Ninth Quarterly Progress Report

January 1, 2004, through March 31, 2004

Speech Processors for Auditory Prostheses

NIH Contract N01-DC-2-1001

submitted by

Donald K. Eddington

Massachusetts Institute of Technology
Research Laboratory of Electronics
Cambridge, MA

Joseph Tierney
Victor Noel
Barbara Herrmann
Margaret Whearty

Massachusetts Eye and Ear Infirmary
Boston, MA

Charles C. Finley

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

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 was directed at three areas: (1) continuing experiments in the use of triphasic stimulation waveforms to reduce nonsimultaneous electrode interactions, (2) measures of speech-reception, ITD sensitivity and localization in bilaterally-implanted subjects and (3) analysis of electrically-evoked, intracochlear potentials recorded during single- and two-electrode stimulation conditions in a number of monolaterally-implanted subjects using the Clarion CII/HiFocus implant system. In this QPR, we concentrate on psychophysical and speech-reception measures made in monolaterally-implanted subjects using triphasic stimuli.

2.0 Triphasic Stimulation

A significant issue in the design of speech processors for multi-channel auditory prostheses is how to minimize the effects of interactions occurring between separate channels. One way in which such interactions distort the intended patterns of coded neural activity is by the summation of electrical fields generated by multiple channels being stimulated simultaneously. Depending on the polarities of the fields, this summation may in turn intensify or diminish net electric field intensities in various neural populations, thus producing distortions of the intended stimulation patterns. These *simultaneous interactions* are significantly reduced by sequential stimulation of individual channels using trains of modulated biphasic pulses interleaved across channels. There may remain, however, residual effects due to the stimulation by a pulse on a given channel that influence the response to subsequent pulsatile stimulation on a different channel. One factor that may significantly contribute to these *nonsimultaneous interactions* is the nonlinear response of neural membranes to the leading stimulus pulse which may strongly bias the responsiveness of these neurons to stimulation by subsequent pulses on other electrodes. Again, depending on relative polarities of stimulation, this summation may result in a distorted responsiveness of the local neurons.

In this section we describe our continuing studies to reduce these effects by employing triphasic pulses for stimulation in lieu of commonly used biphasic pulses.

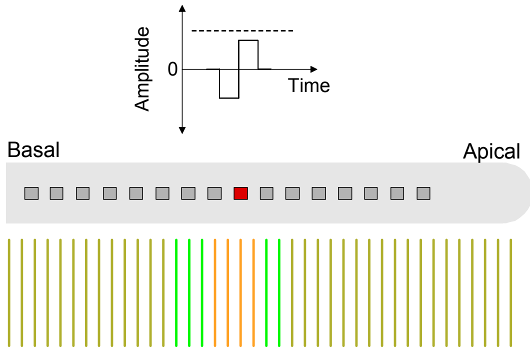

Figure 1. The light gray object represents the cochlea with 16 electrodes. The red electrode is stimulated with the biphasic pulse at an amplitude below threshold (indicated by the horizontal dashed line). The vertical lines represent surviving auditory-nerve fibers and their color represents their state of excitation at the end of the biphasic pulse (olive: at rest; green hyperpolarized; orange: partially

Our motivation for using triphasic stimulation stems from the response of fibers to a *biphasic* stimulus that is too weak to elicit a spike. This is illustrated in Figure 1 for a below-threshold pulse and in Figure 2 for the above-threshold case. In the below-threshold case (Figure 1), the biphasic stimulus does not elicit a spike on any fiber. However, the stimulus level is sufficiently strong for the cathodic phase to drive the orange-colored fibers nearest the stimulating electrode well into a response region that is nonlinear. Due to the nonlinear nature of the response, the hyperpolarizing anodic phase does not completely reverse the impact of the cathodic phase and these fibers are left in a partially depolarized state at the end of the stimulus. Because the green-colored fibers are farther from the stimulating electrode, the stimulus excitation strength is lower than that for the orange-colored fibers reducing the degree to which the nonlinear gating mechanisms control membrane voltage and increasing the relative influence of the linear membrane capacitance. This results in these fibers being left in a hyperpolarized state.

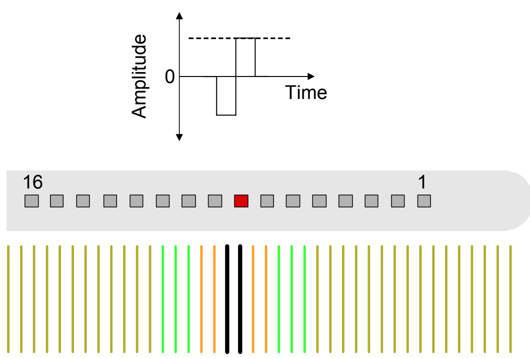

Figure 2. Similar to Figure 1, but with stimulus level increased to threshold where a number of nerve fibers will spike. The color of each fiber indicates its excitation state at the end of the stimulus (olive: resting; green: hyperpolarized; orange: partially depolarized; black: refractory). Electrodes are numbered from 1 (most apical) to 16 (most basal).

Figure 2 illustrates the case in which stimulus level is increased to threshold, eliciting a spike on some fibers. The black-colored fibers will be refractory at the end of the stimulus. Populations of partially depolarized (orange) and hyperpolarized fibers (green) will also exist when the stimulus pulse ends.

It is clear that the response of nerve fibers to a threshold-level second pulse directly following the pulse illustrated in Figure 2 will depend on which electrode delivers this second stimulus. If the second pulse is delivered by electrode 1, the response of fibers at that apical position will likely resemble those excited by electrode 8 since all fibers near electrode 1 are in their resting state. However, if the second stimulus is delivered by electrode 7 directly after a pulse delivered to electrode 8, the response will be more complicated because of the refractory, partially-depolarized and hyperpolarized state of the fibers in that region due to the first pulse. In this case, the response to the second stimulus would interact with the response to the first even though they are not presented simultaneously.

We will use the term "nonsimultaneous interaction" when referring to the phenomenon of the response to one stimulus being influenced by a previous stimulus. Figure 3 plots data from a model nerve fiber (Frijns 1995) that illustrates why one might expect nonsimultaneous interaction to be weaker for triphasic than for biphasic stimulus waveforms.

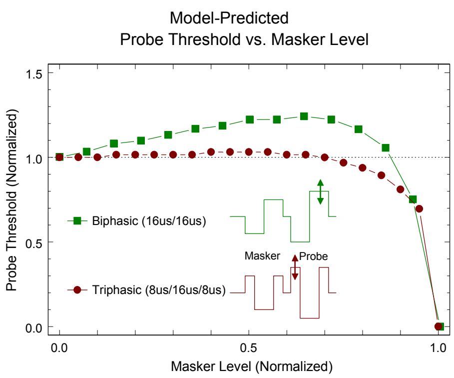

Figure 3. Plot of masked probe threshold (normalized by the nonmasked probe threshold) for single biphasic (green) and triphasic (red) pulses as a function of the masker level (normalized by the threshold of the masker presented alone). In this case the masker and the probe stimuli are applied to the same electrode so the normalized probe and masker thresholds use the same value for normalization (marked by the dotted line).

Nonsimultaneous Interaction: Results From a Single-Unit Model

In Figure 3, the masker and probe stimuli were delivered in sequence to the *same* model electrode. For a given *below*-threshold masker level, the level of the probe stimulus was varied to find the probe level that just elicits a propagating spike on the model fiber. Note that the model results focus on the impact a *below*-threshold masker has on probe threshold. This is because even in the case of *above*-threshold masker stimuli (often the situation when patients use their sound-processor in real life), the fibers generating spikes in response to the masker will be refractory to the following probe stimulus. The fibers able to respond to the probe are those for which the response to the masker stimulus was *below*-threshold.

The data of Figure 3 are replotted in Figure 4 with notations that define several regions of masker level to aid in interpreting psychophysical measures described later in this QPR. .

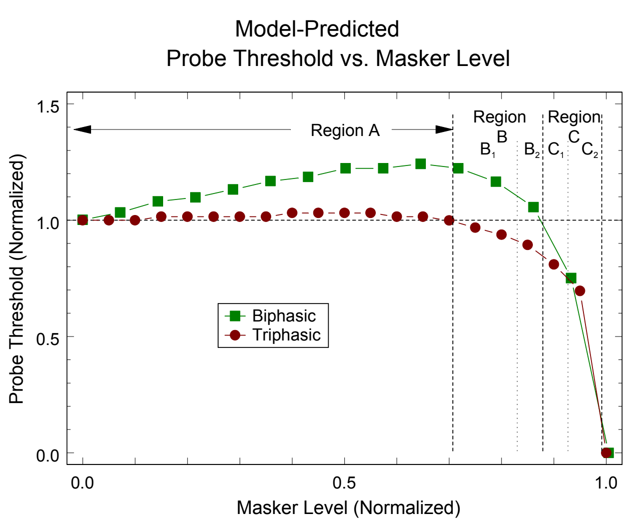

Figure 4. The data of Figure 3 replotted with the definitions of three masker-level regions.

The boundaries of the three major regions (A, B and C) are defined at masker levels where the normalized probe thresholds for either biphasic and triphasic stimuli transition from being >1.0 to <1.0. When normalized probe thresholds are >1.0, the masker stimuli have had a net inhibitory effect on the response to the subsequent probes, thus requiring greater probe stimulation levels to achieve threshold. In contrast, when the normalized probe thresholds are <1.0, the maskers facilitate the response to the probes, thus requiring even smaller probe stimulus levels to achieve threshold.

In Regions A and B for biphasic stimulation (green), the level of the probe stimulus needed to elicit a spike in the presence of a masker (Thr_{P+M}) is greater than the level required with the probe alone (Thr_P). In Region A for triphasic stimulation (red), the masker pulse has a much smaller impact on the fiber's response to the probe than that of the biphasic stimulus.

In Region B, $Thr_{P+M}<Thr_P$ for triphasic stimuli while $Thr_P<Thr_{P+M}$ for biphasic pulses. Region B_1 includes masker levels where $|Thr_{P+M}-Thr_P|$ (magnitude of the difference) is greater for biphasic than for triphasic stimulation. In Region B_2, the magnitude of this difference is greater for triphasic stimuli.

In Region C, $Thr_{P+M}<Thr_P$ for both triphasic and biphasic stimulation. Region C_1 includes masker levels for which $|Thr_{P+M}-Thr_P|$ is greater for triphasic stimuli. In Region C_2, this difference is approximately the same for biphasic and triphasic stimulation.

If one integrates $|Thr_{P+M}-Thr_P|$ for masker levels 0 to 1, the resulting value will be larger for biphasic than for the triphasic stimulation, leading one to conclude that triphasic stimulation should generally result in less nonsimultaneous interaction than biphasic stimulation. The following section describes a psychophysical experiment conducted in implant users that tests this prediction.

Nonsimultaneous Interaction: Definition and Measurement Method for Psychophysical Studies

Figure 5 illustrates the procedure used to make behavioral measures of nonsimultaneous interaction in 16 cochlear implant users. The probe level was varied using an adaptive (one-up, two-down), 3-alternative forced-choice procedure to measure the threshold for detecting a probe stimulus. For each probe-masker electrode combination, the probe-alone threshold (Thr_P) and "probe with masker" threshold (Thr_{P+M}) was measured for both biphasic and triphasic stimuli. The masker levels tested were -6dB, +6dB and +12dB re the masker threshold. The subjects were eight Clarion CII implantees (2-mm separation between probe and masker electrodes) and eight Ineraid users (4-mm masker-probe separation).

In the case of the -6 dB masker level, we assume the excitation picture look something like Figure 1 just after the masker stimulus and before the probe is delivered. It is unlikely that any fibers will have elicited spikes and consequently Figure 1 shows none in

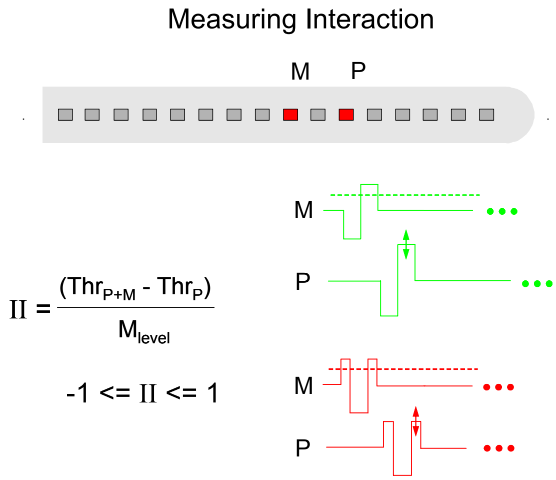

Figure 5. Procedure for measuring nonsimultaneous interaction. For a given masker (M) and probe (P) electrode, the threshold of the probe was measured for biphasic (300 ms duration, cathodic/anodic phase order, 16 µs phase durations, 4000 pulses per second (4kpps)) and triphasic (300 ms duration, anodic/cathodic/anodic phase order, 8µs/16µs/8µs phase durations, 4 kpps) stimuli in two conditions: probe alone (Thr_P) and probe with masker (Thr_{P+M}). The waveforms for the P+M condition are shown on the right side of the figure. Notice that the masker level is greater than threshold (horizontal dashed line) for the case shown (see text for additional details. An Interaction Index was computed for each set of measurements using the formula shown on the left side of the figure.

a refractory state. The condition of the fibers nearest the masker electrode is probably similar to that depicted in Figure 4 (hyperpolarized) for the modeled neuron responding to a normalized masker level of approximately 0.5. As one examines fibers located farther from the masker electrode, the effective masker excitation strength for each neuron will decrease and the predicted excitation state will behave as if the normalized masker level of Figure 4 is decreasing.

In the case of the +6 dB and +12 dB masker levels, the excitations states of nerve fibers just after the masker stimulus (and before the probe) should be distributed in a manner similar to that shown in Figure 2. Some segment of fibers nearest the masker electrode will elicit spikes (normalized masker level > 1) and be refractory to the probe stimulus. As one the distance between the fiber and the masker electrode increases, the normalized excitation strength of the masker will decrease below 1 and, based on the model results, one should find fibers in the various excitation states predicted by the model (Figure 4).

Nonsimultaneous Interaction: Model Predictions

Given the definition of Interaction Index (II) used in this report ($II=[Thr_{P+M}-Thr_P]/M_{level}$), the model results of Figure 4 lead to several predictions regarding the interaction indices (IIs) for biphasic (II_{Bi}) and triphasic (II_{Tri}) stimulation and for the relative magnitude (absolute value) of the biphasic ($magII_{Bi}$) and triphasic ($mag\ II_{Tri}$) IIs. For biphasic stimuli, if most fibers recruited by the probe stimulus are in a state consistent with Region A, then Thr_{P+M} will likely be substantially greater than Thr_P, $[Thr_{P+M}-Thr_P]$ will be greater than 0, and hence $II_{Bi}>0$. In the case of triphasic stimuli, the difference $[Thr_{P+M}-Thr_P]$ will also tend to be positive but the magnitude lower than for the biphasic case, leading to the predictions that $II_{Tri}>0$ and $magII_{Bi}> magII_{Tri}$.

In the biphasic case of Region-B fibers, $[Thr_{P+M}-Thr_P]$ will tend to be greater than 0, thus $II_{Bi}>0$. For triphasic stimulation $[Thr_{P+M}-Thr_P]<0$ and consequently $II_{Tri}<0$. For Region-

B_1 fibers, the model predicts $magII_{Bi}>magII_{Tri}$ and whereas for Region-B_2 fibers $magII_{Bi}<magII_{Tri}$.

When fibers are in the partially-depolarized state associated with Region C, $[Thr_{P+M}-Thr_P]<0$ for both biphasic and triphasic stimuli. Thus $II_{Bi}<0$ and $II_{Tri}<0$. The $magII_{Bi}<magII_{Tri}$ in Region C_1 and $magII_{Bi}\approx magII_{Tri}$ in Region C_2.

The model-predicted nonsimultaneous interaction relationships for fiber populations dominated by the excitation states defined by the regions diagrammed in Figure 4 are summarized in Table I.

Table I

Region (see Figure 4)				
A	B_1	B_2	C_1	C_2
$II_{Bi}>0$ $II_{Tri}>0$ $magII_{Bi}>magII_{Tri}$	$II_{Bi}>0$ $II_{Tri}<0$ $magII_{Bi}>magII_{Tri}$	$II_{Bi}>0$ $II_{Tri}<0$ $magII_{Bi}<magII_{Tri}$	$II_{Bi}<0$ $II_{Tri}<0$ $magII_{Bi}<magII_{Tri}$	$II_{Bi}<0$ $II_{Tri}<0$ $magII_{Bi}\approx magII_{Tri}$

<u>Nonsimultaneous Interaction: Psychophysical Results</u>

The results of the behavioral interaction measures are shown in the six bar graphs of Figure 6. Each graph presents a pair of bars that represent the two interaction indices (green for biphasic and red for triphasic stimulation) measured for each subject in each condition. The top three panels are data collected with the same eight Clarion subjects at three different masker levels. The masker and probe electrodes were the same for all subjects and conditions (masker: EL7; probe: EL5). The bottom three panels represent the measures made in eight Ineraid subjects using the same three relative masker levels. The masker electrode was also selected from the middle of the electrode array and the probe electrode located apical to the masker (masker: EL3; probe: EL2).

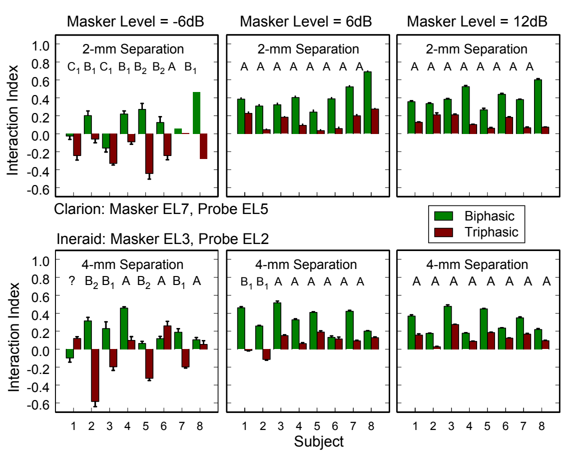

Figure 6. Plots of Interaction Index (II) measured using biphasic (green bars) and triphasic (red bars) stimuli for 8 subjects using the Clarion CII implant system (top row of panels) and for 8 Ineraid implantees (bottom row). II is plotted for three masker levels: -6dB re masker-alone threshold (left column of panels), +6dB (middle column) and +12dB (right column). The row of letters in each panel associate each subjects triphasic-biphasic results with the regions identified in Figure 4 (see also Table I). The stimulation parameters are described in caption to Figure 5.

The IIs for both Clarion and Ineraid subjects are much more homogeneous in sign (greater than zero) and relative magnitude ($magII_{Bi}>magII_{Tri}$) for the *above*-threshold masker conditions than for the sub-threshold masker. One approach to interpreting these results makes use of the model predictions summarized in Table I. While we are only beginning this process, we present the following discussion to provide an introduction to the approach we are taking.

Notice that each pair of biphasic/triphasic IIs is labeled by one of the excitation regions defined in Figure 4. The assignment of these labels is based on the model predictions summarized in Table I. Take for example Clarion subject 8. The IIs measured using a 12-dB masker are plotted as the top-most and right-most two bars of Figure 6. In this case, $II_{Bi}>0$, $II_{Tri}>0$ and $magII_{Bi}>magII_{Tri}$. Because these relationships are consistent with the majority of fibers that generate spikes in response to the probe stimulus being in an excitation state represented by Region A (see Table I) at the end of the masker stimulus, this pair of bars is labeled "A." In contrast, consider the IIs for Clarion subject 1 tested with a -6-dB masker (top-most and left-most two bars of Figure 6). In this case, $II_{Bi}<0$, $II_{Tri}<0$ and $magII_{Bi}<magII_{Tri}$. These II relationships are consistent with mainly fibers in excitation state C_1 influencing the degree to which the masker impacts the responses to the probe. Similar reasoning was applied to the IIs measured in each subject and condition to arrive at the labels for each II pair. Except for one condition in one subject (Ineraid subject 1; -6dB masker; labeled as "?"), the results of each subject and condition were consistent with one of the regions defined in Figure 4.

Results consistent with four of the five excitation regions (A, B_1, B_2, C_1) are represented in these psychophysical data. There are 34 of the 48 cases where the IIs for both biphasic and triphasic stimulation are both positive. In 33 of those cases, $magII_{Bi}>magII_{Tri}$ making them consistent with Region A. Seven cases are consistent with fibers in an excitation state labeled Region B_1 and four with Region B_2. Region C_1 is represented by results from two Clarion subjects in the below-threshold condition. The results of one subject/condition were not consistent with the model predictions and one result category (C_2) was not observed.

Nonsimultaneous Interaction: Interpretation of Psychophysical Results

In the 3-alternative, forced-choice task used in these experiments, each trial consists of three time intervals with both the masker and probe (masker+probe) stimuli presented nonsimultaneously in one, randomly-selected interval and the masker stimulus presented alone in the remaining two intervals. For test conditions using a *below*-threshold masker (left panels of Figure 6), the subject identifies in which of the three intervals an audible sensation was detected. A criterion number of fibers (N_{below}) will need to spike in response to the masker+probe stimulus in order for the subject to reliably detect the masker+probe interval. (Presumably, no fibers will elicit spikes in the masker-alone intervals.)

In the *above*-threshold masker conditions (middle and right panels of Figure 6), the subject hears a sensation in each of the intervals and must select the interval that is different. In this case, some fibers will respond with spikes in the masker-alone intervals. In order to reliably distinguish the masker+probe interval from the masker-alone intervals, the number of fibers producing spikes in the masker+probe condition must be greater (N_{above}) than in the masker-alone condition. We assume that $N_{below} < N_{above}$ since, in general, the detection of the probe in the presence of an *above*-threshold masker will be more difficult than with a *below*-threshold masker.

We also assume (for both biphasic and triphasic stimulation) the basic picture of excitation states in the local fiber population represented in Figure 7 for the *below*-threshold masker condition. Note that the number of fibers in the "C" excitation state is

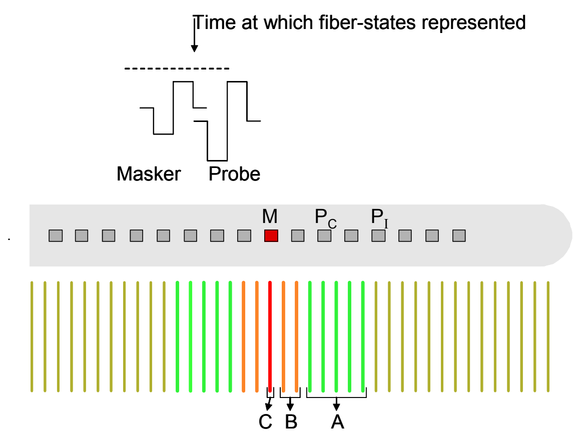

Figure 7. Top: time waveforms of the *below*-threshold masker and probe stimuli. The vertical arrow indicates the time at which the fiber-states were sampled to determine the fiber colors (see below). Middle: unrolled cochlea with Clarion electrode contacts represented as squares. M = masker electrode; P_C = probe electrode for Clarion electrode and P_I = position of Ineraid probe electrode. Bottom: vertical lines represent auditory-nerve fibers. The colors code their excitation state at the end of the masker stimulus (red: partially depolarized for both biphasic and triphasic stimuli (state-region "C" of Figure 4); orange: hyperpolarized for biphasic and partially-depolarized for triphasic (state-region "B"); green: hyperpolarized for biphasic and triphasic stimuli (state-region "A").

assumed to be fewer than the number of B-state fibers and that the majority of fibers not at rest are in excitation state "A." While the number and distribution of fibers in each of the excitation regions are likely to vary considerably from subject-to-subject, we find the schematic of Figure 7 to be helpful in interpreting overall trends. For instance, in the case of probe electrode P_c, we hypothesize that the relatively small number of spiking fibers (N_{below}) needed for the subject to detect the masker+probe stimulus condition tend to come from the fiber pools that are partially depolarized (Regions B and C for triphasic stimuli and Region C for biphasic) rather than those from the hyperpolarized Region A. This is consistent with the psychophysical results that show the biphasic/triphasic II pairs are consistent with excitation states B and C for 11 subjects (69%) and only 4 (25%) consistent with A. Likewise it is not surprising that the number of IIs below zero is greater for triphasic (10 of 16; 64%) than for biphasic (3 of 16; 19%) stimuli because the range of relative masker levels resulting in a partially-depolarized fiber is greater for triphasic than biphasic stimulation (see Figure 4).

In the case of the Ineraid subjects, the probe (P_I) is farther from the masker electrode than P_C (see Figure 7). We therefore hypothesize that P_I is farther from the partially-depolarized fibers than P_C. This means that as probe-level increases, P_I is more likely than P_C to cause fibers in excitation-state A to spike before recruiting C- and B-state fibers. This is consistent with the *below*-threshold results in which the IIs of Ineraid subjects may be more likely to produce results consistent with region A than Clarion subjects (e.g., 3 A-state IIs for Ineraid vs. 1 for Clarion).

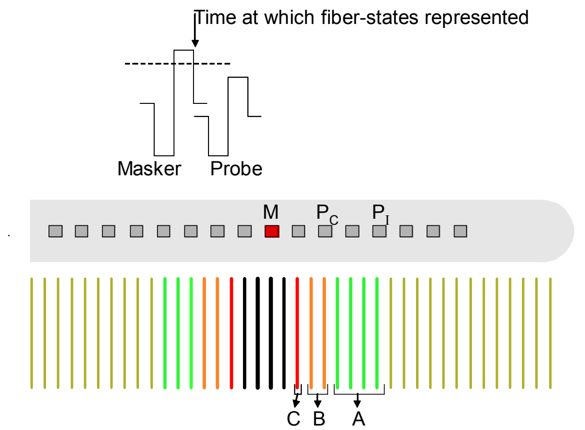

Figure 8. Top: time waveforms of the *above*-threshold masker and probe stimuli. The vertical arrow indicates the time at which the fiber-states were sampled to determine the fiber colors (see below). Middle: unrolled cochlea with Clarion electrode contacts represented as squares. M = masker electrode; P_C = probe electrode for Clarion electrode and P_I = position of Ineraid probe electrode. Bottom: vertical lines represent auditory-nerve fibers. The colors code their excitation state at the end of the masker stimulus (black: refractory; red: partially depolarized for both biphasic and triphasic stimuli (state-region "C" of Figure 4); orange: hyperpolarized for biphasic and partially-depolarized for triphasic (state-region "B"); green: hyperpolarized for biphasic and triphasic stimuli (state-region "A").

In the case of *above*-threshold masker levels, we assume a pattern of excitation something like that pictured in Figure 8. In this case, a number of fibers will conduct spikes in response to the masker and those fibers will be refractory to the probe (black). Like the *below*-threshold case, a number of fibers in both partially-depolarized and hyperpolarized states will result from the masker stimulus and impact responses to the probe stimulus.

We assume that in most conditions, the number of fibers producing spikes in response to the probe that are required for the subject to reliably discriminate the masker+probe from the masker alone condition is relatively large compared with the *below*-threshold case. This means that it is unusual to be able to recruit that number of fibers by simply recruiting the C- and B-state fibers and, therefore, the IIs for the *above*-threshold conditions will tend to reflect more A-state fibers being recruited. This is the pattern of IIs seen in the middle and right panels of Figure 6, where 30 out of 32 (94%) II pairs are consistent with A-state fibers.

We should also note that the model results of Figure 4 predict consequences of nonsimultaneous interaction beyond those itemized in Table I and discussed in this section. For instance, the hyperpolarization predicted for excitation states A and B using biphasic stimuli peaks at the boundary between Regions A and B. Thus, fibers experiencing a normalized masker excitation strength of 0.7 will require a stronger probe excitation strength to fire than fibers more distant from the masker (that experience a weaker normalized masker excitation). This means that depending on the position of the probe electrode, the hyperpolarization of fibers near the masker electrode could serve to sharpen the longitudinal extent of the probe-elicited, fiber excitation pattern on the side nearer the masker. This characteristic could also result in two longitudinally separate groups of fibers firing in response to the probe stimulus: one group associated with region A where the biphasic masker's excitation strength was small and another associated with region C where the fibers are partially depolarized.

<u>Nonsimultaneous Interaction: Triphasic Carriers in CIS Sound-Processing Strategies</u>

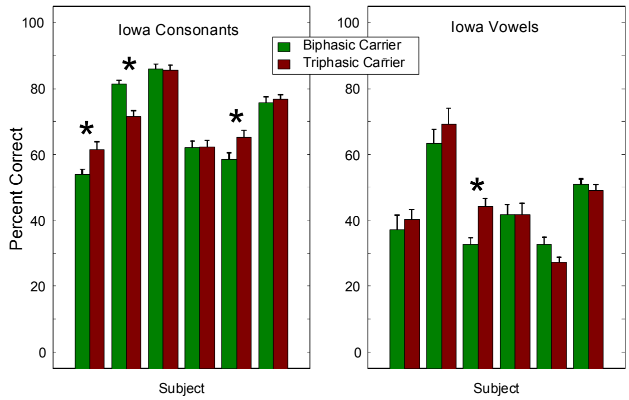

Figure 9. Measures of consonant and vowel reception for six subjects using CIS sound-processing strategies that employ biphasic or triphasic carrier waveforms. Bars represent the average percent of items correctly identified and error bars the standard error of the mean. Number of randomized lists presented varied from 6 to 60. Asterisks mark subjects where the difference between biphasic and triphasic scores were statistically significant ($p<0.05$, t-test and Wilcoxon sum-rank)

In the case of CIS sound-processing strategies that employ high-rate pulse-train carriers (4000 pps) and operate at levels producing comfortable listening levels, the *above*-threshold single-pulse psychophysics of Figure 6 are probably most relevant. In this case the $magII_{Bi}>magII_{Tri}$. Consequently, one might suspect that switching from biphasic to triphasic carriers would reduce interaction between channels and increase performance.

Figure 9 shows acute consonant and vowel reception scores for two CIS sound-processing strategies used by six Ineraid subjects. In the biphasic strategy, each channel's carrier was a biphasic pulse train (cathodic phase first, 16 µs/phase, 3.9 kpps). The carriers for the triphasic strategy were triphasic pulse trains (phase order: anodic/cathodic/anodic, 8µs/16µs/8µs respectively and 3.9 kpps).

In the case of consonant recognition, two of six subjects score significantly better using the triphasic strategy and one scores significantly worse. For vowels, only one subject scores significantly higher using triphasic stimulation. While these differences are modest, without longitudinal testing it is difficult to conclude whether triphasic stimulus waveforms can lead to changes in performance that are functionally important in some individuals.

Figure 10 plots preliminary results from a study designed to evaluate the performance of triphasic processors after several months of use. The carrier rates and phase durations associated with the CIS implementation in this chronic listening study were limited in some subjects by the stimulus amplitude required to produce comfortable listening levels. This means that the repetition rate and phase duration associated with the carrier pulse trains used in the chronic study were not consistent across subjects and, therefore, not always the same as in the acutely-applied laboratory implementation previously described in Figure 9. For instance, carrier rates in the chronic study vary from approximately 2 to 4 kpps. We will give a complete description of these differences in a future QPR when we have finished collecting these chronic data and had an opportunity to relate performance differences across subjects to differences in their sound-processing strategies. We present the data of Figure 10 in this QPR as a preliminary snap shot of a work in progress.

Overall, the largest differences tend to favor biphasic carriers (the sound-processing system most familiar to the subjects). At this point, the data do not support the

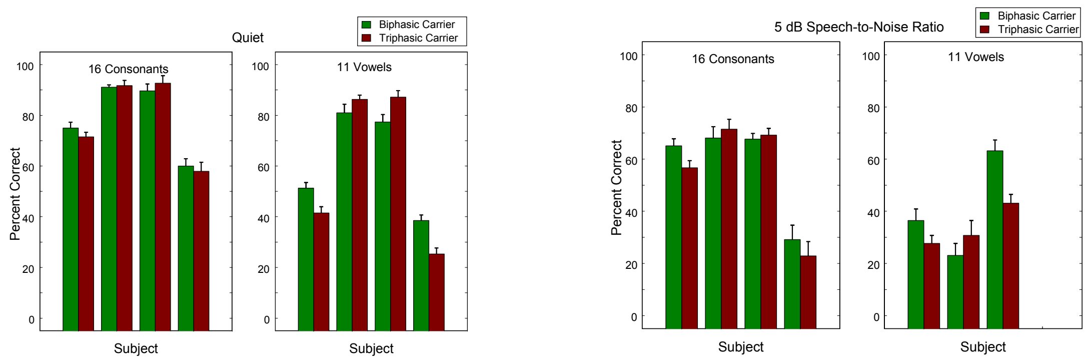

Figure 10. Speech-reception scores measured in 4 Clarion subjects using interleaved pulses sound-processing strategies with carrier rates of 2 kpps or greater. Green bars represent scores for a sound-processing strategy using biphasic carriers and red bars for triphasic carriers. All measures were made after at least 3 weeks wearing the processing strategy tested. The two left-most panels are scores measured in quiet and the two right-most panels plot scores measured in noise (5 dB speech-to-noise

hypothesis that the reduction of interaction using triphasic interleaved pulses results in better performance than biphasic strategies for carrier rates running at the limit of today's *clinical* technology. A few of the many factors that may explain the current results are: (1) additional time is needed for the subjects to adjust to the conversion from biphasic to triphasic carriers, (2) the decrease in interaction at these carrier rates (2 to 3 kpps) is not significant or (3) the reduction in interaction using triphasic carriers is simply not functionally significant at any carrier rate.

Another month of listening experience by the subjects will help us evaluate factor (1). In order to evaluate factor (2), we plan to measure the relative interaction as a function of delay between the masker and probe using the same techniques described in the section on psychophysics above. If these experiments suggest the reduction in interaction will be considerably greater for carrier rates higher than 2 kpps, we will implement triphasic and biphasic strategies at these higher carrier rates and test their longitudinal performance. For carrier rates between 2 and 3 kpps, the current data indicate performance with CIS strategies will not benefit from using triphasic stimulation to reduce nonsimultaneous interaction.

3.0 Future Work

We are beginning binaural psychophysical testing of two subjects who have used a monolateral implant for at least 6 months and recently underwent implantation of their unimplanted ear. 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 in the three bilaterally-implanted subjects described in earlier QPRs. We are also evaluating split-spectrum processors using asynchronous sound processors. 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.

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.

4.0 References

Frijns, J. H. M. (1995). Cochlear implants: a modeling approach. Faculteit der Godgeleerdheid. Eindhoven, Rijksuniversiteit te Leiden: 184.