Fifth Quarterly Progress Report

January 1, 2003, through March 31, 2003

Speech Processors for Auditory Prostheses

NIH Contract N01-DC-2-1001

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) psychophysical and speech-reception measures associated with bilateral intracochlear stimulation, and (3) refining the stimulation/recording tools for the Clarion CII/HiFocus implant system that have enabled us to begin intracochlear field and evoked-response measures in subjects who have received the Clarion CII implant system. In this QPR, we concentrate on our work related to the selection of interaural electrode pairs for bilateral intracochlear stimulation.

2.0 Bilateral Stimulation

As we reported in our Third Quarterly Progress Report (QPR) (Eddington, et al. 2002), 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) in the 1st and 2nd quarters of this contract. A summary of these subjects is provided in Table I.

Table I: Bilaterally-Implanted Subjects

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

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.

We have two major goals for these bilaterally-implanted subjects before they receive 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 and electrically-naive ears) 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, et al. 1997) and also in response to the electric stimulation we deliver (e.g., Snyder, 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 use measures corresponding to the first four items of the above list (plus CT data about the relative insertion depths of each electrode) to guide the pairing of interaural electrodes/channels. We hope these measures will lead to sound-processing strategies that not only optimize short-term performance, but also provide a basis for 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.

As reported in our 3rd QPR (Eddington, et al. 2002), 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). As we made the other physiological and psychophysical measures described below, the difference in timbre between the two ears reported by the subjects decreased. At that point we returned to measures of interaural pitch comparisons before fitting the subjects with a wearable sound processor for their second implant.

The following subsections summarize the current state of results from experiments exploring interaural pitch, fusion, ITD sensitivity, and binaural interactions in electrically-evoked brainstem responses. All of these measures were made before the subjects received a wearable sound processor to activate their second implant and guided the mapping of sound-processing analysis channels to their respective interaural electrode pairs.

2.1 Interaural Pitch Comparisons

These experiments were designed to explore the relative pitch of the sensation elicited by the monopolar activation of each intracochlear electrode (using the same far-field return). Because of the tonotopic organization of the normal cochlea, the degree to which interaural electrodes elicit sensations with similar pitch is one criterion used to select interaural electrode pairs likely to be sensitive to interaural cues. Long's work with a single subject in our laboratory showed that pitch similarity can serve as a general aid for selecting interaural electrode pairs but it also demonstrated that for any particular electrode in one cochlea, selection of an electrode in the second cochlea based on pitch similarity does not guarantee the selection of the second-ear's electrode that will result in an interaural pair with the best ITD sensitivity (or even a pair with significant ITD sensitivity) (Long 2000). Measures of interaural pitch comparisons will enable us to determine the extent to which using a relative pitch criterion for pairing interaural electrodes results in the same set of matches as other pairing criteria (e.g., fusion, ITD sensitivity and binaural interaction).

The stimuli used in this task were 300 ms, biphasic (108 μs/phase, cathodic phase first, 850 pps) pulse trains with 300 ms interstimulus intervals. Typically, for each block of trials, four right and four left electrodes were selected and the stimulus level for each electrode adjusted to elicit the same comfortable listening level. Each of the 16 possible interaural pairs was presented 20 times in a three-interval, two-alternative, forced-choice task. Each three-interval trial included one left (L) electrode and one right (R) electrode stimulated in one of the following four trial sequences: LRL, LLR, RRL, RLR. The subject's task was to identify which of the last two elicited sensations was higher in pitch. Sixteen interaural pairs presented five times in each of the four trial sequences equals a total of 320 trials for a typical block. The order of these 320 trials was randomized.

Figure 1 shows the results of interaural pitch comparison measures collected with the three subjects to date. If the electrodes were perfectly aligned in cochleotopic position across the two ears, one would expect the transition from darkly-colored elements to lightly-colored elements to be distributed along the major diagonal representing interaural pairs of equal electrode number. In the cases of C092 and C105, the interaural pairs where the left electrode was consistently judged higher in pitch than the right tend to be positioned above and to the left of the pairs where the right electrode was judged higher in pitch. This is consistent with the tonotopic organization of the cochlea and the configuration of the implanted electrodes (Electrode 1 is most apical).

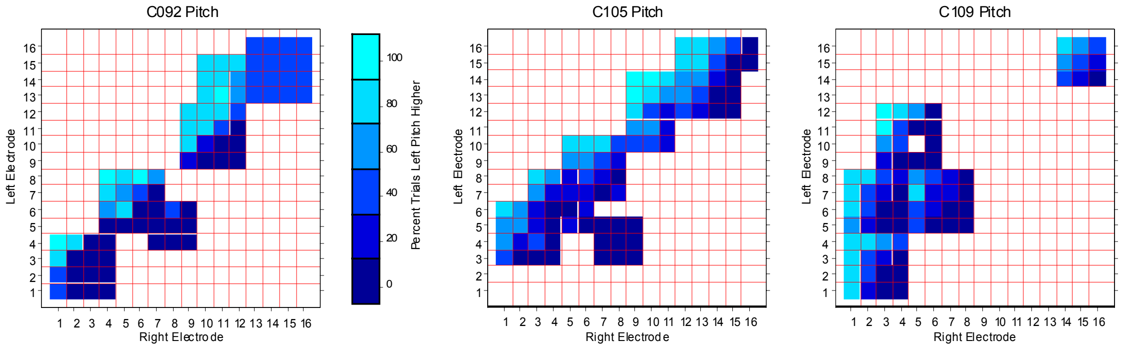

Figure 1. The results from interaural pitch comparisons are shown for three bilaterally implanted subjects. Each panel represents the data for a single subject as a matrix representing all possible combinations of interaural electrode pairs. For the pairs tested, the percentage of trials where the left electrode was judged higher in pitch is coded by the color of the matrix element corresponding to the specific interaural electrode pair. As shown by the vertical color scale, the lighter the color, the higher the percentage of trials where the left electrode was judged higher than the right. White matrix elements signify interaural electrode pairs that have not yet been included in an interaural pitch comparison task.

In order to more easily identify those interaural electrodes pairs judged most similar, the results plotted in Figure 1 are replotted in Figure 2 with lighter colors representing greater pitch similarity. In the case of C092, electrodes L13-16 and R13-16 were judged similar in pitch and the small number of other pairs judged similar in pitch were scattered near the major diagonal. C105's results show a larger number of pairs with Similarity Index (SI) greater than 39. These are distributed in a region near and above the main diagonal. C109's results do not show this orderly relationship. Except for the block of trials including L14-16 and R14-16 where the most similar judgements were found on the main diagonal, results from the other trials do not show a pattern that is consistent with the normal tonotopic organization of the cochlea.

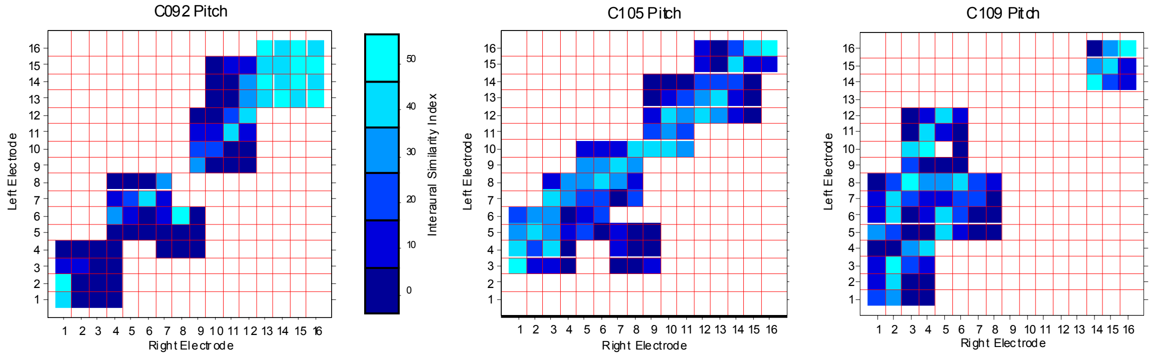

Figure 2. The results from interaural pitch comparisons are plotted with matrix elements representing interaural electrode pairs producing the most similar pitch colored lightest. The similarity index was computed using the formula: $SI = 50 - |50-P_{LE}|$, where SI is the similarity index and P_{LEH} is the percentage of times the left electrode was judged higher in pitch than the right electrode.

These pitch data do not provide unambiguous guidance in selecting interaural electrode pairs to be assigned to a set of a sound-processing strategy's analysis channels. If one assumes the electrodes are not kinked (an assumption consistent with CT reconstructions), the yellow lines in Figure 3 show regions that include 45° diagonals that define sets of interaural electrode pairs that might be suggested by the pitch data. In the case of C092, the sets of pairs meeting one of the following two conditions are consistent with the pitch data: $R_{el}=L_{el}$ or $R_{el}=L_{el}+1$. The results from C105 suggest sets based on the following relationships: $R_{el}=L_{el}$, $R_{el}=L_{el}+1$, $R_{el}=L_{el}+2$, $R_{el}=L_{el}+3$ or $R_{el}=L_{el}+4$. The data from C109 are so irregular that it is difficult to select candidate pairings. Depending on the subset of C109's data selected, sets ranging from $R_{el}=L_{el}$ to $R_{el}=L_{el}+7$ might be considered.

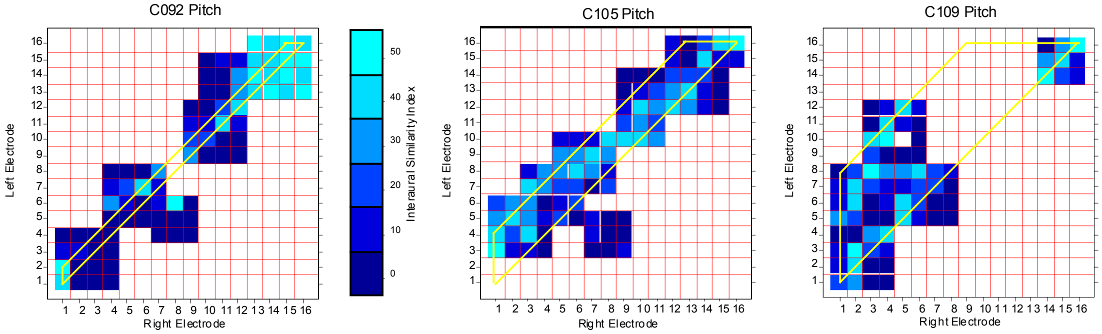

Figure 3. Results of the interaural pitch comparisons plotted as SI. The regions inclosed by the yellow lines include 45° diagonals that, based on the pitch data, might be considered as sets of pairs to be assigned channels in a bilateral sound processing strategy.

2.2 Fusion

The degree to which simultaneously stimulating an interaural electrode pair produces a single sensation localized to a small region in space is another potential criterion for selecting interaural electrode pairs for use in bilateral sound-processing strategies.

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 (ITD=0) and the subject asked to describe the sensation they experience. For electrodes that are cochleotopically far apart (e.g., R1/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 Response Categories

Description	Fusion Index
● ● 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 was large, but consistent across subjects. Table II lists the major categories of responses we encountered in conducting the fusion experiments (see also (Eddington, et al. 2002)). The Fusion Index assigned to each of the response categories is an arbitrary number ranging from 0 to 5 and represents the degree to which a sensation was fused.

Figure 4 presents plots of the fusion index representing the fusion data we have analyzed to date for each of the 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 are consistent with an interpretation that interaural electrode pairs near the diagonal representing equal left/right electrode numbers are more likely to be fused.

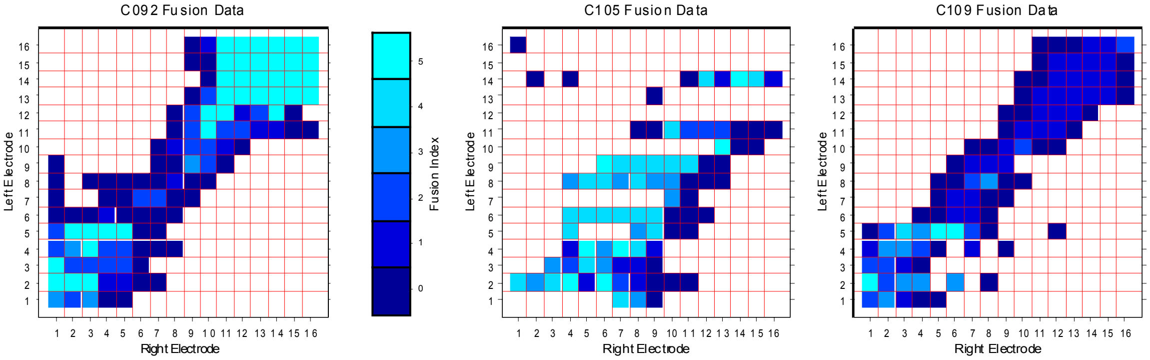

Figure 4. Plots of fusion data for three bilaterally-implanted subjects. For each interaural electrode pair tested, a color is plotted that represents the Fusion Index value associated with the subject's response. As shown by the Fusion Index scale, lighter colors represent higher Fusion Index values (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

In the case of C092, a region of highly fused sensations was identified for the basal interaural pairs including electrodes L13-16 and R11-16. Note that this group of interaural pairs includes the group of basal pairs judged similar in pitch (see Figure 3). Interaural pairs formed from electrodes toward the electrode array's apical end also tend to produce sensation with higher fusion indices than those in the middle of array. The data for C109 show very few interaural pairs with Fusion Indices of four or greater and these tend to be grouped toward the apical end of the arrays. However, there is a trend for interaural pairs near the major diagonal to elicit sensations with Fusion Indices greater than zero. The data of subject C105 show very large regions of fusion. For instance, electrode L2 produced relatively highly fused sensations when paired with electrodes R1-R6.

When taken together with the pitch data (Figure 3), the fusion data for subject C109 help constrain the sets of interaural electrode pairs one might select for use in a bilateral sound-processing strategy to: $R_{el}=L_{el}-1$, $R_{el}=L_{el}$, and $R_{el}=L_{el}+1$. The fusion data for C092 are consistent with the constraints imposed by the pitch data, but do not impose further constraints. In the case of C105, the fusion data are of little benefit in guiding the selection of interaural electrode pairs to be used in a bilateral speech-processing strategy.

2.3 Just-Noticeable Differences (JNDs) for Interaural Time Discrimination (ITD).

The degree to which a subject can use the perceptual features of sensations elicited by simultaneous stimulation of an interaural electrode pair to discriminate timing/phase differences between the stimuli delivered to the two electrodes may serve as another criterion for selecting pairs of interaural electrodes for use in bilateral speech-processing strategies.

The stimuli used to measure ITD-JNDs were 300 ms, biphaisce pulse trains (cathodic phase first, 108 μs/phase, 200 pps) delivered simultaneously to a single, interaural electrode pair. Interaural time differences were generated by delaying the stimulus of one ear relative to the other. After selecting the pair, the stimulus level was adjusted to give a comfortably loud sensation centered in the subject’s head for pairs eliciting fused sensations. If the sensation was not fused, stimulus level was adjusted to elicit equal sensation levels when the two electrodes were stimulated sequentially. An adaptive, two-interval forced-choice procedure was used to measure the ITD-JND. The delayed stimulus was randomly assigned to one interval and the ITD=0 stimulus to the other. The subject’s task was to identify whether the sensation elicited moved left or right. The ITD was adjusted based on a two-down/one-up rule.

Only a small number of interaural electrode pairs showed ITD-JNDs below 200 μs. Figure 5 plots the ITD-JNDs measured in subjects C092 and C109. We were not able to measure ITD-JNDs in subject C105. In general, the limited number of measures shown in Figure 5 was not a result of limited time allocated to this testing, but to our limited ability to identify interaural pairs that showed a sensitivity to ITD. The one exception to that general observation was in C092’s large basal region of fusion (R11-16/L13-16; see Figure 4) where time limited the number of interaural pairs tested. We spent several hours in each subject searching for interaural pairs sensitive to ITD without success. Thus, the

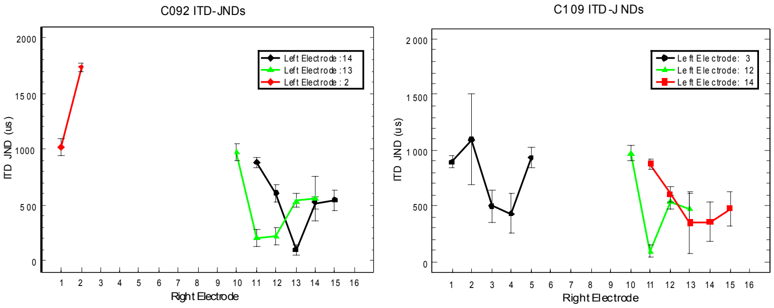

Figure 5. ITD-JNDs measured using single interaural electrode pairs in subjects C092 and C109.

paucity of data for C105 and for the middle part of the array for C092 and C109 reflects a lack of sensitivity to ITD as measured by our procedure.

The interaural pairs for which ITD-JNDs are plotted in Figure 5 are marked with filled circles on the fusion data for subjects C092 and C109 in Figure 6. The large circles associated with each row mark the interaural pairs in regions of lowest JND. The red lines mark the set of interaural electrode pairs used in the first (and to date the only) bilateral sound processors provided to C092 and C109 for use inside and outside the laboratory.

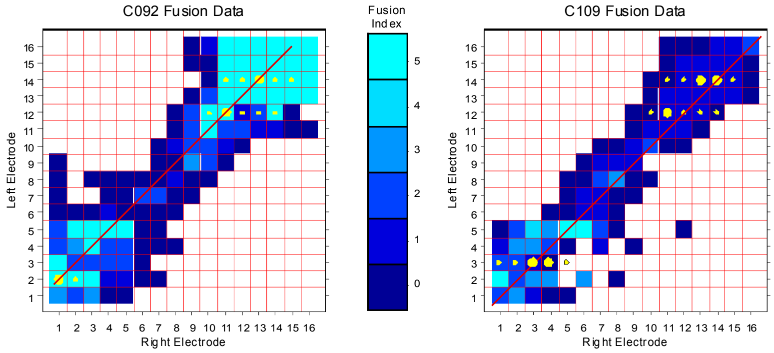

Figure 6. Fusion data from subjects C092 and C109 with filled circles marking the interaural electrode pairs for which ITD-JND data are plotted in Figure 5. The large filled circles in each row mark the interaural pairs with relatively small JNDs.

2.4 Binaural Interaction in Electrically-Evoked Brainstem Responses

Binaural interactions associated with electrically-evoked responses are another candidate measure for guiding the selection of interaural electrode pairs. The description of binaural interactions in acoustically-evoked brainstem responses (e.g., Dobie and Berlin 1979, Levine 1981) led Pelizzone to record the first interactions in a bilaterally-implanted subject (Pelizzone, et al. 1990). We have attempted to measure such interactions using three interaural pairs in all three subjects and found interactions in the cases of C105 and C109. Because we have only begun these measurements and their analysis, the details of the techniques, procedures and results will be presented in a future QPR. However, a qualitative comparison of the interaction magnitudes measured in subject C105 had an impact on the assignment of interaural pairs in this subject’s bilateral sound-processing strategy and are, therefore, summarized here.

Measures of electrically-evoked brainstem responses (as described in our last QPR (Finley, et al. 2003)) were made using monolateral stimulation of electrodes R4, L5, L8 and L14 and using bilateral stimulation (ITD=0) of interaural electrode pairs R4/L5, R4/L8 and R4/L14. The stimuli were biphasic, cathodic-first, 52 µs/phase pulses presented at 10 pps. The stimulus level for R4 (in both monolateral and bilateral configurations) was set to produce a sensation level near maximum comfortable loudness in the monolateral configuration. The stimulus levels for L5 and L8 (monolateral and bilateral configurations) were also set to produce a sensation level near maximum comfortable and then adjusted to center the sound image when played together in the bilateral configurations (R4/L5 and R4/L8). In the case of the L14 monolateral (L14) and bilateral (R4/L14) configurations, the stimulus level was set to elicit a sensation level when stimulated monolaterally to match that produced by monolateral stimulation of R4. A vertex to linked earlobe electrode montage was used for recording.

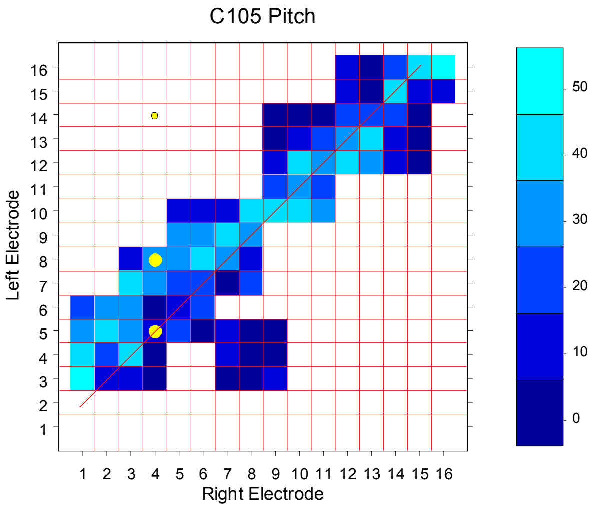

Figure 7. Fusion data from subject C105 with filled circles marking the interaural electrode pairs for which bilateral, electrically-elicited auditory brainstem responses were measured. The relative magnitude of the binaural interaction is represented by circle diameter. The red line marks the interaural electrode pairs used in the subject's bilateral sound-processing strategy

The magnitude of the binaural interaction response for the R4/L5 combination was computed by the following operations: $R_{BI} = R_{R4/L5} - (R_{R4} + R_{R5})$. Similar binaural interaction responses were also computed for the R4/L8 and R4/L14 conditions. Informal inspections of these results indicated the presence of an interaction component at the wave V latency for the R4/L5 and R4/L8 conditions but not for the R4/L14 condition. The magnitude of the R4/L5 interaction component was judged similar to that for the R4/L8 condition. These relationships are plotted on the pitch data from Figure 2 in Figure 7. These measures of binaural interaction were used together with the relative pitch data to select the interaural electrode pairs used in this subjects bilateral sound-processing strategy (identified by the red line in Figure 7).

2.5 Bilateral Sound-Processing Strategies

After collecting the psychophysical/physiological results presented above, each of the three subjects was provided with a second wearable sound processor that controls the implant of their most-recently implanted ear. In each case, the processing strategy was implemented using the same type of processor used by the subject to control their first implant (the CII BTE sound processor for subjects C092 and C109 and the Platinum sound processor (body worn) for C105). The right and left sound processors run asynchronously and, except for the mapping of analysis channels to electrodes, the CIS sound-processing strategies (16 analysis channels, 1460 pps carrier rate, 21 μsec/phase cathodic-first biphasic pulses) are the same across ears and subjects. The analysis-channel/electrode maps for the three subjects are shown in Table III below. In this table, an "X" indicates that the specified analysis channel was not implemented in the processing strategy for the specified ear. The "Zero" analysis channel is one that assigns a zero stimulus level to the specified electrode/stimulus channel.

Note that in subjects C092 and C105, the mapping of analysis channel to electrode is offset by one electrode between the right and left ears. This means that an electrode/stimulation channel is not assigned to analysis-channel 1 of the right-ear sound-processing strategy (indicated by "X" in Table III). Right electrode/stimulation-channel 16 is set to produce a zero-level stimulus in subject C092. In the case of subject C105, right electrode/stimulation-channel 16 is controlled by analysis-channel 16. This means the stimulus waveforms delivered to electrodes 15 and 16 are the same (although the waveform levels may differ depending on the level-mapping function of each stimulus channel).

Table III
Mapping of Analysis Channels to Electrode (EL)

Analysis Channel	Subject C092 Electrode/Stim.Channel		Subject C105 Electrode/Stim.Channel		Subject C109 Electrode/Stim.Channel	
	Left	Right	Left	Right	Left	Right
1	1	X	1	X	1	1
2	2	1	2	1	2	2
3	3	2	3	2	3	3
4	4	3	4	3	4	4
5	5	4	5	4	5	5
6	6	5	6	5	6	6
7	7	6	7	6	7	7
8	8	7	8	7	8	8
9	9	8	9	8	9	9
10	10	9	10	9	10	10
11	11	10	11	10	11	11
12	12	11	12	11	12	12
13	13	12	13	12	13	13
14	14	13	14	13	14	14
15	15	14	15	14	15	15
16	16	15	16	15,16	16	16
ZeroAmp	X	16	X	X	X	X

3.0 Future Work

In the last third of this Quarter (when all three subjects had received their 2nd sound processor), emphasis in the area of bilateral stimulation switched from psychophysical and physiological measures designed to guide the selection of interaural electrode pairs for bilateral sound-processing strategies to the measurement of the subjects' ability to localize sound sources and receive speech in conditions of single and multiple noise sources. While we will continue to monitor the relationships of pitch, fusion, ITD-JND and binaural interactions in electrically-evoked brain stem responses, most of our effort in the next Quarter will now be focused on localization and speech reception using the asynchronous sound-processing systems described above.

We plan to continue work directed at triphasic stimulation waveforms. We are finishing the collection of interaction measures in 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.

Measurements of intracochlear evoked potentials (IEPs) are continuing using the custom software developed and tested during the first three Quarters in a group of monolaterally-implanted Clarion CII/HoFocus subjects. The primary objectives for collecting these initial data are to (1) better characterize system measurement noise and (2) characterize the magnitude and quality of IEP measures in a pool of subjects with a range of speech-reception performance. In addition, software development for the measurement of interaction based on the IEP is continuing. We expect to make IEP-based interaction measures in the next quarter and compare them to similar behavioral measures.

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