Thirteenth Quarterly Progress Report

April 1 through June 30, 2005
NIH Project N01-DC-2-1002

Speech Processors for Auditory Prostheses

Prepared by

Dewey Lawson, Blake Wilson, and Xiaoan Sun

Center for Auditory Prosthesis Research
Research Triangle Institute
Research Triangle Park, NC

CONTENTS

I. Introduction

The main objective of this project is to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, such processors will represent the information content of speech in a way that can be perceived and utilized by implant patients. An additional objective is to record responses of the auditory nerve to a variety of electrical stimuli in studies with patients. Results from such recordings can provide important information on the physiological function of the nerve, on an electrode-by-electrode basis, and can be used to evaluate the ability of speech processing strategies to produce desired spatial or temporal patterns of neural activity.

Work and activities in this quarter included:

- Visits by NP-6, a subject with a research version of the Nucleus device that provides percutaneous access to a Contour electrode array, March 28-30, April 11-12, May 3-4, and May 17-24.
- A one-week visit by NP-7, another Nucleus percutaneous subject, May 9-13.
- Five weeks of visits by a third Nucleus percutaneous subject, NP-9, April 4-8, April 18-22, and May 23 through June 14.
- Blake Wilson was the keynote speaker for the *Annual Meeting of the British Cochlear Implant Group: Pushing the Boundaries of Cochlear Implantation*, Birmingham, UK, April 18-19.
- A visit by Dr. Peter Roland, Chairman of the Department of Otolaryngology -- Head and Neck Surgery, University of Texas Southwestern Medical Center, Dallas, June 15-17.

In addition to the above-mentioned activities, work continued on analyses of previously collected data and on the preparation of manuscripts for publication.

In the present report we describe progress on the current Nucleus percutaneous studies, including completion of testing this quarter with two of the four subjects.

II. Progress in the Nucleus percutaneous studies

The Devices

Our research implants are Cochlear Pty. CI24R systems, offering percutaneous access to the Nucleus Contour electrode array. The surgeries are performed by Dr. Debara Tucci, and clinical audiological care is provided by Molly Justus, both of the Otolaryngology Head and Neck Surgery Division of the Department of Surgery at Duke University Medical Center. Our master processor, with 24 optically-isolated and battery-powered current sources [van den Honert *et al.* (1996)], is connected directly to each subject's percutaneous connector for our laboratory studies. Outside the lab, each subject attaches the equivalent of a standard Nucleus Esprit 3G clinical implant system to the percutaneous pedestal's connector. Cochlear Corporation in the U.S. provides the research devices and, at the conclusion of each subject's studies with us, standard clinical transcutaneous systems for permanent use, along with unreimbursed surgical and audiological costs associated with both. Dr. Chris van den Honert of Cochlear Corporation and Cochlear Pty. has worked closely with us in support of the devices, and is conducting studies with a similar group of patients implanted with the same research device in Denver.

The Subjects

NP-6

NP-6 was born in 1977 and began using amplification at age 5. His hearing loss progressed to the point that, immediately prior to receiving his right ear implant, he was profoundly deaf bilaterally and had some low frequency sensitivity but poor speech reception with his hearing aids.

Unforeseen personal circumstances limited the availability of this subject to only 19 days of testing. He now has undergone a second surgery and programming to replace the research percutaneous device with a standard transcutaenous device for permanent clinical use.

NP-7

Born in 1942, NP-7's hearing loss was first noticed following a blow to the head at age 12. There was no family history of hearing loss. She began use of a hearing aid in her left ear at age 19 and bilateral aids at age 30. She reports having had many ear infections. Progressing hearing loss resulted in her ceasing to use aids at age 47, by which time she was receiving no benefit in the right ear. Her left ear was implanted at age 61.

Testing is continuing with this subject, 14 days having been completed to date.

NP-8

Subject NP-8 was born in 1956. Her hearing loss, associated with Wegener's granulomatosis disease, progressed from mild in late 2000 to profound bilaterally by late 2001. At the time of her left ear implant surgery many other symptoms associated with her Wegener's had improved markedly, including her returning to ambulatory status. At surgery, however, active formation of tissue characteristic of Wegener's was observed, and healing of her surgical incision required multiple hyperbaric oxygen treatments and IV antibiotics.

Testing is continuing with this subject, with 13 days having been completed thus far.

NP-9

Born in 1973, NP-9 had a 50 dB flat hearing loss at age 4. There was some history of hearing problems in her mother's family. NP-9's progressive loss was punctuated by at least one sudden increase – after exposure to loudspeakers at a junior high school dance – and came to be accompanied by tinnitus. Having used bilateral aids in the past, by the time of left ear cochlear implantation she was aided in that ear only. Amplification of her residual hearing below 1 kHz, however, was providing little benefit. After implantation, tinnitus essentially disappeared, seldom noticed except when the speech processor was not functioning.

This subject completed a total of 32 days of testing in our laboratories, and now has undergone a second surgery to remove the percutaneous research device and replace it with a standard transcutaenous clinical system. Newly formed bone prevented reinsertion of the new array in the same scala tympani, and the clinical device was implanted contralaterally. The new device has been programmed, and the subject is doing well with it.

The Tests

The overall performance levels of these four subjects span a substantial range; in order of increasing performance NP-6, NP-7, NP-9, and NP-8. This is reflected in the choice of tests for each subject in order to obtain sensitivity across the compared processing strategies. Consonant identification scores for NP-6 and NP-7 are limited to 16 consonants in quiet. For NP-9, comparisons among processors also have been obtained using 16 consonants at a S/N ratio of +10 dB using CCITT long term speech spectrum noise. NP-8's overall performance is so high that comparison tests include identification of 24 consonants at a S/N of +5 dB. Each measurement is based on a minimum of 10

presentations of each consonant in a medial context, with uncertainties expressed as standard error of the mean.

A second type of test used to compare processor performance is identification of words in CUNY sentences. The sentences have been presented in quiet for all four subjects. In addition they have been presented at +10 dB S/N for NP-9 and +5 dB S/N for NP-8. Each measurement is based on presentation of 4 CUNY lists of 12 sentences each, containing a total of more than 400 words.

The final processor comparison test routinely used in these studies is melody recognition. A closed set of 12 melodies was selected from those identified by each subject as being familiar, from a master list of childhood, patriotic, folk, and holiday songs. Each melody is presented as a sequence of 16 notes of identical duration to minimize rhythmic cues, and in each of three different musical transpositions to reduce biases due to interactions between specific pitches and the analysis bands used by specific processing strategies. Two such tests, including 72 melody presentations, form the basis for each measurement.

Intracochlear evoked potential studies also are being conducted with each of these subjects.

The Processors

A core set of 100 distinct processing strategies has been chosen for comparisons across these four subjects. Because of the unique opportunities afforded by percutaneous access to the Contour electrode array, priority has been given to strategies that require one or more of those opportunities – *e.g.* simultaneous stimulation of multiple electrodes, use of unusual pulse forms, and/or location of electrodes close to the modiolar wall of scala tympani. Also included are processors designed to serve as controls for assessing benefits of the new approaches.

Because of the unexpectedly limited time available with subject NP-6, only 37 of those processors could be evaluated across all four subjects. It is anticipated that each of the other processors will be compared across three subjects. All 100 processors have been realized and tested with at least one subject. Data are already in hand comparing 11 of the processors across all four subjects.

All the processors were realized on our laboratory's master processor hardware and software, either running in real time or pre-processed for streaming mode presentation [Schatzer *et al.* (2003)]. Many of the new processing approaches included among the specific designs being tested across these subjects were described generally in QPRs 6, 7, and 9 for the current project [Schatzer *et al.* (2003a), Wilson *et al.* (2003), and Wilson *et al.* (2004)].

The core processors may be grouped conveniently into 7 fundamental **types**: continuous interleaved samplers (**CIS**), fine structure (**FS**) [including some processors using virtual

channels as well as single electrodes], conditioner pulses (**CP**), dual-resonance nonlinear filter (**DRNL**), combined DRNL and FS, simultaneous stimulation across channels (**SS**) and hybrid peak-picking/CIS (**PP**). Of the 100 processors, 52 fall into the CIS group (including a single-channel processor more accurately identified as a "continuous sampler"). There are 34 FS processors in the core group, 8 in the CP category, one PP, and 2 each in the DRNL, DRNL/FS, and SS categories.

Other important characteristics of the processors include the number and range of the frequency bands used to analyze the incoming acoustic signal and define the processing **channels**, and the number of distinct **stimulation options** available for outputs. In 60 of the processors each analysis channel is paired exclusively with output to a single electrode from the 22 available in the Contour implanted array. The numbers of channels among such processors (with the number of instances for each shown in parentheses) include 1 (1), 2 (1), 3 (1), 4 (8), 5 (4), 6 (24), 7 (1), 8 (4), 10 (8), 11 (5), and 21 (3). In the remaining 40 processors, the analysis channels direct their outputs to a greater number of output stimulation options, which can include both single electrodes and simultaneously stimulated pairs of electrodes. Such arrangements may be described compactly as n/m, where n is the number of analysis channels and m the number of stimulation options. Assignments between channels and stimulation options may be fixed or dynamic, with individual stimulation options available to only one, or to more than one channel, as will be discussed in greater detail below. The n/m combinations represented among our processors (with the number of instances for each shown in parentheses) include: 8/16 (2), 6/18 (14), 5/21 (2), 7/21 (3), 10/21 (3), 21/22 (2), 5/41 (2), 10/41 (3), 20/41 (2), 10/43 (1), and 21/43 (6). Cases in which m exceeds the number (22) of available electrodes in the implanted array indicate the inclusion of additional "virtual" sites of stimulation through simultaneous currents to pairs of electrodes.

In 95 of the 100 processors the frequency bands defining the analysis channels are logarithmically equal in width, extending upward from 350 Hz. In 77of those cases the upper limit of the overall range is 7.0 kHz, in 17 cases it is 5.5 kHz, and in a single case it is 3.0 kHz. The remaining 5 processors, all with 6 analysis channels, span an overall frequency range of 80 Hz to 5.5 kHz, with the lowest two bands equal linearly (widths of about 400 Hz) and the other four equal logarithmically (factors of about 1.58).

All the processors deliver pulsatile stimulation, at **pulse rates** (with number of instances for each shown in parentheses) of: approximately 5000 p/s/channel (3), 3670 p/s/ch (1), 833 p/s/ch (88), 791 p/s/ch (2), and 667 p/s/ch (6). In 92 of the 100 processors, the pulses are balanced biphasic pulses with negative phase leading. The **pulse durations** in those cases (with number of instances for each shown in parentheses) include: 500 μs/ph (1), 60 μs/ph (14), 40 μs/ph (17), 27 μs/ph (56), and 17 μs/ph (4). The remaining 8 processors utilize triphasic pulses of two types – with durations of 27/54/27 μs/ph with equal amplitudes for each phase, and 27/27/27 μs/ph with the middle phase double the amplitude of each of the others -- both alternating phases of -/+/- and +/-/+ are represented. One variant of a 27 μs/ph biphasic processor using split-phase timing, with a 27 μs interval of no stimulation between the phases, is included for comparison with the triphasic and normal biphasic cases.

For the CP processors, conditioner pulse rates of 2.5 kp/s/channel and 4.0 kp/s/ch are used with information pulse rates of 667 p/s/ch and 833 p/s/ch. Conditioner pulse widths used include 12 μs/ph and 16 μs/ph.

The stimulation **envelopes** for each channel are obtained by full-wave rectification in 62 of the 100 processors, and by Hilbert transform analysis in the other 38. The low-pass **smoothing filters** limiting the envelopes are 4^{th} order Butterworth in all cases. The upper frequency limit is set at 200 Hz in 89 of the processors and at or about 400 Hz in the other 11.

When each analysis channel is associated with a **group** of stimulation options, there are design choices related to the number and exclusivity of such associations. Among the 40 processors in which this is an issue, each stimulation option is associated with a single analysis channel in 20 cases, with groups of 2, 3, and 4 stimulation options associated with each channel in 2, 17, and 1 instances respectively. In the other 20 processors involving multiple stimulation options for each channel, individual stimulation options may be **shared** among more than one channel, with group sizes of 2, 3, 5, and 9 options in 2, 11, 5, and 2 instances respectively. In some cases the number of options in a group may vary at one or both ends of the electrode array.

In some of the FS and DRNL/FS processors, instantaneous frequencies calculated for the signals within each analysis band, as part of the fine structure analysis, are restricted ("**clipped**") to the frequency range of the band.

In the one PP processor, with 11 analysis channels, the 3 channels corresponding to the lowest bands do peak picking analyses while the other 8 channels perform standard CIS analysis. The electrodes associated with the first 3 channels are stimulated in order of ascending bands, at rates related to their analysis band frequencies, while the remaining electrodes are stimulated in staggered order in normal CIS fashion. Stimulation order is staggered among all channels in all the other multi-channel processors.

The distribution of all these characteristics among the 100 core processors is summarized in Table I.

Table I. Processor Parameters

[The columns, from left to right, contain: processor type, stimulation rate in p/s/channel, pulse duration in μs/phase, overall frequency range analyzed in Hz, envelope smoothing filter upper frequency limit (in Hz) and filter order, envelope detector type (fullwave rectification or Hilbert transform), stimulation option groups ("sh" indicates sharing among more than one channel, "ns" indicates no such sharing, with the number of stimulation options in each channel's group), whether instantaneous frequencies are clipped to the range of the respective analysis band, the number of analysis channels and -- if different -- the number of stimulation options, and notes about any special pulse configuration or electrode assignment.]

type	rate	dur	frange	sm filt	env	grp	clip	chs	pulse, el. details
CIS	833	27	350-7k	200-4	fw			1	
CIS	833	27	350-7k	200-4	fw			2	
CIS	833	27	350-7k	200-4	fw			3	
CIS	833	27	350-7k	200-4	fw			4	
CIS	833	27	350-7k	200-4	fw			4	
CIS	833	27	350-7k	200-4	fw			5	
CIS	833	27	350-7k	200-4	fw			6	split phase 27,27,27 us; -0+
CIS	833	27	350-7k	200-4	fw			6	
CIS	833	27	350-7k	200-4	fw			7	
CIS	833	27	350-7k	200-4	fw			8	
CIS	833	27	350-7k	200-4	fw			10	
CIS	833	27	350-7k	200-4	fw			10	
CIS	833	27	350-7k	200-4	fw			10	split phase 27,27,27 us; -0+
CIS	833	27	350-7k	200-4	fw			11	
CIS	833	27	350-7k	200-4	fw			21	
CIS	833	27	350-7k	200-4	fw			11	
CIS	833	27	350-7k	400-4	fw			6	
CIS	833	40	350-3.0k	200-4	fw			6	
CIS	833	40	350-5.5k	200-4	fw			6	
CIS	833	40	350-5.5k	200-4	fw			6	
CIS	833	40	350-5.5k	200-4	fw			6	rev el order
CIS	833	40	350-5.5k	200-4	fw			8	
CIS	833	40	350-5.5k	200-4	fw			11	
CIS	833	40	350-5.5k	200-4	fw			11	
CIS	833	40	350-5.5k	385-4	fw			4	
CIS	833	40	350-5.5k	385-4	fw			4	
CIS	833	40	350-5.5k	385-4	fw			5	
CIS	833	40	350-5.5k	385-4	fw			5	
CIS	833	40	350-5.5k	385-4	fw			5	
CIS	833	40	350-5.5k	400-4	fw			6	
CIS	833	40	350-7k	400-4	fw			6	
CIS	833	40	LinLog	200-4	fw			6	
CIS	833	60	350-5.5k	200-4	fw			6	
CIS	833	60	350-5.5k	400-4	fw			6	
CIS	833	60	350-7k	200-4	fw			4	

type	rate	dur	frange	sm filt	env	grp	clip	chs	pulse, el. details
CIS	833	60	350-7k	200-4	fw			6	
CIS	833	60	350-7k	200-4	fw			8	
CIS	833	60	350-7k	200-4	fw			10	
CIS	833	60	350-7k	400-4	fw			6	
CIS	3670	17	350-7k	200-4	fw			8	
CIS	4893	17	350-7k	200-4	fw			6	
CIS	4893	17	350-7k	400-4	fw			6	
CIS	4993	17	350-7k	200-4	fw			4	
CIS	833	*	350-7k	200-4	fw			6	triphasic 27,54,27us; +-+
CIS	833	*	350-7k	200-4	fw			6	triphasic 27,54,27us; -+-
CIS	833	*	350-7k	200-4	fw			6	triphasic 27,27,27 us; -+-
CIS	833	*	350-7k	200-4	fw			6	triphasic 27,27,27 us; +-+
CIS	833	*	350-7k	200-4	fw			10	triphasic 27,54,27us; -+-
CIS	833	*	350-7k	200-4	fw			10	triphasic 27,54,27us; +-+
CIS	833	*	350-7k	200-4	fw			10	triphasic 27,27,27 us; -+-
CIS	833	*	350-7k	200-4	fw			10	triphasic 27,27,27 us; +-+
CP	667	27	350-7k	200-4	Hil	3		6/18	16us/ph, 4kp/s conds, ampl 50
CP	667	27	350-7k	200-4	Hil	3		6/18	12us/ph, 4kp/s conds, ampl 160
CP	667	27	350-7k	200-4	Hil	3		6/18	12us/ph, 4kp/s conds, ampl 250
CP	833	27	350-7k	200-4	Hil	3		6/18	12us/ph, 2.5kp/s conds, ampl 160
CP	833	27	350-7k	200-4	fw			6	12us/ph, 2.5kp/s conds, ampl 160
CP	667	27	350-7k	200-4	fw			6	12us/ph 4kp/s cond pulses, ampl 0
CP	667	27	350-7k	200-4	fw			6	12us/ph 4kp/s cond pulses ampl 160
CP	667	27	350-7k	200-4	fw			6	12us/ph 4kp/s cond pulses ampl 250
DRNL	833	27	350-7k	200-4	fw			21	
DRNL	833	27	350-7k	200-4	fw			21	
DRNL/FS	791	27	350-7k	200-4	Hil	sh2	yes	21/22	
DRNL/FS	791	27	350-7k	200-4	Hil	sh2	yes	21/22	
FS	833	27	350-5.5k	200-4	Hil	3	yes	6/18	
FS	833	27	350-7k	200-4	fw	sh3		21/43	
FS	833	27	350-7k	200-4	fw	sh3		21/43	
FS	833	27	350-7k	200-4	Hil	sh9		5/41	
FS	833	27	350-7k	200-4	Hil	sh9	yes	5/41	
FS	833	27	350-7k	200-4	Hil	sh5		10/41	
FS	833	27	350-7k	200-4	Hil	sh5	yes	10/41	
FS	833	27	350-7k	200-4	Hil	4	yes	10/43	
FS	833	27	350-7k	200-4	Hil	sh5	yes	5/21	
FS	833	27	350-7k	200-4	Hil	sh5		5/21	
FS	833	27	350-7k	200-4	Hil	3	yes	6/18	
FS	833	27	350-7k	200-4	Hil	3	yes	6/18	
FS	833	27	350-7k	200-4	Hil	3		7/21	
FS	833	27	350-7k	200-4	Hil	3	yes	7/21	
FS	833	27	350-7k	200-4	Hil	2	yes	8/16	
FS	833	27	350-7k	200-4	Hil	sh3		10/21	
FS	833	27	350-7k	200-4	Hil	sh3	yes	10/21	
FS	833	27	350-7k	200-4	Hil	sh3		20/41	
FS	833	27	350-7k	200-4	Hil	sh3	yes	20/41	
FS	833	27	350-7k	200-4	Hil	sh3		21/43	
FS	833	27	350-7k	200-4	Hil	sh3	yes	21/43	
FS	833	27	350-7k	200-4	Hil	sh3		21/43	

type	rate	dur	frange	sm filt	env	grp	clip	chs	pulse, el. details
FS	833	27	350-7k	200-4	Hil	sh3	yes	21/43	
FS	833	27	LinLog	200-4	Hil	3	yes	6/18	
FS	833	27	LinLog	200-4	Hil	3	yes	6/18	
FS	833	40	350-5.5k	200-4	Hil	3	yes	6/18	
FS	833	40	LinLog	200-4	Hil	3	yes	6/18	
FS	833	60	350-5.5k	200-4	Hil	3	yes	6/18	
FS	833	60	350-7k	200-4	Hil	sh5		10/41	
FS	833	60	350-7k	200-4	Hil	3	yes	6/18	
FS	833	60	350-7k	200-4	Hil	3		7/21	
FS	833	60	350-7k	200-4	Hil	2	yes	8/16	
FS	833	60	350-7k	200-4	Hil	sh3		10/21	
FS	833	60	LinLog	200-4	Hil	3	yes	6/18	
PP	833	27	350-7k	200-4	fw			3+8	
SS	833	27	350-7k	200-4	fw			4	
SS	833	500	350-7k	200-4	fw			4	

As they become more complete, test results will be reported and discussed in a subsequent quarterly report. To date, 11 of the core processors have been tested with all four subjects, work has been completed with two of the four subjects, and patient testing is approximately 65% complete overall.

References

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Wilson B, Sun X, Schatzer R, and Wolford R, "Representation of Fine Structure or Fine Frequency Information with Cochlear Implants" *International Congress Series* **1273**: 3-6, (2004) [also included in Ninth Quarterly Progress Report, NIH Project N01-DC-2-1002 (2004)].

III. Plans for the next quarter

Among the activities planned for the next quarter are:

- Attendance by Dewey Lawson, Blake Wilson, and Xiaoan Sun at the Conference on Implantable Auditory Prostheses (CIAP), Asilomar Conference Grounds, Pacific Grove, CA, July 30 – August 4, 2005.
- Blake Wilson will chair a session at the CIAP, August 1, 2005.
- The Center for Auditory Prosthesis Research of RTI International will move into its newly renovated facility at 200 Park, RTP, NC.
- Continuing studies with Nucleus percutaneous subjects NP-7 and NP-8.

IV. Acknowledgments

We thank volunteer research subjects NP-6, NP-7, NP-8, and NP-9 for their participation in studies conducted during this quarter and discussed in this report.

Appendix 1: Summary of reporting activity for this quarter

Invited talks

Wilson BS: Where are we and where can we go with cochlear implants? The keynote speech for the *Annual Meeting of the British Cochlear Implant Group: Pushing the Boundaries of Cochlear Implantation*, Birmingham, UK, April 18-19, 2005.

Wilson BS, Lorens A, *et al.*: Evaluation of combined electric and acoustic stimulation of the auditory system in studies at the Research Triangle Institute. *8th International Conference on Advances in Diagnosis and Treatment of Auditory Disorders*, Kajetany, Poland, May 19-21, 2005. (Presented by Artur Lorens.)

Additional presentation

Lorens A, Wilson BS, Piotrawska A, Sharzynski H: Electric and acoustic pitch perception after Partial Deafness Cochlear Implantation (PDCI). *8th International Conference on Advances in Diagnosis and Treatment of Auditory Disorders*, Kajetany, Poland, May 19-21, 2005.