Third Quarterly Progress Report

July 1, 2002, through September 30, 2002

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 effort was directed at three areas: (1) continuing experiments in the use of triphasic stimulation waveforms to reduce nonsimultaneous electrode interactions, (2) measures gathering information to guide selection of interaural electrode pairs for bilateral sound-processing strategies to be designed for our three bilaterally-implanted subjects, and (3) refining the stimulation/recording tools for the Clarion CII/HiFocus implant system that have enabled us to begin field and evoked-response measures in these subjects. Additional details of these stimulation and recording tools, along with initial measures from subjects will appear in subsequent Quarterly Progress Reports (QPRs). In this QPR, we concentrate on two areas: (1) psychophysical measures of interaction using waveforms designed to reduce the influence that stimulation at one electrode has on a neighbor and (2) psychophysical measures made using bilateral stimulation that will be used to design wearable sound-processing strategies for bilaterally-implanted subjects.

2.0 Triphasic Stimulation

In our first QPR (Eddington, Tierney et al. 2002), we described initial measures of the extent to which above-threshold, biphasic and triphasic stimulus waveforms (maskers) delivered by an intracochlear electrode influenced the threshold of a biphasic waveform (probe) delivered to a neighboring electrode. Electrode 3 was selected as the masker electrode in eight subjects with Ineraid cochlear implants. In one condition, the masker electrode received a train of biphasic pulses (300 ms duration, cathodic/anodic phase order, 16 µs phase durations, 4000 pulses per second (4kpps)) at a level that produced a comfortably loud sound sensation (approximately 40% of the functional range of loudness). In another condition, the masker stimulus was a triphasic pulse train (300 ms duration, anodic/cathodic/anodic phase order, 8µs/16µs/8µs phase durations, 4 kpps) delivered at the same (40%) sensation level. The threshold of a probe stimulus (biphasic pulse train, 300 ms duration, cathodic/anodic phase order, 16 µs/phase, 4 kpps) delivered to electrode 4 (4 mm masker/probe electrode separation) was measured in three conditions: (1) probe alone, (2) probe with biphasic masker and (3) probe with triphasic masker. In the masked conditions, the masker stimulus was interleaved with the probe stimulus such that the probe pulses followed their respective masker pulses within 2 µs (see waveforms inset in Figure 1). An adaptive, three-interval, forced-choice procedure was used to make the threshold measures (typical level steps were approximately 5% of the threshold).

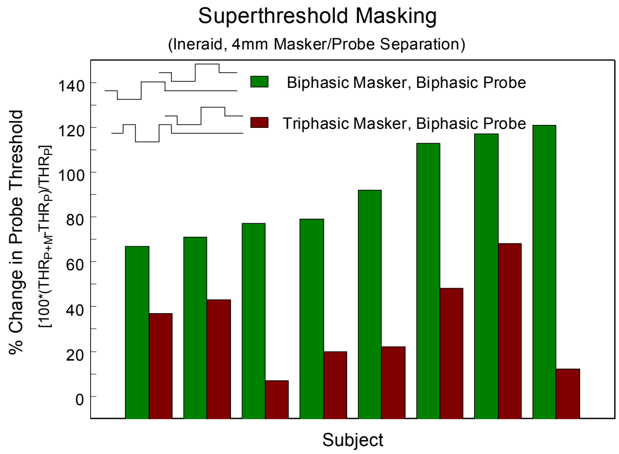

Figure 1. The percent change in the probe threshold measured in eight Ineraid subjects for biphasic and triphasic maskers delivered to an electrode 4 mm apical to the probe electrode. The

The degree to which the biphasic and triphasic masker stimuli influenced the threshold of the biphasic probe stimulus for each of eight Ineraid subjects is shown in Figure 1. The percent change in the probe threshold was computed by subtracting the probe threshold without masker (THR_P) from the masked probe threshold (THR_{P+M}), normalizing by the THR_P, and multiplying by 100. Note that the percent change in probe threshold is significantly lower for the triphasic masker in all subjects. This result leads one to wonder whether use of triphasic stimuli in sound processors might benefit performance by reducing temporal interactions across channels.

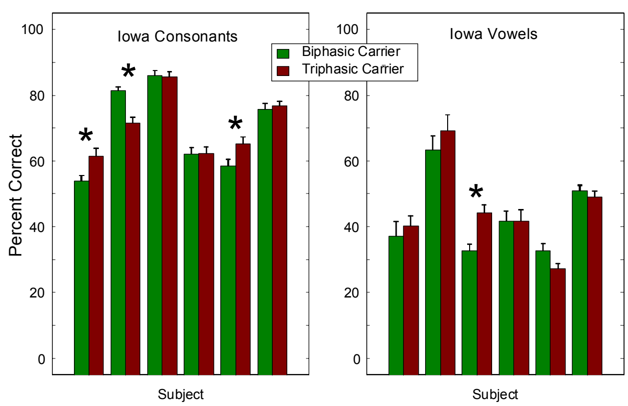

Figure 2. Measures of consonant and vowel reception for six subjects using CIS sound-processing strategies that employ biphasic or triphasic carrier waveforms. Bars represent the average percent of items correctly identified and error bars the standard error of the mean. Number of randomized lists presented 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)

Figure 2 shows 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. We are currently preparing to provide a number of Clarion C2 implantees with triphasic stimulation strategies that they will wear for approximately two months to determine asymptotic performance.

3.0 Bilateral Stimulation

In the first and second quarters of this contract, three subjects who had already received monolateral Clarion CII/HiFocus (with positioner) implants underwent cochlear implantation of their unimplanted ear (also with the Clarion CII/HiFocus [with positioner] implant system). A summary of these subjects is provided in Table I.

Note that each subject wore their first implant for at least six months before receiving their second implant. This made it possible to insure that their monolateral performance using the first implant was (1) not substantially improved when used together with a hearing aid in the unimplanted ear and (2) significantly better than their performance using a hearing aid alone in the unimplanted ear.

Table I: Bilaterally-Implanted Subjects

Subject (ear)	Duration Deaf (years)	1st Implantation (date)	2nd Implantation (date)	CNC Score (% words)
C092(r)	5		3/2002	
C092(l)	3	6/2001		98%
C105(r)	10		5/2002	
C105(l)	1	6/2001		38%
C109(r)	3	8/2001		90%
C109(l)	3		5/2002	

We have two major goals for these bilaterally-implanted subjects before providing them with wearable bilateral sound-processing strategies: (1) determining the optimum interaural electrode pairs for use with bilateral sound-processing strategies and (2) documenting bilateral and monolateral (electrically-experienced ear and electrically-naive ear) performance on a battery of psychophysical and speech-reception measures that include:

1. Interaural pitch comparisons
2. Fusion (see text below for definition)
3. ITD/ILD sensitivities
4. Binaural interaction components (evoked response)
5. Speech reception in quiet and with a spatially separated noise source
6. Localization

Because anatomical and physiological changes probably occur centrally as a consequence of deafness (e.g., Shepherd, Hartmann et al. 1997) and also in response to the electric stimulation we deliver (e.g., Snyder, Rebscher et al. 1990), we are faced with two problems. First, measures of bilateral interaction based on anatomical, physiological and perceptual measures may be dissociated in the naïve state prior to experience with bilateral stimulation. Second, the choice of the initial interaural electrode pairings may influence subsequent plastic changes and ultimate outcome. To the extent possible in these bilaterally naïve subjects, we plan to use measures corresponding to the first four items of the above list (plus CT data to compare the relative insertion depths of each electrode) to guide selection of interaural electrodes. We hope these measures will lead to sound processing strategies that not only optimize short-term performance, but also provide a basis for the CNS adaptation that will maximize improvements of (1) speech reception in the presence of one or more spatially separated noise sources and (2) localization of sound sources.

We began by exploring the relative pitch of interaural electrodes and found that the timbre of the sounds produced by stimulating a single electrode in the first-implanted ear was much different than that elicited by stimulation of an electrode in the second-implanted ear. All three subjects spontaneously observed that this difference was sufficiently large to make reliable pitch comparisons across the two ears impossible. They each described the sounds elicited by stimulating electrodes in the recently-implanted ear as sharp and strident. One patient called it the “Munchkin” effect after the voice characteristics of those characters in the classic “Wizard of Oz” movie. Based on these subject observations, we decided to move (at least temporarily) from pitch to explore the extent to which the sensation produced by simultaneous stimulation of interaural electrode pairs would be fused (i.e., a single, punctate sound sensation). We note that as we make the other measures described below, the difference in timbre between the two ears reported by our subjects decreases. This means we will return to interaural pitch comparisons before the subjects begin using a wearable sound processor with their second implant.

The fusion experiment is conducted by selecting one electrode from each of the right and left electrode arrays. Each electrode of this interaural pair is stimulated alone (biphasic pulse train, 300 ms duration, cathode/anodic phase order, 108 μs/phase, 200 pps) and the stimulus level adjusted to produce a criterion sensation level (typically just below the subject’s most comfortable listening level). This procedure results in a stimulus level assigned to each electrode that elicits sensations of equal loudness (one in each ear) when the two electrodes are stimulated sequentially. The interaural pair is then stimulated simultaneously and the subject asked to describe the sensation they experience. For electrodes that are cochleotopically far apart (e.g., right electrode 1 [R1] with left electrode 16 [L16]), the subject will likely report hearing two different sounds, one in each ear. For some interaural electrode pairs that are presumably similar in cochleotopic position (e.g., L14/R13), the subject might report hearing a single, punctate (fused) sound at a location inside their head.

Table II: Fusion Experiment Responses

Description	Fusion Score
Two different sounds, one at each ear	0
The same sound, at two different points	1
The same sound, at two different regions	1.5
Diffuse, fills head with two concentrated regions	2
Diffuse, fills head	3
Diffuse, fills head with one concentrated region	4
One punctate sound	5

The range of sound sensations reported by the three subjects is large, but consistent across subjects. Table II lists the major classifications of responses we encountered in conducting the fusion experiments. The fusion scores listed in the right-hand column are a first attempt to quantify the degree of fusion associated with each class of response. Quantitative scales will be useful as we begin to combine various classes of data. For instance, we expect the fusion data we collect will provide some guidance in selecting interaural electrode pairs for bilateral sound-processing strategies (e.g. pairs producing responses with fusion scores of 0 or 1 may be less effective than pairs eliciting responses with fusion scores of 5). Measures of an interaural electrode pair's sensitivity to interaural time differences may lead one to select a different set of pairs. Being able to numerically combine these different kinds of data (pitch, fusion, ITD/ILD sensitivity, binaural interaction and position based on CT data) with different weights will facilitate the exploration of the total data set and its prediction of which interaural pairs will be optimum for a sound-processing strategy.

Figure 3 presents plots of the fusion data we have collected to date for each of our three bilaterally-implanted subjects. While these data sets are not complete (white space represents interaural electrode pairs not tested), the results from subjects C092 and C109

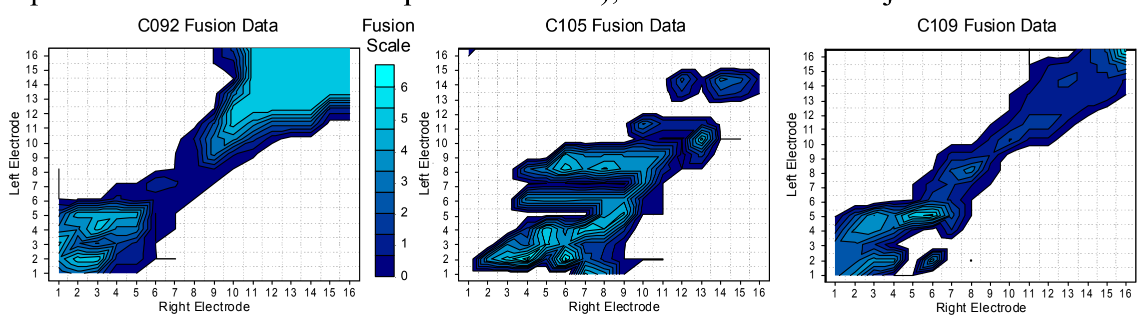

Figure 3. Plots of fusion data for three bilaterally-implanted subjects. For each interaural electrode pair tested, a color is plotted that represents the subject's response. As shown by the Fusion Scale, lighter colors represent higher Fusion Scale values (see Table II for the correspondence between the Fusion Scale and the categories of responses). White space marks interaural electrode pairs that have not been tested

are consistent with an interpretation that interaural electrode pairs near the diagonal representing equal left/right electrode numbers are more likely to be fused. The collection of additional data will determine whether this interpretation holds up or whether a more complex pattern like that for subject C105 will emerge.

The data of C092 show a region of highly fused sensations produced by interaural electrode pairs in the upper-right quadrant. One wonders to what extent this fusion plateau indicates a large set of interaural electrode pairs with relatively good binaural sensitivity. In order to explore this issue, we have begun measures of just-noticeable differences (JNDs) of interaural time difference (ITD) for electrode pairs in this region.

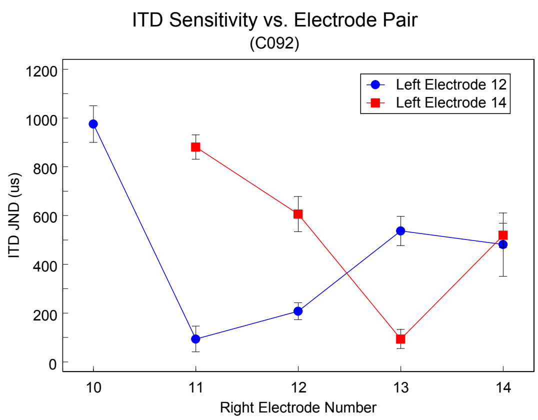

Figure 4. Plot of the JND for ITD as a function of interaural electrode pair. The data represented in blue are the means and standard deviations for right electrodes paired with left 12 and the red for those paired with left 14. An adaptive, two-interval, forced-choice protocol was used where the subject reported whether the sound sensation elicited by the second stimulus was to the right or left of that elicited by the first. The stimulus with ITD was randomly assigned to the first or second interval and only right-ear stimuli were delayed. Stimuli were biphasic pulse trains (300 ms, 200 pps, 108 μs/phase) with right-electrode and left-electrode levels adjusted to give a centered image with 0 ITD.

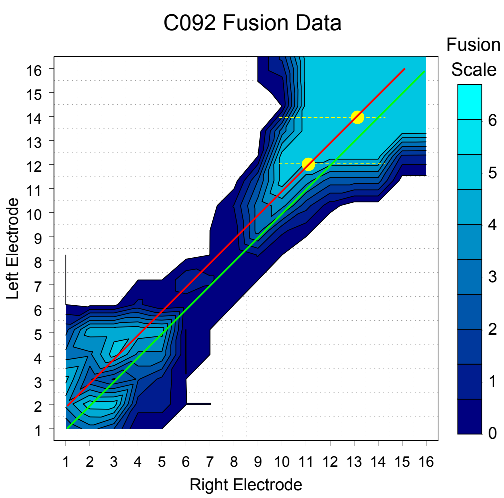

Figure 5. The filled circles mark the interaural electrode pairs with smallest ITD JNDs from Figure 4. The dashed yellow lines show the range of interaural electrode pairs for which ITDs have been measured.

Initial measures of ITD JND are shown for nine interaural electrode pairs from this "fusion plateau" in Figure 4 (see caption for a description of methods). Notice that the ITD sensitivity is far from homogeneous across these electrode pairs. In the case of right electrodes paired with left-electrode 12 (L12), the L12/R11 pair shows the highest sensitivity. When examining pairs including L14, the L14/R13 combination is most sensitive to ITD.

The interaural pair giving the best ITD-JND for L12 and L14 in the data of Figure 4 are plotted as circles on subject C092's fusion data in Figure 5. The green diagonal line represents electrode pairs where the left electrode number equals the right (e.g., L1/R1 and L10/R10). This very limited set of ITD-JND results is consistent with interaural electrode pairs and suggests selecting a set of electrodes represented by the red diagonal line where the left electrode number is one greater than the right (e.g., L2/R1 and L11/R10).

As we expand the fusion and ITD sensitivity measures to include additional interaural electrode pairs in each of the subjects and add additional measures (e.g., interaural pitch comparisons, cochleotopic position and perhaps binaural interaction of evoked response measures), we will use the combined results for each subject to select interaural electrode pairs for their wearable, bilateral sound processors. These results, along with similar measures made longitudinally with bilateral sound processor usage, will enable us to track changes that occur with the restoration of bilateral input.

4.0 Future Work

Next Quarter we plan to continue work directed at triphasic stimulation waveforms. We have begun to make the interaction measures described in this QPR with subjects implanted with the Clarion CII/HiFocus implant system. Because we can implement the triphasic, CIS sound-processing strategy with this implant system, we expect to provide wearable versions for subjects to wear for a period of several months. This will enable us to measure and compare asymptotic performance of high-rate triphasic and biphasic stimulation strategies.

We will also continue the measures associated with bilateral stimulation as described in this QPR. By the end of the 5th Quarter, we expect that: (1) the first set of measures (see list on page three) will be completed, (2) each subject will have been provided a sound processor for their second-implanted ear with both the left and right processors programmed with a sound-processing strategy based on the first set of psychophysical and evoked response measures, and (3) collection of a second set of measures will have begun. One priority in this work is to use our new evoked potential system for electric stimulation in combination with our synchronized, bilateral stimulator to derive bilateral interaction components from mono- and bilaterally elicited EABR measures. We hope to complete this work prior to the subjects receiving their wearable bilateral processors.

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) to survey the pool of prospective subjects with regard to the magnitude and quality of their intracochlear evoked potential (IEP) measures.

Hardware and software development of the evoked potential system will continue with the goal of objectively characterizing the operation of the implant before embarking on extensive data collection. In addition, modification of the IEP measurement tools to enable measurement of channel interaction will be initiated as a compliment to the previously described psychophysical measures of channel interactions.

5.0 References

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