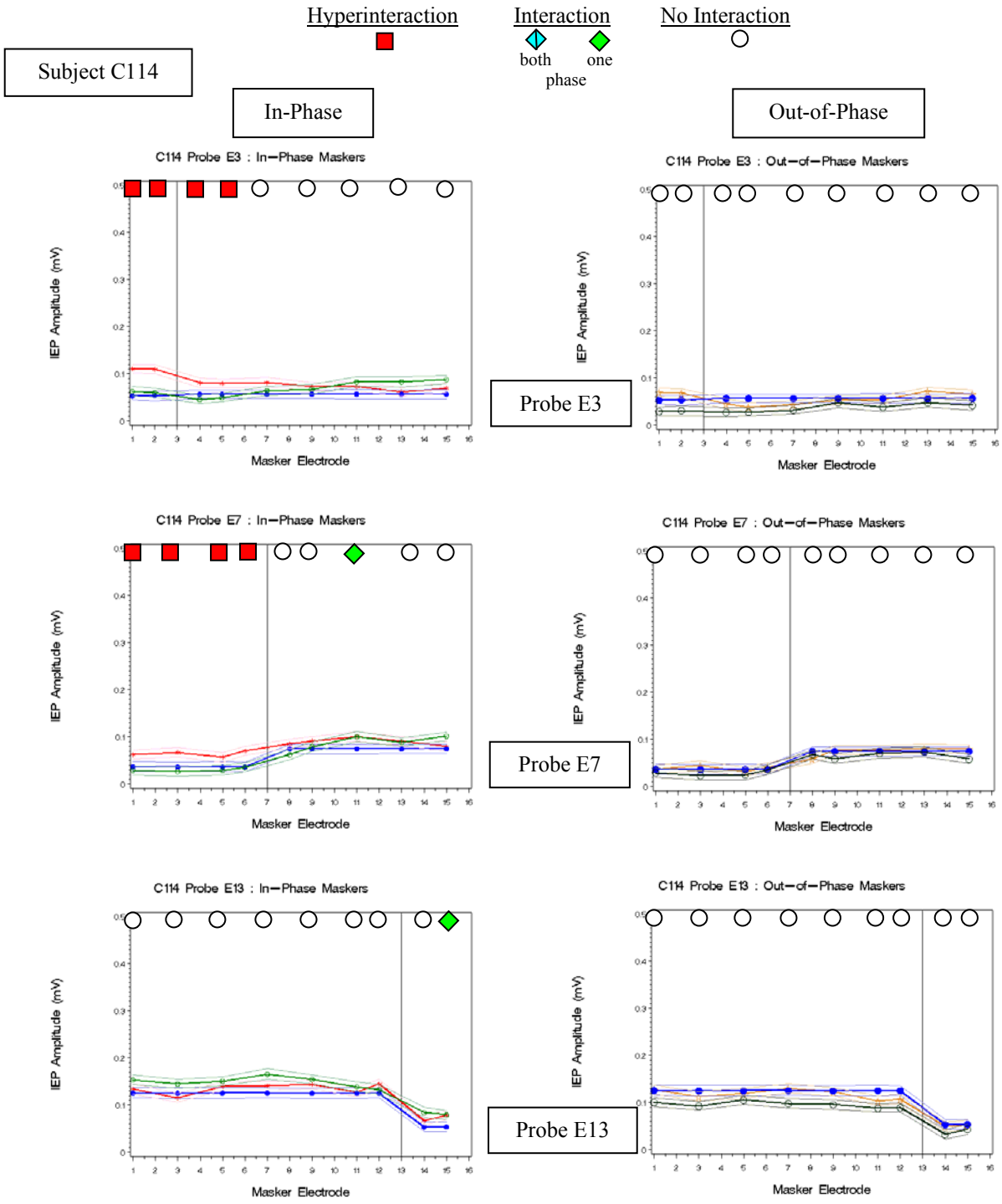


Figure 4. Complete data set of IEP channel interaction measures for subject C114. Left and right columns are for in-phase and out-of-phase masker probe stimulus conditions. Each row represents apical, middle and basal probe electrode positions from top to bottom. Each in-phase panel contains aIEP data values as a function of masker electrode position for test Conditions A, C, and E, whereas

when interactions are observed, they occur only for in-phase stimulus conditions and primarily when masker-probe distances are small. The Probe E7 data show the bias for interactions with maskers located apical to the probe electrode. Interestingly, although this subject has relatively few interactions compared to C97, when they do occur the interactions are pronounced, being of the hyperinteraction type. It is also interesting that this subject had the shallowest growth of the aIEP for a single-electrode stimulus. Comparisons of aIEP for conditions A, E and B show small and often non-significant changes in aIEP with current level. Larger and more significant increases in aIEP are observed when subthreshold current is applied to apical electrodes than when the same ΔμA is applied to the probe.

Another observation in the present data that captured our attention can be seen in Figure 3 for Subject C97. In both panels of Figure 3 for Probe E7, two data sets have been marked with an asterisk (*). In the leftmost, "in-phase" panel the marked data set is for Condition A in which stimulation on the probe electrode is *Base μA + ΔμA* (see Table 1) and *zero* on the masker electrode. In the rightmost, "out-of-phase" panel the asterisk marks data for Condition B in which the probe stimulus is *Base μA – ΔμA* and again *zero* on the masker. In both cases the masker stimulation level is zero, yet there appears to be a tendency for the aIEP measures to increase as the masker electrode is moved basally. Ordinarily, because no stimulus is being delivered on the masker electrode, one would not expect any changes in aIEP levels that are dependent on which masker electrode is selected. The same tendency is also seen in the panels for Probe E3, but to a lesser extent. Because the order of tested conditions has been randomized during data collection, it is unlikely that these data trends represent a time-dependent phenomenon. Similar effects were seen in data for other subjects.

One hypothesis as to the cause of these trends was that there are systematic changes in either the stimulation or recording characteristics of the hardware/software systems of the internally implanted device that influence the results. It was essential that this possibility be investigated before proceeding further. Four potential mechanisms were explored: 1) a software error or a defect in the logical design of the code, 2) a systematic variation in probe current as a result of masker electrode selection, 3) a systematic change in the IEP recording amplifier gain as a result of masker electrode selection, and 4) an alteration of the electrical environment in the cochlea due to a change in masker electrode impedance. Our examination of each of these topics follows:

1) *Hypothesis: the bias is due to a previously undetected software error or logical processing flaw.* A complete review of the software for stimulus control, telemetry of recorded data back from the ICS, averaging, storage and final data analysis was made, particularly with regard to how specification of the masker electrode might influence results. Known sets of backward telemetry data were substituted into the code and were processed through the averaging, storage and data analysis software. No coding errors or problems with the software logic were found.

Our next approach was to perform functional tests of the combined software/hardware system under controlled conditions in which stimulus output and recorded input signals were carefully monitored while varying the specified masker electrode condition in software. To fully appreciate each of the hardware mechanisms we examined, it is helpful to understand how stimulus currents are delivered to and signals recorded from electrodes in the Clarion C-II implant system.

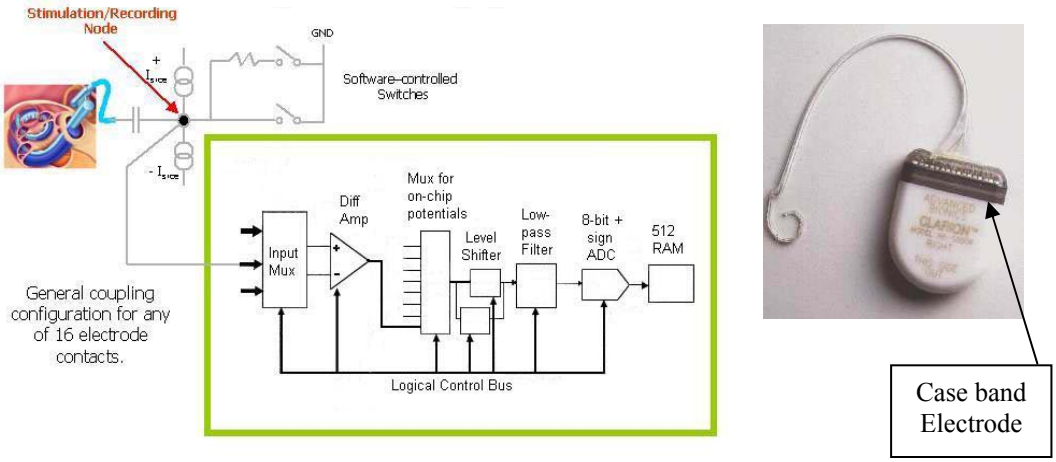


Figure 5. Schematic representation of the stimulation and recording circuits for one of sixteen electrode channels for the Clarion C-II implant system. The inset photograph indicates the location of the case band ground return electrode on a Clarion ceramic case. See text for discussion.

Figure 5 shows a simple schematic of this arrangement for one of the sixteen electrodes in the C-II system.

Each intracochlear electrode in the system is capacitively-coupled to a common stimulation/recording circuit node. Each of these nodes is connected to two current sources for generating either positive or negative stimulation currents on the electrode relative to system ground. During monopolar stimulation the "case band" electrode on the surface of the implantable cochlear stimulator (ICS) is connected to system ground to provide a full stimulation pathway. In this mode current passes first from a current source connected to the stimulation/recording node then through the coupling capacitor along the electrode lead wires across the electrode contacts into the tissue and back to the case band. During bipolar stimulation, currents are pushed and pulled through the tissue between discrete intracochlear contacts being driven by their respective positive and negative current sources. Also connected to each node are software-controlled switches, which allow the stimulation/recording node to be connected to system ground through either a direct short or higher impedance bleeder resistor(s) so that residual charge on the electrode-coupling capacitor may be removed. The combined stimulation/recording node circuit of current sources, coupling capacitor and grounding switches is repeated for each of the sixteen electrodes. Finally, a signal line is also connected from each stimulation/recording node to a signal multiplexer that controls which nodes are being

monitored by the back-telemetry ADC system for IEP recording (see green box in Figure 5). All of the active circuits are implemented as part of a custom integrated circuit chip mounted on a silicon substrate inside the ICS package. Inside the hermetically-sealed ICS package stimulation signals for each electrode channel are routed from the stimulation/recording nodes via circuit traces and wire bonds to a coupling capacitor located on the silicon substrate. The coupling capacitors are in turn connected through glass feed-through terminals to the electrode leads on the outside of the case. The electrode signals then pass along the electrode leads into the cochlea to the contacts. These tightly packed and relatively long circuit pathways provide significant opportunity for leakage pathways and parasitic capacitances to alter the normal function of the stimulation and recording circuits. The purpose of the following work was to determine if the unexpected masker electrode-dependent trends in our data could be explained by such mechanisms.

2) *Hypothesis: the bias is due to systematic variation in probe stimulus output based on specification of the masker electrode.* Two possible mechanisms by which this may occur in hardware include (1) errors in the level control of the current sources and (2) the introduction of alternative circuit pathways for current to flow before reaching the probe electrode. Alternative circuit pathways that may shunt stimulation current could be leakage resistances and/or parasitic capacitances. Similarly, the software-controlled switches could also be in inappropriate states, thus shunting currents away from their intended path across the electrode contacts. The existence of these mechanisms was evaluated through two functional bench-level tests. First, probe-electrode output levels into a dummy resistive load were measured directly with an oscilloscope using a bench-level CII ICS device connected to a 10kohm load. Under control of our research data collection software, measured peak output levels of 32 μsec/phase biphasic pulses were compared with intended levels specified in software. Outputs tracked commanded levels. The test was repeated for different masker electrode specifications with masker current set to zero. Masker electrode selection appeared to have no effect on probe output levels. This test was then repeated in a saline bath using a different, hermetically-sealed CII ICS device connected to a HiFocus electrode array (see Figure 6). Control of the ICS was achieved by placing the headpiece RF transmitter beneath the plastic bottom of the bath adjacent to the ICS package. Our research software was then used to run the same summed alternation data protocol used in subject data collection. Biphasic current pulses (32 μsec/phase) of alternating polarity were delivered from a probe

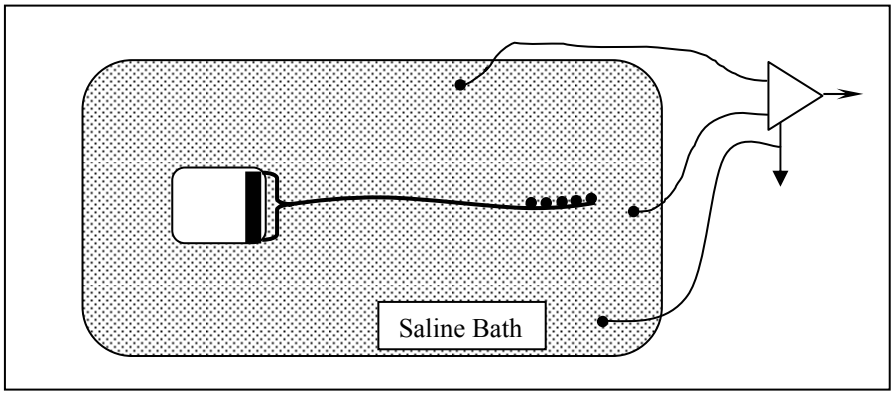


Figure 6. Schematic diagram of hermetically-sealed ICS with electrode array in saline bath. Stimulation was monopolar coupled from a contact on the array to the case band. Recording electrodes were placed in the bath at arbitrary positions for differential measurement of electrical field artifact.

electrode (E7) on the electrode array at various stimulus levels of 200 and 800 µAmp peak. Electrode E5 was specified as the IEP recording electrode. Electrodes 1, 3, 5-6, and 8-16 were specified randomly as masker electrodes with zero current level in separate measurement trials. The magnitude of the probe stimulus delivered by the ICS was measured indirectly by monitoring electrical artifact potentials at a fixed, arbitrary point in the bath. Using an amplifier gain of 10, individual biphasic-shaped stimulation artifacts were readily captured and measured with a digital storage oscilloscope. There were no observable differences in peak-to-peak amplitude of either positive-leading or negative-leading artifacts. Individual pulses were captured and their peak-to-peak magnitude measured using the electronic cursor of the scope. Figure 7 plots artifact levels recorded for the range of masker electrode conditions for a probe current level of 800 µAmp (peak). A linear regression line with ±95% confidence intervals is included in the figure. Although there appears to be a slight trend in increased artifact level with masker electrode selection the effect is not significant.

Figure 7. Probe output stimulus level as a function of masker electrode specification. Probe stimulus of 800 µamp(peak). Masker stimulus of zero varied across electrode position. See text for full explanation.

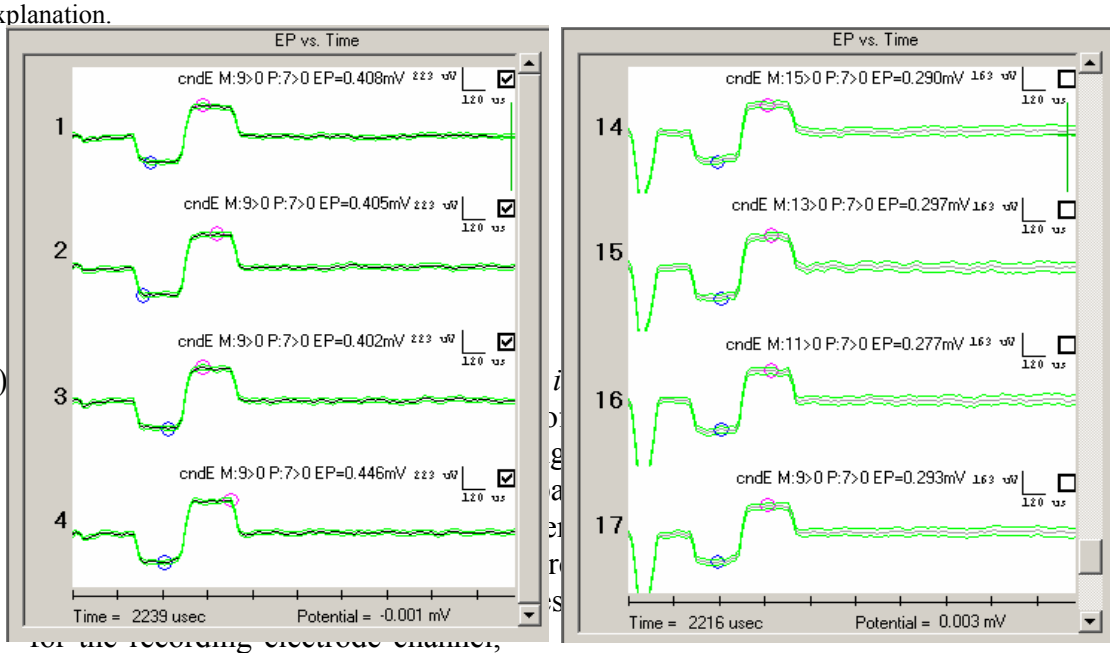


Figure 8. Individual averaged "responses" recorded from electrode E5 collected in a bath using the on-board ICS recording system. The "responses" are residual artifacts in the bath generated by synchronous injection of biphasic current pulses (200 µsec/phase) from an external current source. The "responses" are injected at a latency and magnitude approximating that expected for an average IEP neural response that may be recorded in a test subject. Each panel is a screen capture from the data collection software showing residual stimulus artifact and the measured artifact of the externally injected biphasic pulse "response". In the left panel the probe stimulus level into the bath is zero, whereas in the right panel the probe stimulus level is 400 µA peak applied to E7. The level of the externally injected biphasic response was adjusted to approximate a typical aIEP level. This level is different in the two panels with the left panel injected response approximately 40% greater than the right panel. Each trace is an average of 256 trials with ± 95% confidence intervals shown. During averaging the probe stimulus polarity is alternated to minimize residual stimulus artifact; whereas the externally-injected "response" is held constant. The vertical scale factor in each panel is adjusted automatically to the specific data being displayed and is consequently different in each panel with the right panel vertical scale being smaller. This graphical scaling difference gives rise to the apparently broader confidence limits in the right panel. The measurement noise in both test conditions is the same.

mimics a typical IEP measure. Then the ICS may be operated in its normal operating modes while recording this external "response". Our data collection software was modified minimally to allow presentation of external analog stimuli synchronously with masker-probe ICS stimulation in the saline bath. These analog stimuli (charge-balanced ramps and biphasic pulses) were applied to a precision, isolated current source, which in turn stimulated arbitrarily-placed disc electrodes in the bath, thus injecting an externally-controlled, known artifact or "response" into the bath. The "response" signal was injected at a delayed time in the record so that internally generated probe stimuli from the ICS would not obscure the recording of the externally-injected "response". Probe and masker stimulus levels for the ICS were both set to zero initially. Averages of 256

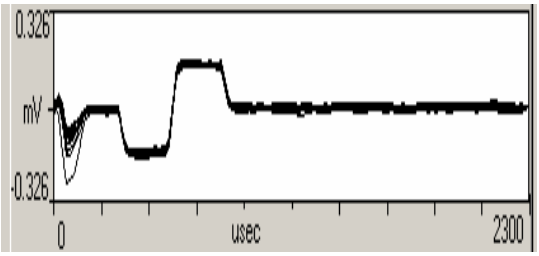


Figure 9. Overlayed averaged response records collected in a bath using the on-board ICS recording system showing residual stimulus artifact and an externally applied biphasic pulse injected into the bath. Probe stimulation was 400 μamp (peak) applied to electrode E7. The recording electrode was fixed as E5. The figure shows overlayed averaged (256 trials) responses for each of the remaining electrodes being specified as the masker electrode with zero stimulus level.

presentations of the external artifact were collected through the ICS recording system for a variety of masker electrode selections as shown in Figure 8. Masker electrode selection did not influence the magnitude of the injected "response" collected through the ICS recording system and subsequent software processing. The left panel of Figure 8 shows a screen capture of typical records for zero probe stimulus level where each record was collected with a different masker electrode being specified. Next, the procedure was repeated with non-zero probe stimulus levels. The right panel of Figure 8 shows similar measured "responses" recorded immediately after presentation of a 400 μAmp (peak) probe stimulus on electrode E7 for different masker electrode specifications. In this case, the residual probe stimulus artifact can be seen early in the record. The averaged, externally-injected "response" measures showed no dependency on masker electrode selection and demonstrated by the overlaid responses in the Figure 9.

4) *Hypothesis: the bias is due to alteration of the electrical environment in the cochlea caused by current flowing through the masker electrode because of an effectively low output impedance of its stimulator circuit.* The key hypothesis here is that the electrode specified as the masker with zero stimulus level may have a low impedance level that allows current to flow from the tissue through the masker electrode, thus distorting the electrical environment within the tissue. Such distortion could have two effects. One is alteration of the applied stimulus field generated by the probe electrode. The other is possible distortion of the neural response fields resulting in an altered IEP measure. Both mechanisms may operate separately or together to influence IEP measures. Electronically, there is

no reason to expect that the current sources should alter their normally high output impedances when commanded to deliver zero output. However, if the dynamically-driven switches for the residual charge control are closed there may be a lower impedance pathway to ground. To explore this issue, we undertook another functional saline bath test similar to the one just described. The HiFocus electrode of the test device was placed inside a 3mm (inside diameter) section of shrink tubing in order to create a restrictive, high impedance region oriented longitudinally along the electrode array. The tube extended from the tip of the array to the insertion depth marker. There was no attempt to control the position of the array within the tube. Both ends of the tube were kept open. With the tube in place around the array, all stimulation and recording currents must pass longitudinally through the tube along the array. This in turn would increase the sensitivity of detecting any influence that specification of the masker electrode may have on recorded responses. The previous experiment described in section 3 above was repeated for two geometries of electrodes. The two external stimulating contacts for injecting the external "response" were placed in the bath to form a dipole stimulus field oriented from one end of the bath to the other. The ICS and the electrode array within the tube were then placed between these two poles. In one configuration the tube with electrode array was oriented orthogonal

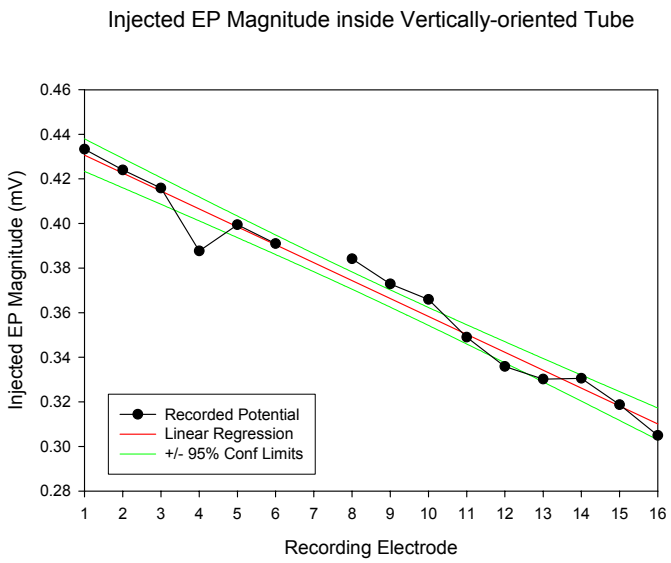


Figure 10. Distribution of the magnitude of the externally-injected "response" within the vertically-oriented tube configuration. Data are collected using different electrodes along the array to record averaged measures of the injected "response" signal. The magnitudes of the injected "response" are plotted as a function of recording electrode number.

to the current flux lines expected for the externally applied "response". This configuration is referred to as the "horizontal" position. In this position both ends of the tube would be expected to be at roughly equal potentials within the bath. Consequently, only a small amount of externally applied "response" current would be expected to flow through the tube, and all electrodes on the array would see the same potentials. The other configuration, referred to as the "vertical" position, consists of the tube being rotated 90˚ so that the tube is aligned with the current flux lines for the externally-applied "response" field. In this configuration, there should be a steady gradient of potential along the array inside the tube. Figure 10 shows the expected linear gradient distribution of the "response" magnitude when recorded from each of the 16 electrodes along the array.

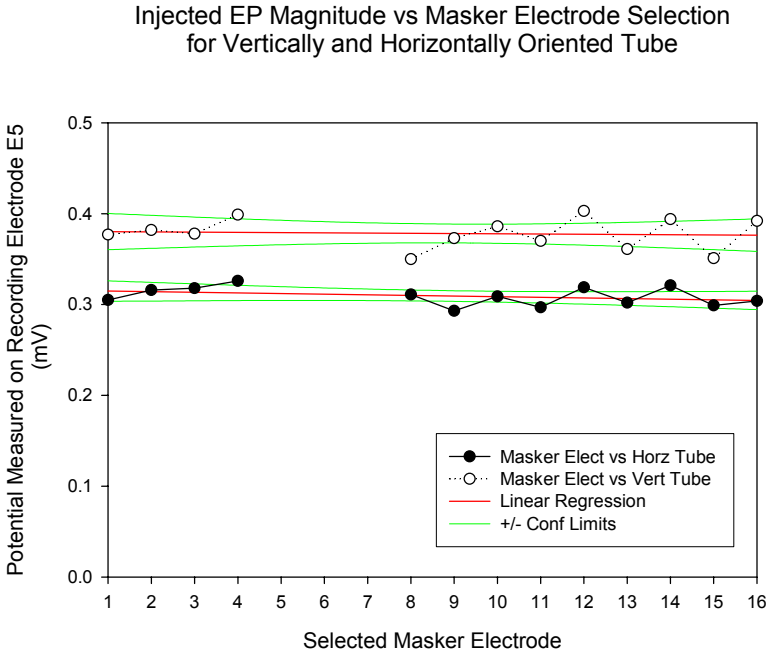


Figure 11. Distribution of the amplitude of the injected "response" as a function of masker electrode selection. Data for the two orientations of the tube containing the electrode array are included. For all conditions the probe stimulus was 400 μamp on E7. Recording were made using E5 for all conditions.

Using both of these test configurations, externally-injected "response" artifacts were recorded at a fixed electrode site E5 while a probe stimulus was applied to E7. The masker level was set to zero and the masker position varied systematically across electrodes E1-E4 and E8-E16. Figure 11 shows how the magnitude of the injected "response" magnitude, as recorded on fixed recording electrode E5, varied as a function of specified zero magnitude masker position.

For both tube configurations, there was no statistically significant longitudinal change in "response" magnitude as a function of masker position. For the more basal electrodes, however, there does appear to be some alternation in response magnitude depending on whether even- or odd-numbered masker electrodes are used. The physical basis for this alternation is not yet known. Its potential for biasing recorded aIEP data should be considered carefully. The linear regression lines in Figure 11 suggest that taken as a whole such effects would have little net effect. However, if only odd or even masker positions are recorded to reduce experimental time, it is possible that a bias may be introduced that is similar to the behavior we have seen in our data. It is important to note as well that our data include only measures from the odd-numbered masker electrodes. Figure 12 illustrates this point by plotting the basal masker data from Figure 11 in terms of only even- or odd-numbered electrodes. Linear regression lines and confidence limits are included. Examination of the plots shows that there are significant differences in the slope of these curves, similar to the effect we have noticed. However, the downward

direction of the slope for the odd-numbered maskers is opposite to the upward trends we see in our data using similarly selected masker electrodes. Clearly, this is an intriguing finding that deserves more investigation.

Two immediate questions are (1) whether we have determined the source of the unexplained trends in our data and (2) if so, to what degree is it influencing our findings. To answer the former will required more investigation to identify the mechanism for the even/odd electrode effect. The answer too the latter is important to our continued data analysis and the collection of future data. On one hand, the potential bias appears to be small and thus may be insignificant with regard to other sources of variability. Similarly, it does not appear in all situations where we might expect to see it.

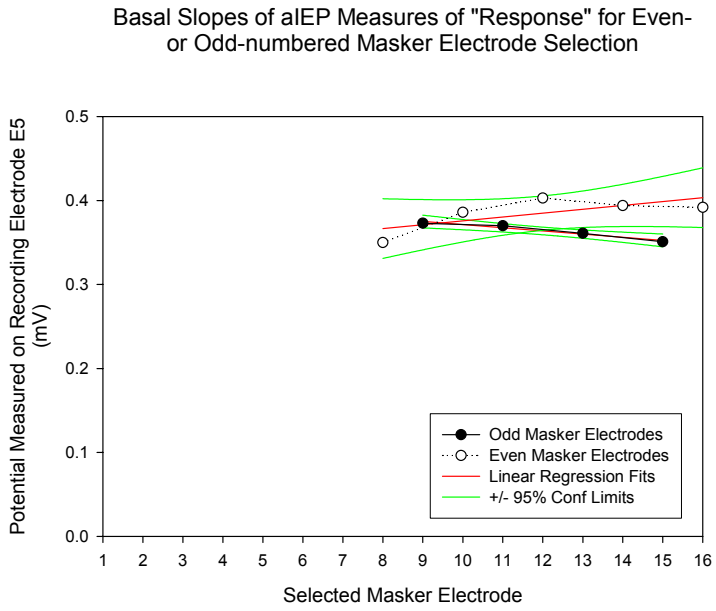
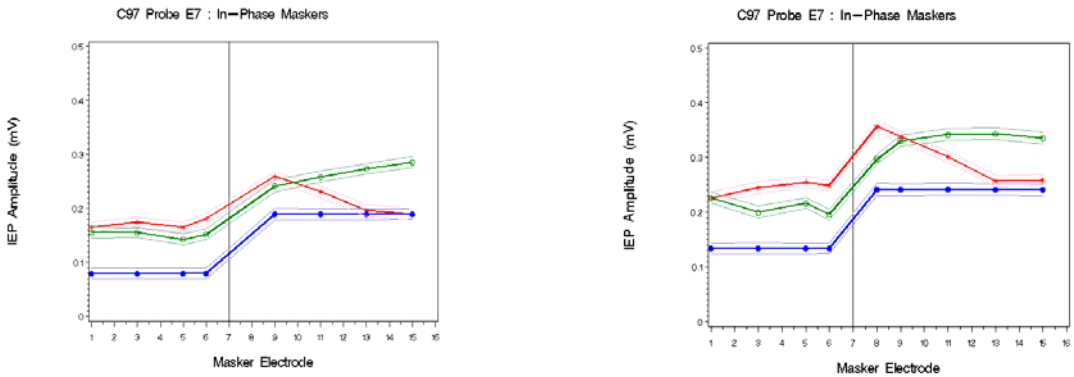


Figure 12. Plots of the basal masker data from Figure 11 presented separately for even- and odd-numbered masker electrodes.

While we remain concerned about this issue, we chose next to repeat our previous measures in a test subject. This would give us insight into the robustness of the effect and a better sense for the overall variability of the general measure. A repeat set of measures was obtained in the subject presenting the greatest degree of bias (Subject C97 with in-phase stimuli for probe E7 – Figure 3, middle-left panel – repeated below left). The repeated measurements were obtained approximately 15 months after the original. The new results are presented below in the right panel of Figure 13.

There are several observations from this repeated experiment. (1) The repetition of the experiment did not show the same bias as a function of masker electrode selection, i.e. the aIEP for Condition A did not change systematically with masker electrode selection. In general, the same overall pattern of interaction was present in the repeated individual measurement as that measured earlier. (2) There is an increase in measured aIEP values between the original and repeated measurement. The basis of this variability in overall aIEP sensitivity to stimulation is not known and could include collectively factors relating to stimulation across the probe electrode, the general responsiveness of the targeted neurons, the characteristics of the recording electrode and the position of the electrode array in the cochlea, among others. Such variation is commonly seen in the repeated measures of the input/output function for subjects over many experimental sessions. Figure 14 shows seven repeated growth function measures for subject C97 for stimulation on electrode E7 with recording on electrode E5. These measures were taken over a period of approximately 24 months. Taken as a whole visually, there is generally good repeatability of these measures over the full stimulus range tested. However, for a

Figure 14. Repeated measures of aIEP growth as a function of stimulus current level. Stimuli were 33 μsec/phase biphasic pulses of alternating polarity presented on electrode E7. Individual aIEP measures were obtained from averaged responses (N = 256) appearing on electrode E5. The seven growth functions presented were collected sequentially over a 24 month period.



Original

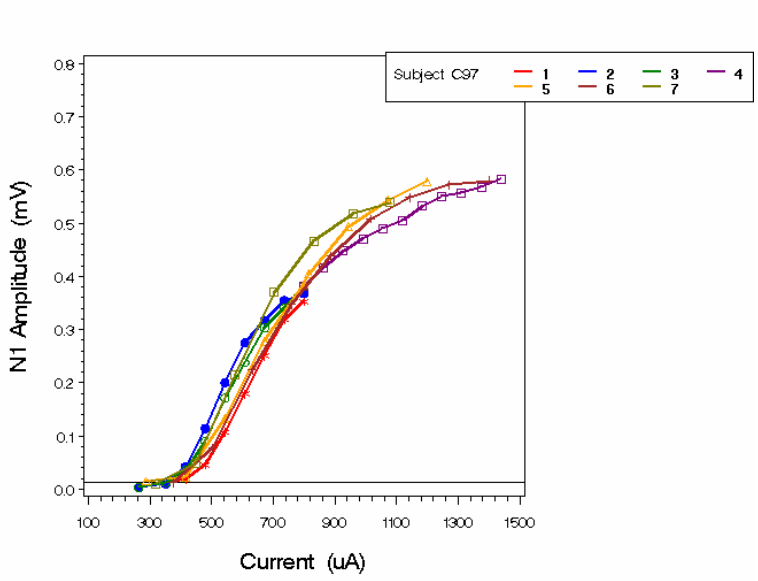
Repeat at 15 mos.

Figure 13. Original and repeat aIEP interaction data sets for Subject C97 using E7 as probe. The details of these panels are described in Figure 3. The time between the original and repeat data sets is approximately fifteen months

specific fixed stimulus current level such as 600 μamp (the base probe stimulus level for the interaction levels for this subject), the aIEP variability can be large percentage wise (35%). Assuming that simultaneous channel interactions are most strongly influenced by electroanatomical factors that would be expected to be stable over time, we anticipate that the channel interaction phenomena presented here will be generally repeatable, as illustrated in Figure 13. We will continue to examine this repeatability issue further to determine what impact such variation has on the measures of channel interaction in general.

In summary, while there apparently is variability in the magnitude of the IEP, it is our impression that the general measurement approach appears to be solid at least with regard to producing repeatable measures of the general interaction phenomena we have described. There are some hardware details to better understand as discussed previously. Our work continues on the physical interpretation of these results and comparison of the findings with psychophysical measures. Both will be reported in future reports, along with further information the hardware and repeatability issues.

3.0 Future Work



We continue to measure relative interaural pitch, fusion, ITD-JND, speech reception, localization and binaural interactions in electrically-evoked brain stem responses as a function of time bilaterally-implanted subjects. Evaluation of split-spectrum processors using asynchronous sound processors will also continue. These data, together with results from current testing designed to determine the cues these subjects use in localization tasks will be reported in future QPRs.

We are also continuing our work directed at triphasic stimulation waveforms. We have finished collecting psychophysical measures that compare interaction for biphasic and triphasic stimuli in subjects implanted with the Clarion CII/HiFocus implant system. The results show an advantage for triphasic stimulation. We have implemented a CIS sound-processing strategy employing triphasic carriers in wearable form for a number of

subjects. The results of longitudinal speech-reception measures are being analyzed and will be reported in a future QPR.

Measurements of channel interaction using intracochlear evoked potentials (IEPs) are continuing. Now that measures using simultaneous stimulation are nearing completion, we plan to move to the interleaved-pulses stimulus condition. We are also beginning to compare the results of these IEP measures with similar behavioral measures made in the same subjects.

Measures of surface potentials have continued to proceed. Pilot studies using our new handheld probe to examine the distribution of artifact potentials on the scale are underway and will be reported in a future QPR.

5.0 References

(Note: the referenced NIH quarterly progress reports can be found at: http://scientificprograms.nidcd.nih.gov/npp/qpr/auditory/qpr_auditory.html.)

Finley, C.C., Herrmann, B., Eddington, D.K. Noel, V., Tierney, J., Whearty, M. 2002. Speech processors for auditory prostheses: Fourth quarterly progress report. Contract N01-DC-2-1001. Neural Prosthesis Program, National Institutes of Health, Bethesda.

Herrmann, B., Finley, C.C., Eddington 2003. Speech processors for auditory prostheses: Eighth quarterly progress report. Contract N01-DC-2-1001. Neural Prosthesis Program, National Institutes of Health, Bethesda.