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Speech Processors for Auditory Prostheses

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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:

- Studies with Nucleus percutaneous subject NP-7, October 3 - 14, 2005.
- Blake Wilson was guest of honor at the Hearing Preservation Workshop IV held at the International Center of Hearing and Speech, Warsaw-Kajetany, Poland, October 14 – 15, 2005.
- Blake Wilson presented an invited lecture at the International Binaural Symposium 2005, Manchester, UK, October 29 – 31, 2005.
- Matthew Bakke and Yifang Xu from Gallaudet University visited our laboratories October 24, 2005.
- Blake Wilson addressed a plenary session at the North American Neuromodulation Society's 9th Annual Meeting in Washington DC, November 10-12, 2005.

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

In the present report we describe further progress in the current Nucleus percutaneous studies.

II. Results from 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 Americas 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 Americas and Cochlear Pty. has worked closely with us in support of the devices, and is conducting studies with a separate group of patients implanted with the same research device in Denver.

Completion of Studies with the Final Percutaneous Subject

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. Progressive 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.

During this quarter, the final two weeks of percutaneous testing was completed with this subject, after which her experimental device was explanted and she received her permanent transcutaneous device.

All four of the subjects [Lawson *et al.* (2005a)] who initially received experimental percutaneous devices as part of this study now are successfully using their permanent transcutaneous clinical cochlear implant systems. They contributed a total of 96 research days to our studies, 70% of the anticipated maximum commitment.

The Processors

A core set of 100 distinct processing strategies was chosen for comparisons across these four subjects. Because of the unique opportunities afforded by percutaneous access to the Contour electrode array, priority was 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.

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)].

Because of the unexpectedly limited time available with subject NP-6, and the unanticipated decision to explant NP-8, only 11 of those processors could be evaluated across all four percutaneous subjects. An additional 27 of the 100 processors have been evaluated across three of the four percutaneous subjects, and a further 21 across two of the four.

Fortunately, other research ongoing in our laboratory offers a way of supplementing the number of subjects tested with the processing strategies selected for this percutaneous study. A unique interface developed in cooperation with colleagues at the University of Innsbruck allows us great flexibility in the control of transcutaneous Med-El PULSAR implants, including the ability to implement processing strategies equivalent to those developed for our current Nucleus Percutaneous studies [Schatzer *et al.* 2004, Lawson *et al.* 2005].

In pilot studies with PULSAR subject ME-27 we have been able to demonstrate that ability, and have included several processing strategies from the Nucleus percutaneous series among those already tested on the PULSAR platform. This has increased the number of those strategies now evaluated across 3 or 4 subjects. The Med-El PULSAR electrode array, while different from the Nucleus Contour array, is also one currently being implanted clinically.

As shown in Table I below, 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, that 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 total 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 delivery of 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 4th 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 analyses. 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 (the number of stimulation options in each channel's group, with "sh" indicating sharing among more than one channel and "ns" indicating no such sharing), whether instantaneous frequencies are clipped to the range of the respective analysis band, the number of analysis channels and -- if different -- the total number of stimulation options, and notes about any special pulse configuration or electrode assignment.]

typ	rate	dur	frange	sm filt	env	grp	clp	chs	processor details
cs	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	300 ms burst thresholds
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			11/11	
cis	833	27	350-7k	400-4	fw			6	300 ms burst psychophys
cis	833	40	350-3.0k	200-4	fw			6/6	
cis	833	40	350-5.5k	200-4	fw			6	
cis	833	40	350-5.5k	200-4	fw			6/6	
cis	833	40	350-5.5k	200-4	fw			6/6	rev el order
cis	833	40	350-5.5k	200-4	fw			8	tonotopic var
cis	833	40	350-5.5k	200-4	fw			11	300 ms thresh, 50 ms MCLs
cis	833	40	350-5.5k	200-4	fw			11	300 ms thresh, 50 ms MCLs
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	rev el order
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			6/6	
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			4/4	

Table I. (continued)

typ	rate	dur	frange	sm filt	env	grp	clp	chs	processor details
cis	833	60	350-7k	200-4	fw			6/6	
cis	833	60	350-7k	200-4	fw			8/8	
cis	833	60	350-7k	200-4	fw			10/10	
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	
cis3ph	833	*	350-7k	200-4	fw			6	triphasic 27,54,27us; +-+
cis3ph	833	*	350-7k	200-4	fw			6	triphasic 27,54,27us; -+-
cis3ph	833	*	350-7k	200-4	fw			6	triphasic 27,27,27 us; -+-
cis3ph	833	*	350-7k	200-4	fw			6	triphasic 27,27,27 us; +-+
cis3ph	833	*	350-7k	200-4	fw			10	triphasic 27,54,27us; -+-
cis3ph	833	*	350-7k	200-4	fw			10	triphasic 27,54,27us; +-+
cis3ph	833	*	350-7k	200-4	fw			10	triphasic 27,27,27 us; -+-
cis3ph	833	*	350-7k	200-4	fw			10	triphasic 27,27,27 us; +-+
cnd	667	27	350-7k	200-4	Hil	ns3		6/18	16us/ph, 4kp/s conds, ampl 50
cnd	667	27	350-7k	200-4	Hil	ns3		6/18	12us/ph, 4kp/s conds, ampl 160
cnd	667	27	350-7k	200-4	Hil	ns3		6/18	12us/ph, 4kp/s conds, ampl 250
cnd	833	27	350-7k	200-4	Hil	ns3		6/18	12us/ph, 2.5kp/s conds, ampl 160
cnd	833	27	350-7k	200-4	fw			6	12us/ph, 2.5kp/s conds, ampl 160
cnd	667	27	350-7k	200-4	fw			6	12us/ph 4kp/s cond pulses, ampl zero
cnd	667	27	350-7k	200-4	fw			6	12us/ph 4kp/s cond pulses ampl 160
cnd	667	27	350-7k	200-4	fw			6	12us/ph 4kp/s cond pulses ampl 250
drnl	833	27	350-7k	200-4	fw			21/21	
drnl	833	27	350-7k	200-4	fw			21/21	
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	ns3	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	ns4	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	ns3	yes	6/18	
fs	833	27	350-7k	200-4	Hil	ns3	yes	6/18	
fs	833	27	350-7k	200-4	Hil	ns3		7/21	
fs	833	27	350-7k	200-4	Hil	ns3	yes	7/21	
fs	833	27	350-7k	200-4	Hil	ns2	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	

Table I. (continued)

typ	rate	dur	frange	sm filt	env	grp	clp	chs	processor details
fs	833	27	350-7k	200-4	Hil	sh3	yes	21/43	
fs	833	27	LinLog	200-4	Hil	ns3	yes	6/18	
fs	833	27	LinLog	200-4	Hil	ns3	yes	6/18	
fs	833	40	350-5.5k	200-4	Hil	ns3	yes	6/18	
fs	833	40	LinLog	200-4	Hil	ns3	yes	6/18	
fs	833	60	350-5.5k	200-4	Hil	ns3	yes	6/18	
fs	833	60	350-7k	200-4	Hil	sh5		10/41	
fs	833	60	350-7k	200-4	Hil	ns3	yes	6/18	
fs	833	60	350-7k	200-4	Hil	ns3		7/21	
fs	833	60	350-7k	200-4	Hil	ns2	yes	8/16	
fs	833	60	350-7k	200-4	Hil	sh3		10/21	
fs	833	60	LinLog	200-4	Hil	ns3	yes	6/18	
pp	833	27	350-7k	200-4	fw	3pp		8+3	
ss	833	27	350-7k	200-4	fw			4	
ss	833	500	350-7k	200-4	fw			4	

Results

In this report, we will present and discuss the results for the eleven processors evaluated across all four percutaneous subjects, placing those results in the context of the best scores achieved by each subject across all processors with which they were tested.

Then we will discuss patterns of relative performance by each subject across the full range of processor types.

The final quarterly report for this project will include a detailed presentation of all the data gathered in these studies.

The parameters for the eleven processors evaluated across all four percutaneous subjects are shown in Table II below. Three CIS and 8 fine structure processors are represented. Pulse rate (833 p/s/channel), pulse phase duration (27 μs/phase), overall analysis frequency range (350 Hz – 7.0 kHz), and smoothing filter characteristics (4^{th}-order, 200 Hz low-pass filters) are held constant across all these processors.

Table II. Parameters for Subset of Processors Tested Across 4 Subjects

[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 (the number of stimulation options in each channel's group, with "sh" indicating sharing among more than one channel and "ns" indicating no such sharing), whether instantaneous frequencies are clipped to the range of the respective analysis band, and the number of analysis channels and -- if different -- the total number of stimulation options.]

typ	rate	dur	frange	sm filt	env	grp	clp	chs
cis	833	27	350-7k	200-4	fw			5
cis	833	27	350-7k	200-4	fw			7
cis	833	27	350-7k	200-4	fw			10
fs	833	27	350-7k	200-4	Hil	sh9	yes	5/41
fs	833	27	350-7k	200-4	Hil	ns3		7/21
fs	833	27	350-7k	200-4	Hil	sh3		10/21
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	sh3		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

Speech reception test results for all four percutaneous subjects and these 11 processors are summarized in Figure 1 and Tables III and IV below.

In Figure 1 the four rows of bar charts contain data for the four subjects, in order of increasing overall level of performance. The four columns of bar charts contain data for four types of test – identification of medial consonants in quiet, identification of medial consonants in noise, identification of words in sentences in quiet, and identification of words in sentences in noise. All speech materials were presented without visual cues and without feedback as to correct or incorrect responses, using recordings of male talkers. The medial consonant tokens were in \ah\-C-\ah\ context, with 3 exemplars of each consonant token, presented in randomized sets to allow calculation of standard error of the mean for percent correct scores, and with a minimum of 10 presentations of each consonant in each condition. The CUNY sentences were used, with a minimum of 4 lists of 12 sentences each (typically a total of 408 words) presented in each condition. The noise was CCITT long-term speech spectrum in every case, with speech and noise digitally mixed. Care was taken to minimize any biasing of test results by familiarity with the materials.

The number of different consonants and the noise levels chosen were appropriate to the overall performance level of each subject, and are indicated to the left of each row. The indicated number of consonants refers to both of the first two columns and the indicated S/N level refers to both the second and fourth columns. Subjects NP-6, NP-9, and NP-7

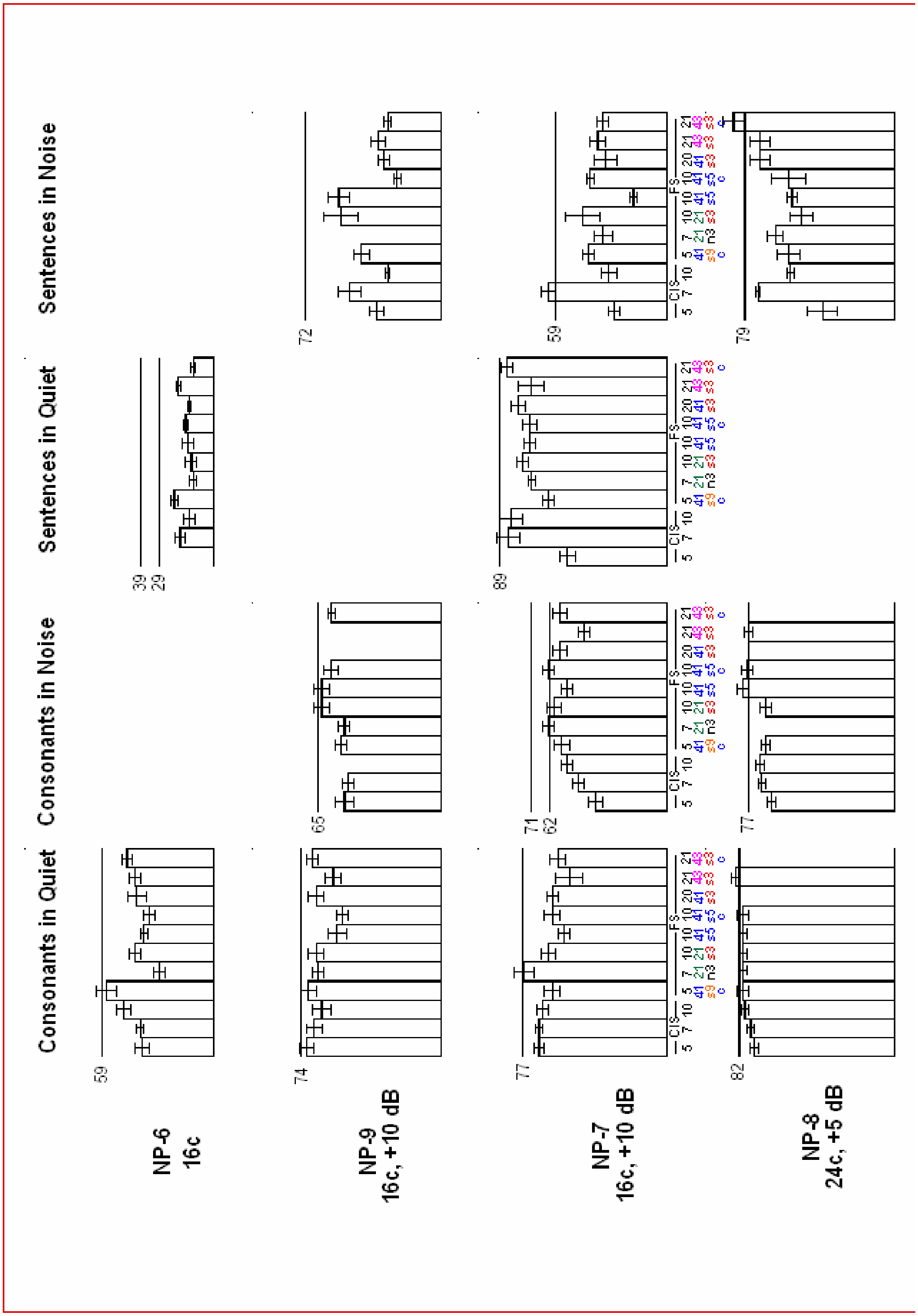

Figure 1. Summary of results for the 11 processors evaluated across all 4 percutaneous subjects.

were tested with 16 consonants, while the high performance levels of subject NP-8 required the use of 24 consonants for sensitivity to differences among processors. Subject NP-6 was tested only in quiet, while subjects NP-9 and NP-7 were tested also at the S/N of +10dB, and NP-8 at the S/N of +5dB.

For each combination of test and subject, percent correct scores for each of the 11 processors are represented in bar charts. Error bars indicate standard deviation of the mean. The base line for each bar chart indicates zero percent correct, and all the charts are plotted to the same vertical scale. A horizontal line near the tops of the bars places the data of each bar chart in the context of that subject's highest performance with any processor on that test. Each such horizontal line is labeled with a percent correct value corresponding to the highest score achieved with any processor, minus the standard deviation of the mean associated with that score (*i.e.,* the position of the horizontal line corresponds to the bottom of the error bar associated with the highest score). To provide a fuller context, two such horizontal lines have been included on the same bar chart in two cases, the upper one corresponding to a single exceptionally high score and the lower to the second-highest score among all processors evaluated with that subject and test. The parameters defining each of the 11 processors are shown in abbreviated labels below each column in the charts in the third row. The top row of those labels indicates type of processor (CIS or FS); the second row the number of analysis channels; the third row the number of stimulation options (if different); the fourth row the number of stimulation options in each group associated with an analysis channel, if relevant, and whether the options are shared (s) among adjacent channels or not (n); and the fifth row whether instantaneous frequencies are clipped (c) to the limits of the respective analysis band.

Tables III and IV display the same data in numerical form. Scores for each processor are displayed in a common column, with parameter values shown in the top few cells with labels to the left. Percent correct scores with uncertainties expressed as standard deviation of the mean are displayed in rows, with each row corresponding to a particular combination of subject and test as labeled on the left. Within the test labels, the letter C indicates a consonant identification test and the letter S indicates a test of identification of words in sentences. The number before each C indicates how many different consonants were included, and following each C or S is either a letter q indicating presentation of the speech in quiet or a number indicating the S/N ratio in dB. The highest scores for each row are highlighted in two shades of green. Various parameters and the four subjects may also be distinguished by color codes, which generally are consistent across all the Tables in this report.

Table III. Speech Reception Results by Subject, across Test Types

typ			cis	cis	cis	fs	fs	fs	fs	fs	fs	fs	fs
chs			5	7	10	5/41	7/21	10/21	10/41	10/41	20/41	21/43	21/43
grp						sh9	ns3	sh3	sh5	sh5	sh3	sh3	sh3
clp						yes				yes			yes
dur			27	27	27	27	27	27	27	27	27	27	27
	subj	test											
	NP-6	16Cq	38±4	39±2	48±4	57±5	29±3	42±3	37±2	34±3	41±5	42±3	46±3
	NP-6	Sq		18±3	13±3	21±+2	11±2	12±3	14±3	15±1	13±1	19±1,	11±1
	NP-9	16Cq	71±4	67±4	63±5	70±4	65±3	66±4	55±5	52±3	66±4	57±4	68±3
	NP-9	16C10	51±5	49±3		53±3	51±3	63±4	63±4	58±4			58±2
	NP-9	S10	34±4	48±6	28±1	42±4		53±9	54±6	23±2	30±3	33±4	28±2
	NP-7	16Cq	68±3	68±2	66±3	61±4	76±5	63±4	55±3	61±4	61±3	52±4	58±4
	NP-7	16C10	38±4	47±3	53±3	56±4	63±3	60±4	53±3	63±3	57±4	44±3	57±4
	NP-7	Sq	53±4	84±6	83±6	63±3	72±2	77±3	73±3	73±4	79±4	72±7	85±3
	NP-7	S10	28±3	63±4	31±4	42±3	34±5	45±9	18±2	41±2	33±6	37±4	34±3
	NP-8	24Cq	74±2	76±2	79±2	80±3	80±2	80±2	80±2	80±3		84±2	
	NP-8	24C5	65±2	70±2	71±2	68±2		68±3	80±3	78±3		77±2	
	NP-8	S5	38±8	72±1	55±2	56±6	63±4	49±6	54±3	56±9	71±5	71±5	85±6

In Table III, the rows are grouped together by subject, to allow easy comparison of processor performance across test types for each subject.

In Table IV, the rows are grouped together by test type, to facilitate comparisons of processors across subjects for the same type of test.

Table IV. Speech Reception Results by Test Type, across Subjects

typ			cis	cis	cis	fs	fs	fs	fs	fs	fs	fs	fs
chs			5	7	10	5/41	7/21	10/21	10/41	10/41	20/41	21/43	21/43
grp						sh9	ns3	sh3	sh5	sh5	sh3	sh3	sh3
clp						yes				yes			yes
dur			27	27	27	27	27	27	27	27	27	27	27
	subj	test											
	NP-6	16Cq	38±4	39±2	48±4	57±5	29±3	42±3	37±2	34±3	41±5	42±3	46±3
	NP-9	16Cq	71±4	67±4	63±5	70±4	65±3	66±4	55±5	52±3	66±4	57±4	68±3
	NP-7	16Cq	68±3	68±2	66±3	61±4	76±5	63±4	55±3	61±4	61±3	52±4	58±4
	NP-8	24Cq	74±2	76±2	79±2	80±3	80±2	80±2	80±2	80±3		84±2	
	NP-6	Sq		18±3	13±3	21±+2	11±2	12±3	14±3	15±1	13±1	19±1,	11±1
	NP-7	Sq	53±4	84±6	83±6	63±3	72±2	77±3	73±3	73±4	79±4	72±7	85±3
	NP-9	16C10	51±5	49±3		53±3	51±3	63±4	63±4	58±4			58±2
	NP-7	16C10	38±4	47±3	53±3	56±4	63±3	60±4	53±3	63±3	57±4	44±3	57±4
	NP-8	24C5	65±2	70±2	71±2	68±2		68±3	80±3	78±3		77±2	
	NP-9	S10	34±4	48±6	28±1	42±4		53±9*	54±6*	23±2	30±3	33±4	28±2
	NP-7	S10	28±3	63±4	31±4	42±3	34±5	45±9	18±2	41±2	33±6	37±4	34±3
	NP-8	S5	38±8	72±1	55±2	56±6	63±4	49±6	54±3	56±9	71±5	71±5	85±6

CIS Processors

The three CIS processors included in the 11 presently under consideration differed only in the number of analysis channels – 5, 7, and 10 – chosen to represent the range over which increasing numbers of channels have previously been found to have decreasing marginal benefits, at least in quiet. [The conditions of these studies represent those at which CIS is at the greatest disadvantage in noise: unilateral implants without any benefit from residual acoustic hearing. Previous studies have shown that bilateral implants and/or combined EAS devices can reduce the negative impact of speech spectrum noise on performance; see for example Lawson *et al.* (2001 and 2001a), Wilson *et al.*(2002),]

In some cases, a subject's best overall performance for speech in quiet was achieved or equaled with a traditional CIS processor: NP-9's consonant scores with 5 channels, and NP-7's sentence scores with 7 and 10 channels. [NP-6's best sentence score was with a 6-channel CIS processor delivering 17 µs/phase pulses at 4893 p/s/channel.

Scores in quiet with CIS processors were better for 10 channels than for 5 or 7 channels in the case of NP-6's consonant identification, and better for 7 and 10 channels than for 5 channels in the case of NP-7's identification of words in sentences. There were no significant differences as a function of number of CIS channels for consonant tests in quiet with NP-9, NP-7, and NP-8, and for sentence tests with NP-6.

In noise, the only best scores achieved with a CIS processor were by NP-7 for sentences (at +10 dB S/N), with the 7-channel version. No fine structure processor provided equivalent performance with sentences in noise for that subject.

Fine Structure Processors

While NP-6's overall performance levels led us to test him only in quiet, certain fine structure processors provided him with significant benefit in those tests. The 5 of 41 channel processor (with groups of 9 stimulation options shared among adjacent channels and clipping of instantaneous frequency determinations at analysis band edges) boosted his performance on consonant identification above that achieved with any CIS processor. [His other best scores on the consonant tests were with 21/21 channel processors using dual-resonance nonlinear filters and stimulating at 833 p/s/channel; a 5 of 21 channel design with groups of 5 stimulation options, sharing, and clipping; and the one peak-picking design tested (see Table I) which also supported this subject's second highest sentence scores.]

Fine structure processors performed generally better than CIS for consonants in noise, for all three subjects tested in noise. For sentences in noise, none of the 8 fine structure processors tested across all four subjects was significantly better than the best CIS for NP-9 and NP-7, while NP-8's best sentence score was with a 21 of 43 channel design with 3 shared stimulation options per channel and – significantly – clipping of instantaneous frequencies. [The best overall scores for sentences in noise for NP-9 were achieved with 6 channel CIS processors utilizing triphasic pulse stimuli, which in the consonant tests also supported scores equivalent to the best observed for that subject with other designs. A different fine structure processor (7 of 21 channels, unshared groups of 3 stimulation options per channel, frequency clipping) performed as well in noise as the best CIS design for NP-7.]

We display our fine structure processor results in order of increasing number of analysis channels (5, 7, 10, 20, and 21). Cases in which there seems to be a pattern of improving performance with additional analysis bands are for NP-7 with sentences in quiet (but not in noise), and for NP-8 with both consonants and sentences in noise.

Candidates for a best processor overall from among these 8 fine structure designs would include a 10 of 21 channels for NP-9, a 10 of 41 channels for NP-7, and 21 of 43 channels for NP-8. We note that such choices would be consistent with a pattern of subjects with better overall performance levels benefiting from additional detail in the information provided by the processor.

The 8 fine structure designs under consideration at present include two pairs of processors that are identical except for clipping of instantaneous frequency determinations. The two pairs are for 10 of 41 channels and 21 of 43 channels. In quiet, there is no significant difference in 8 of 11 direct within-subject comparisons, 2 cases in which clipping produced a significant improvement, and 1 case (for NP-6) in which clipping produced a significant decrement in performance. In noise, there were 5 of 11 cases of no significant difference, 4 cases of significant improvement and 1 case (for NP-9) of significant decrement associated with the sole change of implementing instantaneous frequency clipping. For the two subjects with the highest overall levels of performance, clipping significantly improved performance in 4 of 7 comparisons in noise, with no significant difference in the other 3 cases.

Another pair among these 8 fine structure processors offers a limited opportunity to compare similar designs differing in whether or not the 3 stimulation options associated with each channel are shared across adjacent channels. One of these processors is 7 of 21 channels, with no sharing, and the other is 10 of 21 channels with sharing. Sharing is associated with significantly better performance with consonants in quiet for NP-6, with consonants in noise for NP-9, and with sentences in quiet for NP-7. Sharing is associated with significantly poorer performance with consonants in quiet for NP-7 and with sentences in noise for NP-8. In the latter case, processors with sharing in the context of larger groups of stimulation options achieve higher levels of performance than either processor of this pair.

Summary

A variety of design features included in the processors described in this report are capable of significantly altering speech reception performance under certain combinations of subject and listening conditions. The inclusion of fine structure analysis in general, the exploration of various combinations of the number of analysis channels and the number of stimulus options associated with each channel, and consideration of alternative ways of allocating stimulus options among channels all have potential for improving individual performance. While there is some indication that the marginal utility of additional information from a processor may generally be related to the presence of competing noise and to the overall performance level of a patient, there also is evidence that even relatively poor performers can obtain large benefits from the use of a particular fine structure design. And there continues to be evidence that some patients can do quite well with relatively simple CIS processors, especially – in the case of one subject – with the use of triphasic pulses. Of particular interest is the fact that the subject with the poorest overall performance among these four achieved his highest scores with a 5 of 41 channel fine structure processor, a 21 channel DRNL filter design, a 6 channel CIS processor stimulating at almost 5 kp/s/channel (the processor supporting the highest sentence scores), and a design combining 8 CIS channels with 3 channels dedicated to peak picker outputs.

A fuller picture of the impact of various detailed choices in processor design is expected to emerge from the many within-subject comparisons available in the complete database, to be included in the final quarterly report for this project.

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III. Plans for the next quarter

Among the activities planned for the next quarter are:

- Completion of analysis and reporting of the remaining data from the Nucleus percutaneous studies.
- Continuing analysis of previously collected data and preparation of manuscripts for publication

IV. Acknowledgments

We thank volunteer research subject NP-7 for her participation in studies conducted during this quarter, and subjects NP-6, NP-9, NP-8, and ME-27 for their participation in earlier studies discussed in this report.

Appendix 1: Summary of reporting activity for this quarter

Invited talks

Wilson BS, *et al.*: EAS and possible mechanisms underlying benefits. Guest of Honor Address, *Hearing Preservation Workshop IV,* Warsaw-Kajetany, Poland, October 14-15, 2005.

Wilson BS (Chair): Afternoon session on "Hearing Preservation, Partial Deafness, Cochlear Implantation, and EAS." *Hearing Preservation Workshop IV,* Warsaw-Kajetany, Poland, October 14-15, 2005.

Wilson BS, Müller JM, Wolford RD, Lawson DT: Signal processing for binaural devices. *International Binaural Symposium 2005,* Manchester, UK, October 29-31, 2005.

Wilson BS: The auditory prosthesis as a paradigm for successful neural interfaces. *Ninth Annual Meeting of the North American Neuromodulation Society,* Washington, DC, November 10-12, 2005.