Second Quarterly Progress Report

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Speech Processors for Auditory Prostheses

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I. Introduction

One of the principal objectives of this project is to design, develop and evaluate speech processors for implantable auditory prostheses. Ideally, the processors will represent the information content of speech in a way that can be perceived by implant patients. Another principal objective is to develop new test materials for the evaluation of speech processors, given the growing number of cochlear implant subjects enjoying levels of performance too high to be sensitively measured by existing tests.

Work in the present quarter included:

1. Studies with Ineraid subjects SR3 (weeks of October 30, November 6 and January 29) and SR10 (weeks of November 27 and December 4), including recordings of intracochlear evoked potentials for both subjects, evaluation of new processor designs and fitting procedures for both subjects, and continued evaluation of possible learning effects with extensive use of a portable CIS processor by subject SR3.
2. Completion of studies with Nucleus percutaneous subject NP2 (weeks of November 6 and 13). Studies included comparisons among CIS processors using different numbers of channels, CIS processors using different rates of stimulation, CIS processors using different ranges of spanned frequencies for the bandpass channels (standard range of 350 to 5500 Hz versus alternative range of 350 to 9500 Hz), "n-of-m" processors that stimulate a selected subset of electrodes in each stimulus cycle, and the clinical SPEAK processor used by this subject in her daily life. Studies also included recordings of intracochlear evoked potentials, with special emphasis on determining spatial patterns of neural stimulation (the relatively large number of electrodes in the Nucleus array provides an advantage for such determinations).
3. Initial studies with Nucleus percutaneous subject NP5 (weeks of January 15 and 22).
4. Development of software to support loudness scaling measures and use of such measures in designing channel-by-channel mapping functions for CIS processors, as originally described by the Geneva team.
5. Development of new hardware and software for the measurement of channel interactions with intracochlear evoked potentials, including programmed control of two current sources that can deliver simultaneous or nonsimultaneous stimuli to two channels.
6. Continued development of better current sources and recording amplifiers for evoked potential studies.
7. Installation and initial use (beginning the week of November 6) of two new laboratories at RTI, one fully equipped for speech reception studies and the other for evoked potential studies.
8. Various upgrades to the laboratory systems, including initial development of a multichannel monitoring system for evaluation and documentation of speech processor outputs, initial construction and final design revisions for a bank of 22 current sources for use in the speech reception laboratory, design and construction of a system for continuous monitoring of electrode connection status, and installation and checkout of uninterruptable power supplies for both laboratories.
9. Presentation of project results in invited lectures at the *Thirtieth Anniversary Meeting of the North Carolina Chapter of the Acoustical Society of America* held in Blowing Rock, NC (Lawson), and at the *International Course on Hearing Aids, Vibrotactile Devices and Cochlear Implants in Profound*

Hearing Loss in Children held in Bolzano, Italy (Lawson).

10. Initial development of a Gantt Chart of tasks, schedules and resources for this project, to assist in the planning and coordination of activities. The Chart and related representations (e.g., PERT Chart, breakouts of tasks and schedules for individuals) were produced with the Microsoft Project software package.
11. Continued analysis of speech reception and evoked potential data from prior studies, and continued preparation of manuscripts for publication.

In section II of this report we present results from studies to evaluate effects of manipulations in spatial representations with cochlear implants. By spatial representations we mean the number and sites of intracochlear electrodes used for stimulation. The manipulations involved (a) the use of different numbers of electrodes in conjunction with CIS processors associating a distinct bandpass channel with each electrode and (b) the use of different sets electrodes for two six-channel conditions. Manipulation (a) was conducted for Ineraid subject SR2 and for Nucleus percutaneous subjects NP1 and NP2. Manipulation (b) was conducted for the two Nucleus percutaneous subjects.

In Appendix 1 of this report we also present our broader experience in manipulations of various aspects of spatial representations, including manipulations in channel number, channel to electrode assignments, simultaneous versus nonsimultaneous stimulation, and choices of different subsets of electrodes for a given number of channels. Selected results from studies across our most recent 27 subjects are included in Appendix 1.

Results from other activities and studies in the list above will be presented in future reports.

II. Manipulations in Spatial Representations with Implants

Methods

Effects of manipulations in spatial representations were measured with a test of consonant identification. Twenty four consonants were presented in an /a/-consonant-/a/ context ("aba," "ada," etc.) in blocks of 24. Measures for subject SR2 included 5 blocks with a recorded male speaker and 5 blocks with a recorded female speaker. Measures for subjects NP1 and NP2 included 10 blocks for each of the speakers. Multiple exemplars of each consonant were used, and the consonants were presented in a different randomized order for each block. The tests were conducted with hearing alone and without feedback as to correct or incorrect responses.

The manipulation for Ineraid subject SR2 involved the use of different numbers of electrodes in conjunction with CIS processors providing a distinct bandpass channel for each electrode. Each n-channel processor utilized the apicalmost n electrodes, and filtered the same total frequency range into n sixth order bands of equal width on a logarithmic scale. Other parameters of the processors, such as rate of stimulation on each of the utilized electrodes, were held constant across conditions (see Wilson et al., 1994).

Effects of changes in the number of CIS channels (and associated electrodes) also were evaluated in tests with subjects NP1 and NP2. These subjects had been implanted with an experimental version of the Nucleus device, which provided direct percutaneous access to each of the 22 electrodes in the intracochlear array. Such access allowed implementations of CIS processors with a relatively high pulse rate (833 pps in the present studies) on each of the n electrodes. The conditions for NP1 included 4, 6, 8, 11 and 21 channel processors, and the conditions for NP2 included all of those except for the 21 channel processor. The n electrodes were selected to span at least most of the electrode array and to maximize perceived differences in pitch among the electrodes. In many cases, this resulted in a uniform or nearly-uniform spacing between the selected electrodes.

The studies with NP1 and NP2 also included use of an alternative set of electrodes for the 6 channel condition. In both cases the alternative set also spanned all or most of the electrode array.

Results

Overall percent correct scores and standard errors of means for subject SR2 are presented in Fig. 1 and those for subjects NP1 and NP2 in Fig. 2. The block percent correct scores for both speakers and all conditions were analyzed with a one-way analysis of the variance for each of the subjects, to determine whether significant differences existed among any of the conditions. The ANOVAs were significant for all three subjects (for SR2 $F[5,54] = 73.66$ and $p < .0001$; for NP1 $F[5,114] = 3.54$ and $p < .01$; and for NP2 $F[4,95] = 5.32$ and $p < .001$). Tables 1, 2 and 3 show differences in the means for all combinations of conditions for subjects SR2, NP1 and NP2, respectively. Boldface entries indicate conditions that are significantly different, i.e., those differences exceeding Fisher's Least Significant Difference criterion ($p < .05$) for each of the ANOVAs.

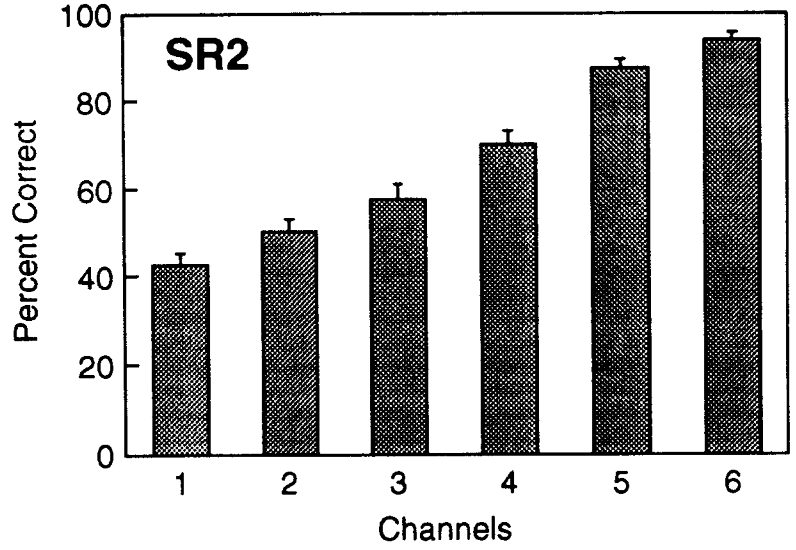

Fig. 1. Percent correct scores from 24 consonant tests for subject SR2. Bars show standard errors of the means.

All differences in the means for SR2 are significant except for the difference between 5 and 6 channels. Thus, for this subject increasing the number of channels up to 5 produced increases in speech recognition performance. Note that the scores for both 5 and 6 channels are quite close to the test's maximum, so a ceiling effect may have reduced the sensitivity of the test to changes in performance for more than 5 channels.

The results for subjects NP1 and NP2 are more complicated. For NP1 the ANOVA and post-hoc comparisons of means showed that the alternative electrode set for the 6 channel processor, along with the 8, 11 and 21 channel processors, were better than the 6 channel processor with the initial choice of electrodes. In addition, the 11 and 21 channel processors were better than the 4 channel processor. For NP2 the 11 and 6 channel processors were better than the 8 channel processor, the 11 and 6 channel processors were better than the 6 channel processor with the alternative electrode set, and the 6 channel processor with the initial electrode set was better than the 4 channel processor. Note that the 21 channel condition was not included in the tests with NP2.

Discussion

In some cases increasing the number of CIS channels can produce increases in speech recognition performance. A striking demonstration of this may be found in the results for SR2, where increases in the number up to five channels produced significant and monotonic increases in performance. Such increases also are seen to a lesser extent for subject NP1. For her, 11 and 21 channel processors were

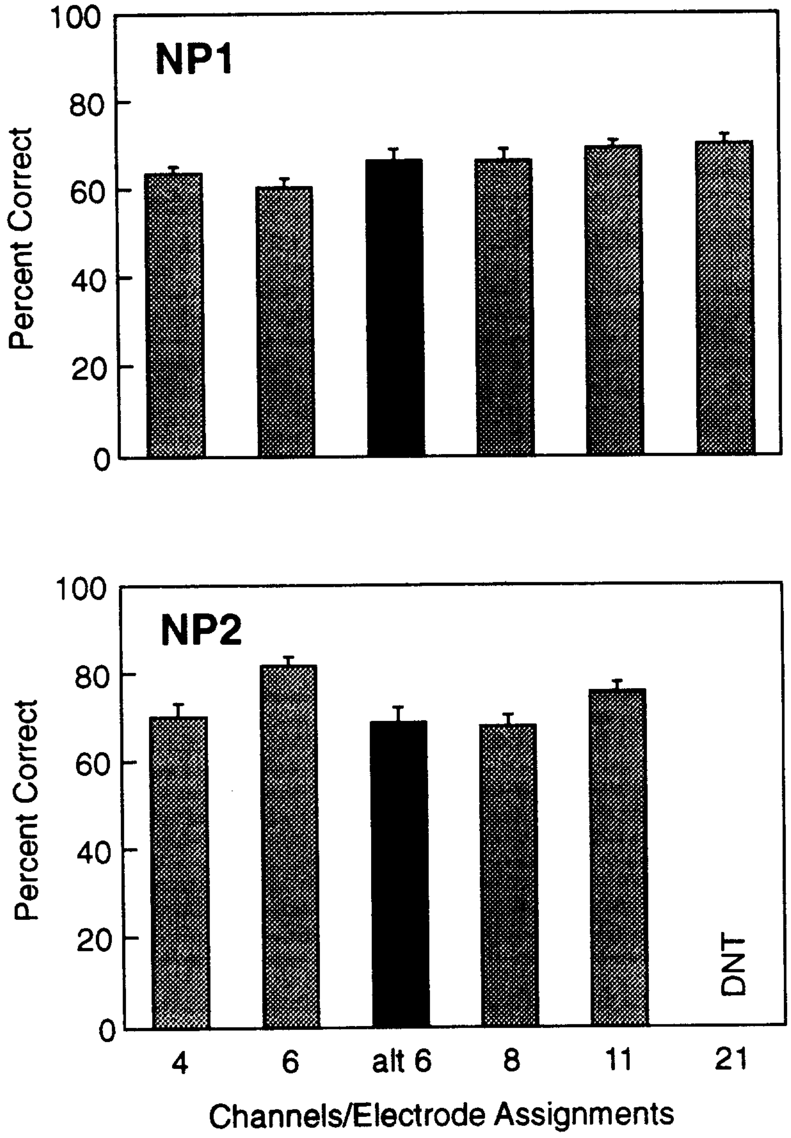

Fig. 2. Percent correct scores from 24 consonant tests for subjects NP1 and NP2. Bars show standard errors of the means.

better than a 4 channel processor and one of the 6 channel processors. However, the difference in scores between the two 6 channel processors, with different sets of electrodes, was similar to the differences produced with manipulations in the number of channels.

The results for NP2 also indicate the potential importance of choice of electrodes for processors using subsets of available electrodes. In this case the difference in scores between the two 6 channel

Table 1. Absolute differences in sample means for subject SR2. Differences exceeding the Least Significant Difference criterion of 6.74 are highlighted with boldface type (p < .05).

	Channels				
Channels	1	2	3	4	5
2	**7.50**				
3	**15.00**	**7.50**			
4	**27.08**	**19.58**	**12.08**		
5	**44.57**	**37.07**	**29.57**	**17.48**	
6	**50.83**	**43.33**	**35.83**	**23.75**	6.27

Table 2. Absolute differences in sample means for subject NP1. Differences exceeding the Least Significant Difference criterion of 5.30 are highlighted with boldface type (p < .05).

	Channels/Electrode Assignments				
Channels/ Elec Assign	6	4	alt 6	8	11
4	2.92				
alt 6	**5.83**	2.92			
8	**6.04**	3.13	0.21		
11	**8.54**	**5.63**	2.71	2.50	
21	**9.59**	**6.67**	3.75	3.54	1.04

Table 3. Absolute differences in sample means for subject NP2. Differences exceeding the Least Significant Difference criterion of 7.04 are highlighted with boldface type (p < .05).

	Channels/Electrode Assignments			
Channels/ Elec Assign	8	alt 6	4	11
alt 6	0.84			
4	2.50	1.67		
11	**7.92**	**7.08**	5.42	
6	**13.75**	**12.92**	**11.25**	5.83

conditions was again comparable to or greater than the differences observed when changing the number of channels. Note also that the results for NP2 do not show a clear pattern of increases in speech recognition scores with increases in the number of channels. Indeed, the highest score for this subject was obtained with a 6 channel processor using the initial choice of electrodes. Although this processor produced a higher score than the 4 channel processor, it also produced a higher score than the 8 channel processor.

These findings demonstrate that both number of channels and choice of electrodes can affect speech reception scores. They also support the idea that a large number of electrodes is desirable. For some patients the best performance may be obtained with a large number of channels (and electrodes), whereas with others the best performance may be obtained by selecting the best subset of a large number of electrodes for a processor with relatively few channels.

We note that the advantages of a large number of electrodes might be increased with electrodes having a greater spatial specificity of stimulation. The contacts in the Nucleus electrode array are in general relatively far away from the target tissue (Hatsushika et al., 1990) and might therefore be expected to have relatively poor spatial specificity (Clark, 1995; Ranck, 1975). Placement of the electrodes closer to the medial wall of the scala tympani could increase substantially the spatial specificity of stimulation. That, in combination with a greater number of contacts, might be a good recipe for a next-generation electrode array.

Acknowledgments

We thank subjects SR2, NP1 and NP2 for their participation. We also are indebted to Patricia Roush, M.A., Deborah Tucci, M.D., and Joseph Farmer, Jr., M.D., for their scientific contributions and for their help in making the studies with NP1 and NP2 possible. Support for clinical costs associated with the implant systems for NP1 and NP2 was provided by Cochlear Corporation.

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V. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. Presentation of project results in an invited lecture at the *Sixth Symposium on Cochlear Implants in Children*, to be held in Miami Beach, FL, February 2-3 (Wilson); in a poster at the *Nineteenth Midwinter Research Meeting of the Association for Research in Otolaryngology*, to be held in St. Petersburg Beach, FL, February 4-8 (Finley); and in an invited lecture at the annual meeting of the *American Association for Audiology*, to be held in Salt Lake City, April 20-21 (Lawson or Wilson).
2. Evaluation by consultant William Rabinowitz of our plans for the recording and validation of new speech test materials (Dr. Rabinowitz is scheduled to visit RTI February 15 and 16).
3. Refinements of the plans, as may be suggested by Dr. Rabinowitz, and initiation of the recordings.
4. Continuation of speech reception and evoked potential studies with Nucleus percutaneous subject NP4 (weeks of February 5 and 12; this will be the second of three visits for this subject).
5. Completion of speech reception and evoked potential studies with Nucleus percutaneous subject NP3 (weeks of March 4 and 11).
6. Speech reception and evoked potential studies with a new Ineraid subject, SR15 (week of March 18). This subject was selected for her quite low levels of speech reception with the clinical Ineraid processor.
7. Speech reception and evoked potential studies with Ineraid subject SR9, another subject with quite low levels of speech reception with the clinical Ineraid processor (weeks of April 15 and 22).
8. Bench evaluation and possible initiation of field studies with a new portable processor developed in a collaborative effort among investigators at the Ecole d'Ingenieurs de Geneve, in Geneva, Switzerland, the Hôpital Cantonal Universitaire also in Geneva, the Massachusetts Eye and Ear Infirmary in Boston, and our group here at RTI.
9. Continued development of evoked potential and speech reception laboratories, along the lines indicated in the Introduction of this report.
10. Visits by the following individuals:
    - Ron West, Jim Patrick and Jim Heller, of Cochlear Corporation and Cochlear Pty. Ltd., principally to review results from our collaborative studies with "Nucleus percutaneous" patients (February 7 and 8)
    - Bill Rabinowitz, mentioned in point 2 above
    - Martin Zimmerling, of the Innsbruck team, to learn about our methods for recording intracochlear evoked potentials (February 23)
    - Russ Snyder, of the University of California at San Francisco, to participate in a site visit for a project proposed to NIH by Dr. Finley of our RTI group and to present a lecture on temporal and spatial patterns of neural responses at the inferior colliculus to electrical stimuli presented through intracochlear electrodes (February 26-28)
    - Michael Dorman and Philip Loizou, of Arizona State University, to observe testing with Ineraid subject SR15 and to learn more about the programming and use of portable speech processors for research studies (March 19-21)
    - Deborah Ballantyne, of the Universita Degli Studi di Roma "La Sapienza" (Department of Otolaryngology), to observe speech reception and evoked potential studies (week of April 15)

11. Refinement and updating of the Gantt Chart for this project (see Introduction).
12. Continued analysis of speech reception and evoked potential data from prior studies.
13. Continued preparation of manuscripts for publication.

IV. Acknowledgments

We thank subjects SR3, SR10, NP2 and NP5 for their participation in studies conducted this quarter.

Appendix 1

Advantages of Multiple Channels in Cochlear Implants

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Advantages of Multiple Channels in Cochlear Implants

Our work on this project and its predecessors has included formal evaluations of the performance of over 950 distinct speech processors with the most recent 27 research subjects. In the course of this research, it has been found that cochlear implant users generally achieve their highest levels of performance with processors sending different information to each of the maximum number of perceptually distinct channels available, at least up to a total of six channels.

The benefits of multiple channels of stimulation are routinely observed in our laboratory and elsewhere, and are fundamental to all our work on this project. When the existence of such benefits was questioned recently in the literature (House, 1995), we decided to assemble a compact set of examples from our testing archives of results that are clearly inconsistent with such doubts.

It is important to note that a functional definition of each channel as capable of supporting parallel transmission of distinct information means that the number of such channels will not necessarily equal the number of stimulable electrodes available. In particular, the Nucleus-22 cochlear implant system would not be characterized as a 22 channel device under this definition.

While our studies have included a few auditory brainstem implant subjects with only a single channel available for electrical stimulation (Lawson *et al.*,1990; Wilson *et al.*, 1992), most of the subjects studied have been users of clinical cochlear implant systems that provided percutaneous access to multiple intracochlear electrodes. Processors using as few as one or two channels (Wilson *et al.*, 1987) have been evaluated in some of the cochlear implant subjects with access to six or more perceptually distinct channels, in the hope of developing better processing strategies for brainstem implantees.

Our studies have relied on speech reception tests both for rapid assessment of the relative performance of a great number of processing strategies in a given subject and for formal documentation of the performance of a relatively small subset of such processors. While standard open set tests (such as Spondee and NU-6 words and SPIN and CID sentences; see Owens and Kessler, 1985) have been used for the latter purpose, problems with the frequent reuse of limited recorded materials in testing the same subject, and the relatively large amounts of time required to administer such tests, have led to the use of an alternative for rapid comparisons. For that purpose identification of single presentations of medial consonants from digital audio recordings is used, without feedback as to correct or incorrect responses. Depending on the overall performance level of each subject, either a 16 or 24 consonant token set is used, group-randomized in tests that include 5 presentations of each token, chosen randomly from among multiple exemplars (Lawson *et al.*, 1993; Wilson, *et al.*, 1995). The percent correct score for each group of 16 or 24 consonants is treated as a single measurement, allowing calculation of standard deviations. Consonant identification tests remain useful even when administered many times to the same subject, and have the additional advantages of supporting calculations of information transmission ratios (Miller and Nicely, 1955), comparisons of the relative efficiency of different processor channels (Lawson *et al.*, 1995), and detection of learning effects or other longer term trends in test performance. High correlations have been demonstrated between information transmission scores on these medial consonant tests and scores on standard open set tests, as may be seen in the table appended to this report. In the comparisons that follow, percent correct medial consonant identification scores will be presented, each accompanied by the appropriate standard deviation of the mean. Also supplied for each comparison will be percent overall information transmission scores, and relevant processor parameters. Unless otherwise indicated, the consonant identification tests used a male talker. All of the processors discussed in this report had channel bands spanning the frequency range of 350 to 5500 Hz, and envelope detection by fullwave rectification in each channel. They all used the same mapping law between channel envelope amplitude and electrode pulse amplitude. Unless otherwise specified, balanced biphasic pulses with positive phase leading were delivered monopolarly to each intracochlear electrode with respect to a common reference electrode in *m. temporalis*.

Performance *vs.* Number of Channels

A study was conducted with subject SR-2, a user of the Ineraid clinical device, in which the number of channels was varied systematically from six to one. Each n-channel processor utilized the subject's apicalmost n electrodes, and filtered the same total input frequency range into n sixth order bands of equal width on a logarithmic scale. The six continuous interleaved sampling (CIS) processors (see Wilson *et al.*, 1991, 1995) were designed to be equivalent in other respects: all used 33 µsec/phase pulses, presented at the rate of 2525 pps on each channel (delays were interposed between sequential pulses for processors with fewer than six channels to maintain this constant rate) and delivered to the electrodes in base-to-apex order; all used first order 400 Hz envelope smoothing filters on each channel. Both male and female talker 24 consonant tests were conducted, with five presentations of each token in each condition. As in each such table in this report, the first three columns indicate the subject, the serial number assigned to the processor for that subject, and the number of processor channels.

Subj	Proc	Chan	Percent Correct Scores		Overall IT Scores	
			Male	Female	Male	Female
SR-2	8	6	97±2	91±2	98	94
SR-2	9	5	90±2	85±2	93	91
SR-2	10	4	76±4	64±3	88	82
SR-2	11	3	58±5	58±4	80	78
SR-2	12	2	49±5	52±2	69	74
SR-2	14	1	42±3	43±4	70	64

As may be seen in the table above and in Fig. 1, there was a clear monotonic decrease in consonant identification score for each decrease in the number of channels. The high absolute scores may have reduced the study's sensitivity to differences in performance between the six and five channel processors. In any event, these curves suggest that even higher performance might be obtained were more than six channels available to this subject.

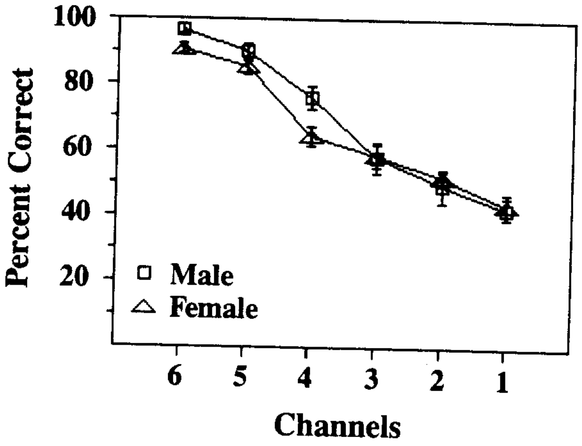

Figure 1. Percent correct scores for CIS processors using different numbers of channels: subject SR-2. Consonant identification tests using 24 medial consonant sounds. Square symbols correspond to male talker, triangles to female talker. The vertical bars indicate standard deviation of the mean for each averaged score.

[The six channel CIS processor used in this study was not optimal for this subject; performance with his best six channel CIS processors lies beyond the range of these 24-consonant tests. Note also that choices of different subsets of electrodes may alter the performance of processors with fewer than the maximum available number of channels, a topic that will be returned to below. The single channel version is more properly referred to as a CS processor, since interleaving is not applicable in that case.]

Tonotopic Use of Multiple Channels

Normal practice in the design of CIS and other multichannel speech processors is to assign the channels to intracochlear electrodes in tonotopic order, following the organization of the normal cochlea. In a recent subject, NP-1, implanted with a percutaneous version of the Nucleus-22 electrode array, that assignment of electrodes for a six channel CIS processor was reversed for comparison with an otherwise identical processor. The comparison was undertaken because of a lack of evidence from psychophysical tests that the subject's percepts could support the ranking of her electrodes. Both processors used twelfth order bandpass filters and fourth order 400 Hz smoothing filters on each channel. In both cases the channels were stimulated in staggered order at 833 pps with 33 µs/phase. The electrodes used -- numbered from the apical end -- were 1, 5, 9, 13, 18, and 22. Scores are based on ten presentations of each of 16 consonants.

Subj	Proc	Chan	Assignment	Correct	Overall IT
NP-1	17	6	tonotopic	86±3 %	89%
NP-1	25	6	reversed	21±4	41

Clearly, tonotopic assignment of spectral channels to intracochlear electrodes was of benefit to this subject.

Nonsimultaneous Stimulation Among Multiple Channels

In CIS and some other processors, pulsatile stimuli are delivered nonsimultaneously to the various electrodes in an effort to increase the independence of the associated channels (Wilson *et al.,* 1991, 1995). Summation of the fields generated by simultaneously pulsing different electrodes might otherwise lead to interactions among channel signals. A direct test of the efficacy of this approach is to compare otherwise identical CIS processors that differ only in whether the electrodes are pulsed simultaneously or nonsimultaneously. The stimulation rate on each channel is held constant. The apicalmost five or six electrodes were used in each case.

The following table illustrates such comparisons of CIS processors for five subjects implanted with the clinical Ineraid device. The first two were tested with 24 consonants, the others with 16. Each score is based on ten presentations of each token, except for SR-10's processor 61 and SR-13's processor 30, for which there were five presentations of each token.

Subj	Proc	Chan	Stimulation	Correct	Overall IT
SR-2	163b	6	Staggered	98±1 %	98
SR-2	270	6	Simultaneous	89±1	92
SR-3	20b	6	Staggered.	80±2	84
SR-3	22b	6	Simultaneous	50±3	63
SR-10	61	6	Staggered	81±4	85
SR-10	63	6	Simultaneous	45±3	70
SR-13	30	5	Apex-to-Base	98±2	98
SR-13	28	5	Simultaneous	80±2	83
SR-14	12	5	Staggered	88±2	88
SR-14	25	5	Simultaneous	62±5	73

In each of these cases, speech reception performance clearly was improved by a feature designed to increase independence among the multiple channels of cochlear stimulation.

Some processor parameters, while common within each compared pair, differed among these five subjects. Those differences are summarized in the following table:

Subject	BP Filter Order	PulseRate and Dur. pps	µs/ph	Smoothing Filter Hz	Order
SR-2	12	2525	33	400 Hz	1
SR-3	6	833	33	200	4
SR-10	6	833	33	400	1
SR-13	12	833	33	400	1
SR-14	12	500	100	200	4

Single Channel Alternatives to Multichannel Processors

For two of the same subjects in addition to SR-2, comparisons were made between single channel CS processors, utilizing various monopolar and bipolar electrode configurations, and multichannel CIS processors using similar parameters. All these processors delivered pulses to each channel at 833 pps and used fourth order 200 Hz smoothing filters on each channel. SR-3's six channel processor used sixth order bandpass filters, while both of SR-14's five channel processors used twelfth order filters. All stimuli were 67 µs/phase pulses except for the first group shown for SR-14, which were 33 µs/phase, and for the five channel processor of that subject's second group, which were 100 µs/phase. The apicalmost five electrodes were used for both of SR-14's multichannel processors, and all three multichannel processors stimulated their channels in staggered order.

Ten presentations of each of 16 consonants underlie the scores in each case except processors 27, 29, 32, and 33 of subject SR-3, for which there were five presentations of each consonant. The range of scores and the average score for the various single channel configurations is indicated in each case.

Subj	Proc	Channels	Correct	Overall IT
SR-3	40	6	75±3 %	79%
SR-3	26-35	1 [10 conditions]	25-61 % (av 47 %)	51-74
SR-14	1	5	77±3%	80
SR-14	20-22,24	1 [4 conditions]	56-66% (av 61%)	66-80
SR-14	7	5	81±3 %	84
SR-14	16-18,26,27	1 [5 conditions]	18-66 % (av 45 %)	38-75

For a patient limited to a single channel, then, the performance of a CS processor may vary enormously depending on the choice of electrode. There is no indication, however, that a single electrode CS alternative can equal the performance of a CIS processor in the same subject.

Without exception, every single channel processor we have evaluated on a subject with multiple available electrodes received intensely negative reviews from its user, even when accompanied by expressions of surprise at how much infomation someone limited to a single channel might be able to receive.

The individual single channel electrode configurations and scores are detailed in the following table:

Subject	Processor	Electrode Config.	Correct	Overall IT
SR-3	26	bipolar 2 wrt 1	27±3	51%
	27	bipolar 1 wrt 2	25±5	57
	28	bipolar 4 wrt 3	61±4	71
	29	bipolar 3 wrt 4	51±6	74
	30	bipolar 5 wrt 4	61±3	71
	31	bipolar 4 wrt 5	51±3	65
	32	1	39±3	63
	33	rev polarity 1	53±3	70
	34	4	46±2	69
	35	rev polarity 4	51±2	68
SR-14	20	bipolar 3 wrt 4	59±3	73
	21	bipolar 4 wrt 3	61±4	80
	22	3	66±4	73
	24	1	56±2	66
	16	bipolar 1 wrt 2	28±3	44
	17	bipolar 2 wrt 1	18±3	38
	18	bipolar 3 wrt 4	66±1	75
	26	bipolar 2 wrt 3	58±4	67
	27	bipolar 3 wrt 2	54±4	70

Note that no systematic difference was observed between the performance of single channel processors using monopolar *vs.* bipolar electrode configurations.

[Neither of the multichannel processors in these comparisons was the best CIS processor identified for that subject. SR-3's best six channel version delivered 40 µs/phase pulses at 2080 pps to each channel and supported a percent correct score of 95±2. SR-14's best five channel CIS processor, using 100 µs/phase pulses at 417 pps, supported a score of 89±2 %.]

Performance Sensitivity to Choices among Available Electrodes

In the previous section it was seen that the performance of otherwise identical single channel CS processors can vary enormously depending on the specific choice among several available electrodes. The same can be true for multichannel CIS processors utilizing fewer than the full number of electrodes available for stimulation.

In some patients, such differences in performance among potential electrode channels can be large enough for the addition of an electrode channel to cause a reduction in multichannel processor performance. This was observed in subject NP-2, implanted with a percutaneous version of the Nucleus-22 electrode array, in a comparison between two CIS processors, one with six channels and the other with five. Both processors delivered 33 µs/phase pulses at the rate of 833 pps to each selected electrode, and used fourth order 200 Hz smoothing filters on each channel. Both used **twelfth** order bandpass filters and stimulated channels in staggered order. Performance was measured from ten presentations of each of 16 consonants in each case. The electrodes selected for each processor (numbered from the apical end) are noted in the table below:

Subj	Proc	Chan	Electrodes	Correct	Overall IT
NP-2	2	6	1,5,9,13,17,21	81±3%	86%
NP-2	14	5	1,5,9,13,21	93±2	94

Subsequent use of electrode 15 rather than 17 allowed a six channel processor to perform at least as well as this five channel version (Lawson *et al.*, 1995). No significant difference was noted between these two electrodes in terms of electrical impedances, thresholds, or most comfortable levels of stimulation. [Combinations of more than six electrodes supported CIS processors with even better performance for this subject.]

DISCUSSION

Not every intracochlear electrode represents an equivalent parallel channel for transmission of speech information. But individual electrodes with widely varying effectiveness in single channel stimulation can be used together in multichannel processors to obtain significant improvements in performance. Departure from a tonotopic assignment of processor spectral information to multiple electrodes can produce large decrements in speech reception scores, as can the use of simultaneous rather than nonsimultaneous stimulation of electrodes.

All these within-patient observations support the validity of speech processor designs that seek to convey distinct spectral information via parallel channels and multiple intracochlear electrodes. It is well established that the availability of more intracochlear electrodes represents greater potential for cochlear implant performance, up to a total of at least six electrodes. The optimal number will depend on electrode design, implant placement, and the survival of neural elements in each patient.

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Acknowledgments

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Appendix 1.

Correlation Coefficients Between Consonant and Open Set Tests

Data in the following table are based on results with Ineraid subjects SR-1 through SR-11 (Wilson *et al.*, 1995). Information Transmission scores ~~are~~ were based on identification of 16 medial consonants in /a/ - consonant - /a/ context. The open set tests included recognition of spondee words, CID sentences, SPIN sentences presented without noise, and NU-6 monosyllabic words. Based on these data, any correlation coefficient greater than .65 is significant at $p < .001$.

	Spondee	CID	SPIN	NU-6
1. Overall	.93	.91	.92	.92
2. Voice	.88	.88	.82	.82
3. Nasality	.88	.82	.89	.85
4. Frication	.89	.84	.93	.88
5. Duration	.87	.83	.86	.92
6. Place	.88	.83	.89	.93
7. Envelope	.92	.91	.87	.84

Appendix 2

Summary of Reporting Activity for the Period of

November 1, 1995 through January 31, 1996

NIH Project N01-DC-5-2103

Reporting activity for the last quarter included the following presentations:

Lawson DT: Cochlear implants. Invited lecture, *Thirtieth Anniversary Meeting of the North Carolina Chapter of the Acoustical Society of America*, Blowing Rock, NC, November 2-3, 1995.

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conditions was again comparable to or greater than the differences observed when changing the number of channels. Note also that the results for NP2 do not show a clear pattern of increases in speech recognition scores with increases in the number of channels. Indeed, the highest score for this subject was obtained with a 6 channel processor using the initial choice of electrodes. Although this processor produced a higher score than the 4 channel processor, it also produced a higher score than the 8 channel processor.

These findings demonstrate that both number of channels and choice of electrodes can affect speech reception scores. They also support the idea that a large number of electrodes is desirable. For some patients the best performance may be obtained with a large number of channels (and electrodes), whereas with others the best performance may be obtained by selecting the best subset of a large number of electrodes for a processor with relatively few channels.

We note that the advantages of a large number of electrodes might be increased with electrodes having a greater spatial specificity of stimulation. The contacts in the Nucleus electrode array are in general relatively far away from the target tissue (Hatsushika et al., 1990) and might therefore be expected to have relatively poor spatial specificity (Clark, 1995; Ranck, 1975). Placement of the electrodes closer to the medial wall of the scala tympani could increase substantially the spatial specificity of stimulation. That, in combination with a greater number of contacts, might be a good recipe for a next-generation electrode array.

Acknowledgments

We thank subjects SR2, NP1 and NP2 for their participation. We also are indebted to Patricia Roush, M.A., Deborah Tucci, M.D., and Joseph Farmer, Jr., M.D., for their scientific contributions and for their help in making the studies with NP1 and NP2 possible. Support for clinical costs associated with the implant systems for NP1 and NP2 was provided by Cochlear Corporation.

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V. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. Presentation of project results in an invited lecture at the *Sixth Symposium on Cochlear Implants in Children*, to be held in Miami Beach, FL, February 2-3 (Wilson); in a poster at the *Nineteenth Midwinter Research Meeting of the Association for Research in Otolaryngology*, to be held in St. Petersburg Beach, FL, February 4-8 (Finley); and in an invited lecture at the annual meeting of the *American Association for Audiology*, to be held in Salt Lake City, April 20-21 (Lawson or Wilson).
2. Evaluation by consultant William Rabinowitz of our plans for the recording and validation of new speech test materials (Dr. Rabinowitz is scheduled to visit RTI February 15 and 16).
3. Refinements of the plans, as may be suggested by Dr. Rabinowitz, and initiation of the recordings.
4. Continuation of speech reception and evoked potential studies with Nucleus percutaneous subject NP4 (weeks of February 5 and 12; this will be the second of three visits for this subject).
5. Completion of speech reception and evoked potential studies with Nucleus percutaneous subject NP3 (weeks of March 4 and 11).
6. Speech reception and evoked potential studies with a new Ineraid subject, SR15 (week of March 18). This subject was selected for her quite low levels of speech reception with the clinical Ineraid processor.
7. Speech reception and evoked potential studies with Ineraid subject SR9, another subject with quite low levels of speech reception with the clinical Ineraid processor (weeks of April 15 and 22).
8. Bench evaluation and possible initiation of field studies with a new portable processor developed in a collaborative effort among investigators at the Ecole d'Ingenieurs de Geneve, in Geneva, Switzerland, the Hôpital Cantonal Universitaire also in Geneva, the Massachusetts Eye and Ear Infirmary in Boston, and our group here at RTI.
9. Continued development of evoked potential and speech reception laboratories, along the lines indicated in the Introduction of this report.
10. Visits by the following individuals:
    - Ron West, Jim Patrick and Jim Heller, of Cochlear Corporation and Cochlear Pty. Ltd., principally to review results from our collaborative studies with "Nucleus percutaneous" patients (February 7 and 8)
    - Bill Rabinowitz, mentioned in point 2 above
    - Martin Zimmerling, of the Innsbruck team, to learn about our methods for recording intracochlear evoked potentials (February 23)
    - Russ Snyder, of the University of California at San Francisco, to participate in a site visit for a project proposed to NIH by Dr. Finley of our RTI group and to present a lecture on temporal and spatial patterns of neural responses at the inferior colliculus to electrical stimuli presented through intracochlear electrodes (February 26-28)
    - Michael Dorman and Philip Loizou, of Arizona State University, to observe testing with Ineraid subject SR15 and to learn more about the programming and use of portable speech processors for research studies (March 19-21)
    - Deborah Ballantyne, of the Universita Degli Studi di Roma "La Sapienza" (Department of Otolaryngology), to observe speech reception and evoked potential studies (week of April 15)

11. Refinement and updating of the Gantt Chart for this project (see Introduction).
12. Continued analysis of speech reception and evoked potential data from prior studies.
13. Continued preparation of manuscripts for publication.

IV. Acknowledgments

We thank subjects SR3, SR10, NP2 and NP5 for their participation in studies conducted this quarter.

Appendix 1

Advantages of Multiple Channels in Cochlear Implants

Dewey T. Lawson, Blake S. Wilson, Charles C. Finley, and Mariangeli Zerbi

Advantages of Multiple Channels in Cochlear Implants

Our work on this project and its predecessors has included formal evaluations of the performance of over 950 distinct speech processors with the most recent 27 research subjects. In the course of this research, it has been found that cochlear implant users generally achieve their highest levels of performance with processors sending different information to each of the maximum number of perceptually distinct channels available, at least up to a total of six channels.

The benefits of multiple channels of stimulation are routinely observed in our laboratory and elsewhere, and are fundamental to all our work on this project. When the existence of such benefits was questioned recently in the literature (House, 1995), we decided to assemble a compact set of examples from our testing archives of results that are clearly inconsistent with such doubts.

It is important to note that a functional definition of each channel as capable of supporting parallel transmission of distinct information means that the number of such channels will not necessarily equal the number of stimulable electrodes available. In particular, the Nucleus-22 cochlear implant system would not be characterized as a 22 channel device under this definition.

While our studies have included a few auditory brainstem implant subjects with only a single channel available for electrical stimulation (Lawson *et al.*, 1990; Wilson *et al.*, 1992), most of the subjects studied have been users of clinical cochlear implant systems that provided percutaneous access to multiple intracochlear electrodes. Processors using as few as one or two channels (Wilson *et al.*, 1987) have been evaluated in some of the cochlear implant subjects with access to six or more perceptually distinct channels, in the hope of developing better processing strategies for brainstem implantees.

Our studies have relied on speech reception tests both for rapid assessment of the relative performance of a great number of processing strategies in a given subject and for formal documentation of the performance of a relatively small subset of such processors. While standard open set tests (such as Spondee and NU-6 words and SPIN and CID sentences; see Owens and Kessler, 1985) have been used for the latter purpose, problems with the frequent reuse of limited recorded materials in testing the same subject, and the relatively large amounts of time required to administer such tests, have led to the use of an alternative for rapid comparisons. For that purpose identification of single presentations of medial consonants from digital audio recordings is used, without feedback as to correct or incorrect responses. Depending on the overall performance level of each subject, either a 16 or 24 consonant token set is used, group-randomized in tests that include 5 presentations of each token, chosen randomly from among multiple exemplars (Lawson *et al.*, 1993; Wilson, *et al.*, 1995). The percent correct score for each group of 16 or 24 consonants is treated as a single measurement, allowing calculation of standard deviations. Consonant identification tests remain useful even when administered many times to the same subject, and have the additional advantages of supporting calculations of information transmission ratios (Miller and Nicely, 1955), comparisons of the relative efficiency of different processor channels (Lawson *et al.,* 1995), and detection of learning effects or other longer term trends in test performance. High correlations have been demonstrated between information transmission scores on these medial consonant tests and scores on standard open set tests, as may be seen in the table appended to this report. In the comparisons that follow, percent correct medial consonant identification scores will be presented, each accompanied by the appropriate standard deviation of the mean. Also supplied for each comparison will be percent overall information transmission scores, and relevant processor parameters. Unless otherwise indicated, the consonant identification tests used a male talker. All of the processors discussed in this report had channel bands spanning the frequency range of 350 to 5500 Hz, and envelope detection by fullwave rectification in each channel. They all used the same mapping law between channel envelope amplitude and electrode pulse amplitude. Unless otherwise specified, balanced biphasic pulses with positive phase leading were delivered monopolarly to each intracochlear electrode with respect to a common reference electrode in *m. temporalis.*

Performance *vs.* Number of Channels

A study was conducted with subject SR-2, a user of the Ineraid clinical device, in which the number of channels was varied systematically from six to one. Each n-channel processor utilized the subject's apicalmost n electrodes, and filtered the same total input frequency range into n sixth order bands of equal width on a logarithmic scale. The six continuous interleaved sampling (CIS) processors (see Wilson *et al.,* 1991, 1995) were designed to be equivalent in other respects: all used 33 μsec/phase pulses, presented at the rate of 2525 pps on each channel (delays were interposed between sequential pulses for processors with fewer than six channels to maintain this constant rate) and delivered to the electrodes in base-to-apex order; all used first order 400 Hz envelope smoothing filters on each channel. Both male and female talker 24 consonant tests were conducted, with five presentations of each token in each condition. As in each such table in this report, the first three columns indicate the subject, the serial number assigned to the processor for that subject, and the number of processor channels.

Subj	Proc	Chan	Percent Correct Scores		Overall IT Scores	
			Male	Female	Male	Female
SR-2	8	6	97±2	91±2	98	94
SR-2	9	5	90±2	85±2	93	91
SR-2	10	4	76±4	64±3	88	82
SR-2	11	3	58±5	58±4	80	78
SR-2	12	2	49±5	52±2	69	74
SR-2	14	1	42±3	43±4	70	64

As may be seen in the table above and in Fig. 1, there was a clear monotonic decrease in consonant identification score for each decrease in the number of channels. The high absolute scores may have reduced the study's sensitivity to differences in performance between the six and five channel processors. In any event, these curves suggest that even higher performance might be obtained were more than six channels available to this subject.

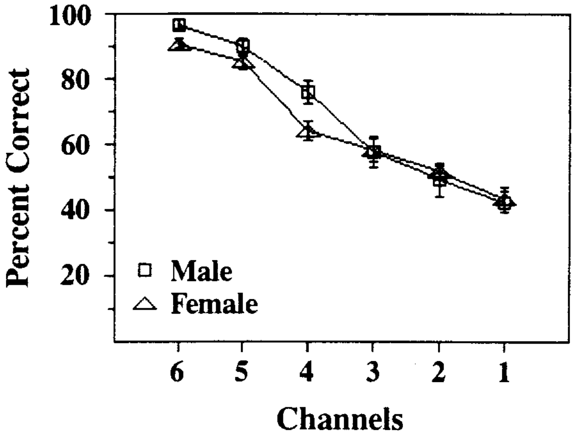

Figure 1. Percent correct scores for CIS processors using different numbers of channels: subject SR-2. Consonant identification tests using 24 medial consonant sounds. Square symbols correspond to male talker, triangles to female talker. The vertical bars indicate standard deviation of the mean for each averaged score.

[The six channel CIS processor used in this study was not optimal for this subject; performance with his best six channel CIS processors lies beyond the range of these 24-consonant tests. Note also that choices of different subsets of electrodes may alter the performance of processors with fewer than the maximum available number of channels, a topic that will be returned to below. The single channel version is more properly referred to as a CS processor, since interleaving is not applicable in that case.]

Tonotopic Use of Multiple Channels

Normal practice in the design of CIS and other multichannel speech processors is to assign the channels to intracochlear electrodes in tonotopic order, following the organization of the normal cochlea. In a recent subject, NP-1, implanted with a percutaneous version of the Nucleus-22 electrode array, that assignment of electrodes for a six channel CIS processor was reversed for comparison with an otherwise identical processor. The comparison was undertaken because of a lack of evidence from psychophysical tests that the subject's percepts could support the ranking of her electrodes. Both processors used twelfth order bandpass filters and fourth order 400 Hz smoothing filters on each channel. In both cases the channels were stimulated in staggered order at 833 pps with 33 μs/phase. The electrodes used -- numbered from the apical end -- were 1, 5, 9, 13, 18, and 22. Scores are based on ten presentations of each of 16 consonants.

Subj	Proc	Chan	Assignment	Correct	Overall IT
NP-1	17	6	tonotopic	86±3 %	89%
NP-1	25	6	reversed	21±4	41

Clearly, tonotopic assignment of spectral channels to intracochlear electrodes was of benefit to this subject.

Nonsimultaneous Stimulation Among Multiple Channels

In CIS and some other processors, pulsatile stimuli are delivered nonsimultaneously to the various electrodes in an effort to increase the independence of the associated channels (Wilson *et al.*, 1991, 1995). Summation of the fields generated by simultaneously pulsing different electrodes might otherwise lead to interactions among channel signals. A direct test of the efficacy of this approach is to compare otherwise identical CIS processors that differ only in whether the electrodes are pulsed simultaneously or nonsimultaneously. The stimulation rate on each channel is held constant. The apicalmost five or six electrodes were used in each case.

The following table illustrates such comparisons of CIS processors for five subjects implanted with the clinical Ineraid device. The first two were tested with 24 consonants, the others with 16. Each score is based on ten presentations of each token, except for SR-10's processor 61 and SR-13's processor 30, for which there were five presentations of each token.

Subj	Proc	Chan	Stimulation	Correct	Overall IT
SR-2	163b	6	Staggered	98±1 %	98
SR-2	270	6	Simultaneous	89±1	92
SR-3	20b	6	Staggered.	80±2	84
SR-3	22b	6	Simultaneous	50±3	63
SR-10	61	6	Staggered	81±4	85
SR-10	63	6	Simultaneous	45±3	70
SR-13	30	5	Apex-to-Base	98±2	98
SR-13	28	5	Simultaneous	80±2	83
SR-14	12	5	Staggered	88±2	88
SR-14	25	5	Simultaneous	62±5	73

In each of these cases, speech reception performance clearly was improved by a feature designed to increase independence among the multiple channels of cochlear stimulation.

Some processor parameters, while common within each compared pair, differed among these five subjects. Those differences are summarized in the following table:

Subject	BP Filter	PulseRate and Dur.		Smoothing Filter	
	Order	pps	µs/ph	Hz	Order
SR-2	12	2525	33	400 Hz	1
SR-3	6	833	33	200	4
SR-10	6	833	33	400	1
SR-13	12	833	33	400	1
SR-14	12	500	100	200	4

Single Channel Alternatives to Multichannel Processors

For two of the same subjects in addition to SR-2, comparisons were made between single channel CS processors, utilizing various monopolar and bipolar electrode configurations, and multichannel CIS processors using similar parameters. All these processors delivered pulses to each channel at 833 pps and used fourth order 200 Hz smoothing filters on each channel. SR-3's six channel processor used sixth order bandpass filters, while both of SR-14's five channel processors used twelfth order filters. All stimuli were 67 µs/phase pulses except for the first group shown for SR-14, which were 33 µs/phase, and for the five channel processor of that subject's second group, which were 100 µs/phase. The apicalmost five electrodes were used for both of SR-14's multichannel processors, and all three multichannel processors stimulated their channels in staggered order.

Ten presentations of each of 16 consonants underlie the scores in each case except processors 27, 29, 32, and 33 of subject SR-3, for which there were five presentations of each consonant. The range of scores and the average score for the various single channel configurations is indicated in each case.

Subj	Proc	Channels	Correct	Overall IT
SR-3	40	6	75±3 %	79%
SR-3	26-35	1 [10 conditions]	25-61 % (av 47 %)	51-74
SR-14	1	5	77±3%	80
SR-14	20-22,24	1 [4 conditions]	56-66% (av 61%)	66-80
SR-14	7	5	81±3 %	84
SR-14	16-18,26,27	1 [5 conditions]	18-66 % (av 45 %)	38-75

For a patient limited to a single channel, then, the performance of a CS processor may vary enormously depending on the choice of electrode. There is no indication, however, that a single electrode CS alternative can equal the performance of a CIS processor in the same subject.

Without exception, every single channel processor we have evaluated on a subject with multiple available electrodes received intensely negative reviews from its user, even when accompanied by expressions of surprise at how much infomation someone limited to a single channel might be able to receive.

The individual single channel electrode configurations and scores are detailed in the following table:

Subject	Processor	Electrode Config.	Correct	Overall IT
SR-3	26	bipolar 2 wrt 1	27±3	51%
	27	bipolar 1 wrt 2	25±5	57
	28	bipolar 4 wrt 3	61±4	71
	29	bipolar 3 wrt 4	51±6	74
	30	bipolar 5 wrt 4	61±3	71
	31	bipolar 4 wrt 5	51±3	65
	32	1	39±3	63
	33	rev polarity 1	53±3	70
	34	4	46±2	69
	35	rev polarity 4	51±2	68
SR-14	20	bipolar 3 wrt 4	59±3	73
	21	bipolar 4 wrt 3	61±4	80
	22	3	66±4	73
	24	1	56±2	66
	16	bipolar 1 wrt 2	28±3	44
	17	bipolar 2 wrt 1	18±3	38
	18	bipolar 3 wrt 4	66±1	75
	26	bipolar 2 wrt 3	58±4	67
	27	bipolar 3 wrt 2	54±4	70

Note that no systematic difference was observed between the performance of single channel processors using monopolar *vs.* bipolar electrode configurations.

[Neither of the multichannel processors in these comparisons was the best CIS processor identified for that subject. SR-3's best six channel version delivered 40 µs/phase pulses at 2080 pps to each channel and supported a percent correct score of 95±2. SR-14's best five channel CIS processor, using 100 µs/phase pulses at 417 pps, supported a score of 89±2 %.]

Performance Sensitivity to Choices among Available Electrodes

In the previous section it was seen that the performance of otherwise identical single channel CS processors can vary enormously depending on the specific choice among several available electrodes. The same can be true for multichannel CIS processors utilizing fewer than the full number of electrodes available for stimulation.

In some patients, such differences in performance among potential electrode channels can be large enough for the addition of an electrode channel to cause a reduction in multichannel processor performance. This was observed in subject NP-2, implanted with a percutaneous version of the Nucleus-22 electrode array, in a comparison between two CIS processors, one with six channels and the other with five. Both processors delivered 33 µs/phase pulses at the rate of 833 pps to each selected electrode, and used fourth order 200 Hz smoothing filters on each channel. Both used **twelfth** order bandpass filters and stimulated channels in staggered order. Performance was measured from ten presentations of each of 16 consonants in each case. The electrodes selected for each processor (numbered from the apical end) are noted in the table below:

Subj	Proc	Chan	Electrodes	Correct	Overall IT
NP-2	2	6	1,5,9,13,17,21	81±3%	86%
NP-2	14	5	1,5,9,13,21	93±2	94

Subsequent use of electrode 15 rather than 17 allowed a six channel processor to perform at least as well as this five channel version (Lawson *et al.,* 1995). No significant difference was noted between these two electrodes in terms of electrical impedances, thresholds, or most comfortable levels of stimulation. [Combinations of more than six electrodes supported CIS processors with even better performance for this subject.]

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Not every intracochlear electrode represents an equivalent parallel channel for transmission of speech information. But individual electrodes with widely varying effectiveness in single channel stimulation can be used together in multichannel processors to obtain significant improvements in performance. Departure from a tonotopic assignment of processor spectral information to multiple electrodes can produce large decrements in speech reception scores. as can the use of simultaneous rather than nonsimultaneous stimulation of electrodes.

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	Spondee	CID	SPIN	NU-6
1. Overall	.93	.91	.92	.92
2. Voice	.88	.88	.82	.82
3. Nasality	.88	.82	.89	.85
4. Frication	.89	.84	.93	.88
5. Duration	.87	.83	.86	.92
6. Place	.88	.83	.89	.93
7. Envelope	.92	.91	.87	.84

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NP1

	1				5				9				13				17				21	
4		●								●					●						●	
6		●				●				●				●					●		●	
6	●				●				●				●					●				●
8	●			●			●			●			●			●			●			●
11		●		●		●		●		●		●		●		●		●		●		●
21	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●

NP2

4	●								●						●						●	
6	●				●				●				●		●						●	
6	●					●				●				●		●				●		
8	●		●				●			●				●		●				●		●
11	●		●		●		●		●		●		●		●		●		●		●	
21																						

NP3

4	●								●				●								●	
6	●				●				●				●				●				●	
6	●		●		●		●		●		●											
8			●		●		●		●		●		●				●				●	
11	●		●		●		●		●		●		●		●		●		●		●	
21	●	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●

NP4

4					●								●		●						●	
6		●				●				●				●				●			●	
6					●				●				●		●				●		●	
8		●			●				●		●		●		●				●		●	
11		●			●			●	●		●		●		●	●	●		●		●	
21	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	

NP5

4			●					●					●					●				
6	●				●				●				●		●			●				
6		●				●				●				●				●			●	
8	●				●			●			●		●		●			●			●	
11		●		●		●		●		●		●		●		●		●		●		●
21	●	●	●	●	●	●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	●

Appendix 4.

Statistically Significant Differences in CIS Performance *vs.* Number of Channels

for subject:	processor:	supports significantly better percent correct scores for consonant identification than processor(s):	ANOVA p:
NP1	6’	6	< 0.01
	8	6	
	11	4,6	
	21	4,6	
NP2	6	4,6’,8	< 0.001
	11	6’,8	
NP3	4	6’	< 0.02
	6	6’	
	11	6’	
	21	6’	
NP4	1	1’’	<0.0001
	2	1,1’,1’’	
	3	1,1’,1’’	
	4	1,1’,1’’	
	6	1,1’,1’’	
	6’	1,1’,1’’	
	8	1,1’,1’’	
	11	1,1’,1’’	
	21	1,1’,1’’	
NP5	2	1,1’	< 0.0001
	3	1,1’,8	
	4	1,1’,8	
	6	1,1’,8	
	6’	1,1’,2,6’’,8,11,21	
	6’’	1,1’	
	8	1	
	11	1,1’’	
	21	1,1’’	

III. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. A site visit for the project by Drs. Terry Hambrecht and William Heetderks (July 23).
2. Presentation of project results in two invited lectures at the *Third European Symposium on Paediatric Cochlear Implantation*, in Hannover, Germany (June 6-8).
3. Speech reception and evoked potential studies with Nucleus percutaneous subjects NP5 (weeks beginning on May 13 and May 20), NP4 (weeks beginning on June 3 and June 10), and NP2 (July 8-10).
4. Recording of tokens for new speech tests.
5. Completion of new current sources, for use in studies to evaluate very high rates of stimulation (*e.g.*, 10000 pulses/s on each channel) in multichannel CIS processors.
6. Continued development of the Evoked Potentials Laboratory, including incorporation of a 22-bit A/D converter (in part to allow recording of both stimulus pulse artifact and evoked potentials in the linear range of the recording system).
7. Continued development of a new type of compression function for use in CIS processors, designed to mimic principal features of the noninstantaneous compression found in normal hearing at the interface between sensory hair cells and adjacent neurons.
8. Speech reception and evoked potential studies with Ineraid subject SR2 (July 22-26).
9. Possible continued studies with our local patient having standard Nucleus implants on both sides.
10. Possible application of one or more of the Geneva/MEEI/RTI portable processors in continuing studies to evaluate possible learning effects with extended use of CIS processors.
11. Continued analysis of speech reception and evoked potential data from prior studies.
12. Continued preparation of manuscripts for publication.

IV. Acknowledgments

We gratefully acknowledge the support by Cochlear Corporation of the device, surgical, and audiological costs of the 22 electrode percutaneous study described in this report, and of the travel and subsistence expenses of the subjects while participating in our studies.

We thank subjects NP1, NP2, NP3, NP4, NP5 for their participation in those studies, and subjects SR15 and SR9 for their participation in other studies conducted this quarter.

Appendix A. Summary of Reporting Activity for this Quarter

Reporting activity for the last quarter, covering the period from February 1 to April 30, 1996, included the following presentations:

Wilson BS: Strategies for representing speech information with cochlear implants. Invited lecture, *Sixth Symposium on Cochlear Implants in Children*, Miami Beach, FL, February 2-3, 1996.

Finley CC, Wilson BS: Spatial distribution of stimulus field and intracochlear evoked potentials as recorded from unstimulated electrodes of implanted cochlear prostheses. *Nineteenth Midwinter Research Meeting, Association for Research in Otolaryngology*, St. Petersburg Beach, FL, February 4-8, 1996.

Lawson DT: Cochlear implant research at Research Triangle Institute and Duke University Medical Center. Invited lecture, *Annual Meeting of the American Association for Audiology*, Salt Lake City, UT, April 20-21, 1996.