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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 bearing aspects 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 SR2 and SR3, including recordings of intracochlear evoked potentials for both subjects, electrophysiological and psychophysical measures of forward masking on single electrodes for both subjects, and evaluation of possible learning effects with extensive use of a portable CIS processor by subject SR3.
2. Initial studies with a patient implanted with transcutaneous Nucleus devices on both sides (subject NU4). Studies included electrode ranking on both sides, electrode ranking across the two sides, speech reception measures with the standard Nucleus speech processor (MPEAK for this subject) for both sides, and speech reception measures for CIS-like processors (using relatively low rates of stimulation imposed by the transcutaneous link) for both sides.
3. Development of CIS-like processors that stimulate a selected subset of electrodes in each stimulus cycle. We refer to these as "n-of-m" processors, where n is the number of electrodes selected for each cycle on the basis of the highest envelope signals and m is the total number of available electrode channels.
4. Completion of studies with Nucleus percutaneous subject NP1. Studies included comparisons among CIS processors using different numbers of channels (4, 6, 8, 11 and 21 channels), CIS processors using different rates of stimulation (250 versus 833 pulses/s on each channel for a 6 channel processor), 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), the "n-of-m" processor mentioned above, 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).
5. Presentation of project results in two invited lectures at the *1995 Conference on Implantable Auditory Prostheses* (Finley and Wilson), and in one invited lecture at the *26th Annual Neural Prosthesis Workshop* (Wilson).
6. Participation in a conference on digital signal processing (Zerbi).
7. Completion of legal and other arrangements for expanding our patient testing capabilities by adding laboratory space at RTI to the present laboratory at Duke University Medical Center.
8. Continued analysis of speech reception and evoked potential data from prior studies, and continued preparation of manuscripts for publication.

In this report we present results from initial evaluations of possible learning effects with extended use of portable CIS processors by two subjects, results from the completed studies with the first subject in the 22 electrode percutaneous series, and results from studies with four subjects (including the first two 22-electrode subjects) to evaluate effects of extending the upper limit of frequencies spanned by CIS channels from 5500 to 9500 Hz. Results from additional studies indicated above, such as those with the bilaterally implanted subject, will be presented in future reports.

II. Learning effects with extended use of CIS processors

Over the years, as we have observed immediate improvements in performance upon substituting various research processing strategies for subjects' clinical processors, a recurring question has been how much additional improvement might be realized with prolonged everyday use of the research processors. We now have available wearable processing hardware capable of supporting a significant subset of our CIS strategies, and can begin to obtain answers to that question.

This report will discuss results from studies of two subjects implanted with the Ineraid percutaneous electrode array, using external electronics components supplied by Erwin Hochmair, Ingeborg Hochmair-Desoyer, and colleagues at the University of Innsbruck. One of these subjects, SR3, used a processor fitted in our laboratory for these studies. The other, SR10, was studied in our laboratory before and after extended experience with a wearable CIS processor fitted by Michael Dorman at Arizona State University. Several other subjects originally tested with CIS strategies in our laboratory are participating in Dorman's studies of extended use. Subject SR2, implanted at the Massachusetts Eye and Ear Infirmary and extensively studied both there and in our laboratory, is participating in a MEEI extended use study with Donald Eddington, et al.

The wearable hardware includes a speech processor essentially like the one that is part of the Med-El corporation's COMBI-40 cochlear implant system in Europe. An ear hook assembly incorporates a microphone, a short cable compatible with the Ineraid percutaneous pedestal connector, and a stimulation current source essentially like that implanted in COMBI-40 users. While the hardware can support up to eight channels, all the processors discussed in this report used six channels corresponding to the six monopolar electrodes available in the Ineraid implanted array.

The performance comparisons in this report will be based on identification of 16 or 24 medial consonant sounds and identification of monosyllabic words from selected NU6 lists. All the reported scores are for tests in which tokens were presented once from audio recordings, with no feedback as to correct or incorrect responses. Each percent correct or percent information transmission score will be based on at least ten presentations of each consonant token. The consonant identification tests were administered in randomized sets, each of which was treated as a measurement, allowing computation of a standard deviation of the mean for each percent correct score. No NU6 list and randomization was administered twice during the same patient visit, in an effort to avoid contamination of results through increasing familiarity with the test materials. Both complete word and phoneme scores are given for the NU6 tests. Consonant identification results for male and female talkers are reported separately; the NU6 results, each for identification of 50 isolated words, are for male talker. Tables are included summarizing all scores discussed: Table I for subject SR3 and Table II for subject SR10.

Subject SR3's hearing loss was generally progressive from its first diagnosis at age 20, becoming quite rapid by age 46. She was implanted with the Ineraid device at age 51, three years after surgery in the same ear to install a shunt in treatment of Mondini syndrome. She is now 58. There is no family history of hearing impairment.

Table I. Summary of Speech Test Results for Subject SR3

		percent									
		correct				overall IT				NU6	
Mo/Da/Yr	Proc	16cm	16cf	24cm	24cf	16cm	16cf	24cm	24cf	Word	Phon
3/24/90	CA	78±2	32±4			80	48			34	58
	13B	84±3	60±4			86	72			58	77
5/11/94	42	91±2	51±3	77±2		91	63	85		40	71
	I1	92±2	64±3	77±2		91	74	82		28	61
	41	95±2	67±2	80±3		95	74	86			
	I2	96±2	54±2			95	66			38	58
4/ 4/95	42c			76±3	53±2			85	72	36	59
4	I5			80±2	41±4			85	67	56	73
13	I5			79±1	57±2			85	71	56	78
4/13/95	I5			81±2	66±2			86	78		
27	I7			80±2	65±1			86	81		
5/ 9	I7			79±2	61±3			86	79		
24	I7			80±2	63±2			87	79		
6/ 7	I7			84±1	67±2			91	79		
23	I7			82±2	65±2			89	81		
7/ 5	I7			82±2	67±3			89	83		
23	I7			84±2	70±2			89	83		
7/31/95	I7			85±1	71±2			91	83	66	80
	I5			81±1	69±2			88	83	64	84
8/ 3	42d			84±2	71±2			88	86	68	83
8/ 7/95	75			94±1	74±2			95	85		
10/31/95	I8			90±2	70±2			94	81	70	85

Differences in Processor Parameters

Processor	Rate	Duration	Smoothing Filter	
13B	2688 pps	31 μs/phase	400 Hz,	2nd order
41	2084	40	400	2
I1	2048	40	400	2
42,42c,42d	1040	80	400	2
I2,I5,I7,I8	1024	80	400	2
75	multi	33	200	2

[all are 6 channel processors, with staggered stimulation order]

SR3 was first seen in our laboratory in March of 1990. During that initial one-week visit, the best CIS processor identified for her was number 13B, which produced substantial immediate improvements in both her consonant and NU6 scores vis á vis performance with her clinical compressed analog (CA) processor. The improvements were especially large for the female talker's consonants.

In the course of a return visit to our laboratory in May, 1994, SR3 was tested with two CIS processing strategies capable of being implemented on the Innsbruck wearable hardware. In Table I, processors I1 and I2 are those strategies running on Innsbruck hardware, while processors 41 and 42 were realized on our more general bench hardware using quite similar parameters. The principal differences between the two designs were stimulus pulse rate and duration, which were approximately 2000 pps and 40 μs/phase for processors 41 and I1 and 1000 pps and 80 μs/phase for processors 42 and I2. Processors 41 and I2 supported the best performance for male voice consonants, while processors 41 and I1 were best for the female consonant tests. Between the two processors running on the Innsbruck platform, I2 supported a substantially higher NU6 word score. SR3's scores on the 16 consonant tests with male talker were so high with these processors that we began use of 24 consonant tests with her. On subsequent visits only the 24 consonant tests were administered.

SR3 received a wearable processor using Innsbruck components in our laboratory in April, 1995, as the first subject in an extended use protocol approved by the DUMC and RTI IRBs for a maximum of four selected patients. The processor, labeled I5 in Table I, was essentially like the earlier tested I2 and 42, but with newly determined stimulus threshold and most comfortable loudness (MCL) amplitudes. At first fitting on April 4, the portable processor compared favorably with a similar processor 42C running on our bench hardware, except for female voice consonants, where performance with I5 was lower. Retesting of I5 after the first nine days of everyday use (during which the subject continued to spend several hours each weekday in our laboratory, mostly not using the portable device) showed significant improvement in female consonant identification.

Based on our extended experience with subject SR3, her background as a registered nurse, the fact that she lived a great distance from our laboratory, and our uncertainty as to the optimal interval before more laboratory tests to assess learning effects with chronic use, we asked the subject to self-administer 24 consonant tests at approximate intervals of two weeks. Our expectation of the utility of these tests was merely that they might aid us in scheduling a return visit for more formal testing. Eight audio tape recordings were prepared, using the same materials and procedures as in our laboratory tests. Each recording contained two repetitions of the full set of 24 consonants in fixed order [for equipment setup and practice listening] followed by ten randomizations of the 24 consonants [for the identification tests]. This entire sequence was repeated on each tape, first for male talker and then for female. The subject completed an answer sheet [Fig. 1] and returned it to our laboratory by mail for data entry and the normal analyses. Given the limited purpose of these takehome tests, sound quality was considered less important than test to test reproducibility. Accordingly, an inexpensive tape player with no "tone" control was supplied to the subject for these tests, along with a cable providing an appropriate input signal for the wearable processor's external input. The subject was instructed to set her wearable processor's controls as she would for live voice under ideal conditions, and then adjust the tape player volume control to obtain a MCL for the tests.

RTI Takehome Consonants Test

1-M	7-SH	13-G	19-Y
2-N	8-vTH	14-K	20-NG
3-F	9-P	15-J	21-H
4-V	10-B	16-L	22-ZH
5-S	11-T	17-R	23-uvTH
6-Z	12-D	18-W	24-CH

Subject's Name ____________________

Test Number __________

Date __________

Put a number in each box, indicating which consonant you heard.
Complete each column before moving to the right.

Male Voice | Male Voice | Female Voice | Female Voice

If you think you have lost your place in the test, place an asterisk near where you think it happened.
The scoring computer will realign your answers if necessary.

Fig. 1.

The results of the eight "takehome" test sessions, spanning the period of April 13 through July 23, 1995, are included in Table I. Detailed information transmission data for each of six features, as well as overall IT and percent correct consonant identification scores, are also plotted in Figure 2. These scores turned out not only to be as sensitive and reliable a guide as we had hoped, but also to be surprisingly consistent on an absolute scale with the results of prior and subsequent laboratory tests. The overall picture was one of steady improvement over the 101 days, perhaps with a period of more rapid improvement near the middle of that span. The change of processor label from I5 to I7 between the first two takehome tests reflects an increase in the maximum stimulus amplitudes allowed by the processor, programmed in at the subject's request just before her return home.

Guided by the takehome test results, we invited SR3 back to the laboratory beginning July 31, 1995, when followup tests were administered with both processor versions I7 and I5 and with processor 42D, a bench processor equivalent of I7. Figure 3 summarizes the 24 consonant and NU6 results for the wearable processor from April 13 through July 31. Also shown there are results from another monosyllabic word test using CNC lists. The subject's additional improvement in performance with chronic use of a CIS processor over this period is clearly indicated in these results.

The unexpected high quality of the data from the takehome tests suggests that such tests might be used to explore in more detail the variations in the transmission of individual feature information with increasing experience. The possibility that patterns in the semiweekly data shown in Figure 2 may reflect patterns of learning, such as exploration of alternative identification strategies, may lead us to request such testing on an even more frequent basis by some future subject.

Note that by the end of this chronic use period SR3 had attained NU6 scores with her wearable processors exceeding those obtained with the best CIS processor identified during her first visit in 1990 (processor 13B).

Later in her July-August 1995 visit, continuing tests with our bench processing hardware found another design that supported still higher consonant identification scores. This processor 75 was a first assessment of the potential benefits of providing different stimulation rates on a channel-by-channel basis. The results, also included in Table I, encourage further exploration of this approach. The individual channel rates for processor 75 (833, 2525, 500, 1263, 417, and 417 pps for channels 1 through 6 respectively) were chosen on the basis of SR3's relative performance with various single channel processors being tested as part of another study. We are presently considering a number of potentially better ways of specifying individual rates for each channel (e.g., evoked potential measurements).

SR3 returned for still another visit just at the end of the current quarter's work. Table I includes data for consonant and NU6 tests administered on October 31, 1995. Processor I8 differs from I7 only in that somewhat lower recently measured thresholds were incorporated in the processor's range of stimulation amplitudes. There is evidence of continued improvement in performance with experience with the wearable CIS processor.

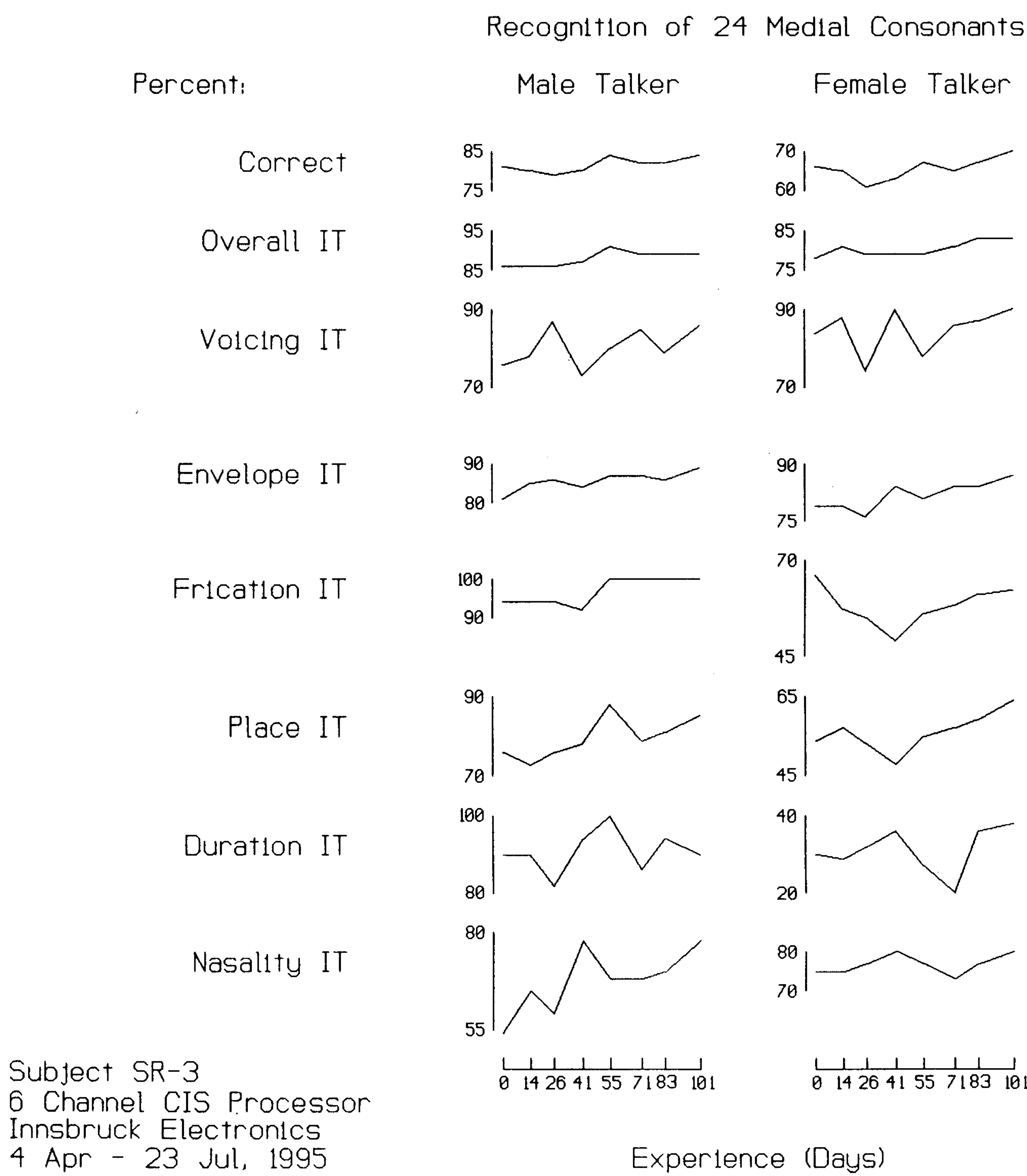
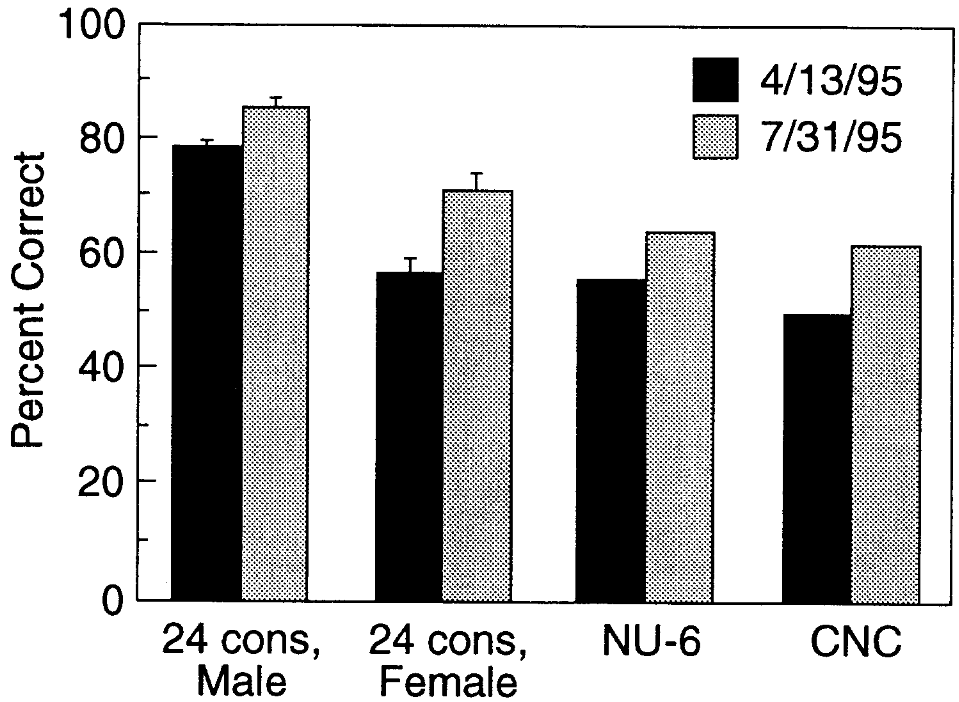

Recognition of 24 Medial Consonants
Percent:
Male Talker
Female Talker
Correct
Overall IT
Voicing IT
Envelope IT
Frication IT
Place IT
Duration IT
Nasality IT
0 14 26 41 55 71 83 101
Experience (Days)
Subject SR-3
6 Channel CIS Processor
Innsbruck Electronics
4 Apr - 23 Jul, 1995

Fig. 2.

Performance Over Time, Subject SR3

Laboratory



Home

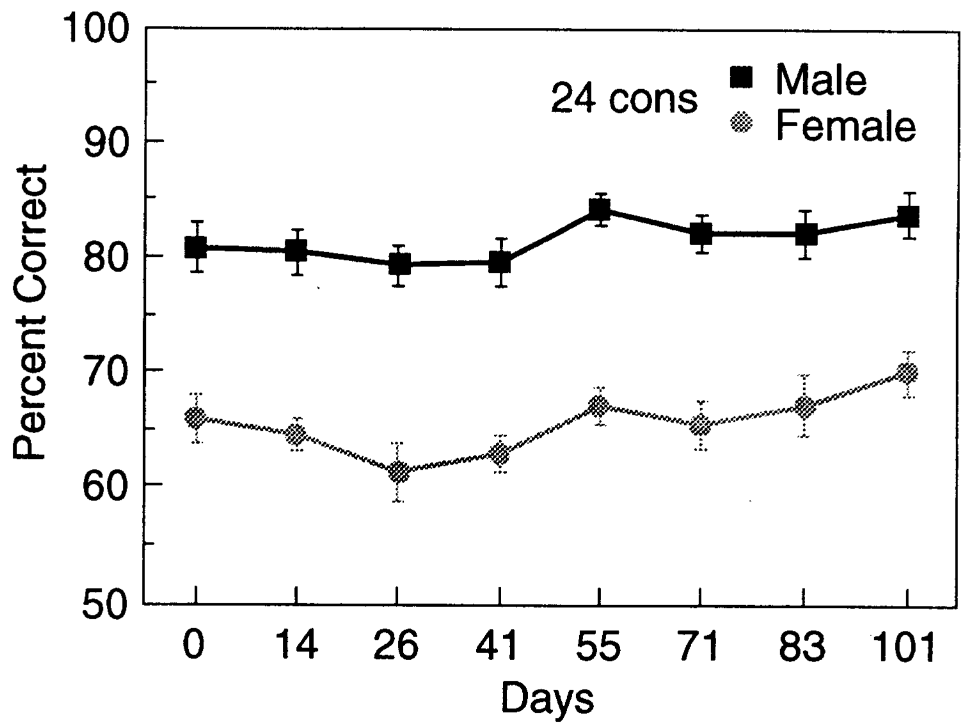


Fig. 3.

Like SR3, subject SR10's hearing loss also was first noticed at age 20, and by age 54 had progressed to the point that it was a major element in his decision to retire at that time. He received an Ineraid implant at age 68, and now is 73. His mother's impairment beginning after age 65 is the only known history of hearing loss among parents or grandparents, but a majority of his children report significant hearing losses.

Table II. Summary of Speech Test Results for Subject SR10

		percent									
		correct				overall IT				NU6	
Mo/Da	Proc	16cm	16cf	24cm	24cf	16cm	16cf	24cm	24cf	Word	Phon
11/91	CA	28±2	22±4			44	39			0	5
	14m4	66±3	47±4			72	59			14	49
5/93	53	87±3	71±4			87	78			26	55
10/93	62	89±2	84±4			89	84			34	61
11/95	I1			70±2	65±1			81	76	42	68
	14n			76±2	71±3			84	80		
	53n			68±2	72±1			77	81		
	62n			72±3	73±2			81	79	42	72

Differences in Processor Parameters

Processor	Rate	Duration	Stim. order	Smoother	
14m4,14n	500 pps	167 µs/phase	stagg	200 Hz,	4th order
53,53n	833	33	stagg	400	1
62,62n	833	33	a-b	400	1
I1	1170	70	a-b	400	2

When SR10 was first seen in our laboratory, for one week in November 1991, the best CIS processor he was tested with (processor 14m4) supported an NU6 word score of only 14%. This represented an enormous improvement in performance, however, over that with his clinical CA processor. As chronicled in previous quarterly reports (e.g., QPR 5, NIH project N01-DC-2-2401), further fitting efforts during visits in May and October, 1993, resulted in performance improvements to 26 and 34% NU6 word scores, respectively. In each case, SR10 had no experience with the use of CIS processors outside his brief visits to our laboratory. Repeated consonant tests with his clinical CA processor on each occasion revealed no change in May, and a moderate improvement primarily for female voice, in October of 1993. The best performance was obtained with CIS processor 62, combining an 833 pps rate, a 33 µs/phase pulse duration, and an apex-to-base order of stimulation in each cycle.

As this report is completed, SR10 has just returned to our laboratory after having been fitted by Michael Dorman at Arizona State University with a wearable CIS processor using the same Innsbruck hardware components we have used with subject SR3. That processor, labeled I1 in our Table II, delivers 70 μs/phase pulses at 1170 pps in an apex-to-base order. After several months of everyday experience with that processor, he now achieves a 42% word score on the NU6 monosyllabic word test. He, too, is performing at such a high level that 24 consonant tests are now required.

While we had not followed SR10's early learning with the wearable processor in detail as was the case with SR3, we were interested in assessing the effects of such learning on present performance with CIS processors that in the past provided quite different levels of benefit. Accordingly, the best processors from each of SR10's previous three visits, processors 14m4, 53, and 62 respectively, were tested contemporaneously with I1. Newly measured thresholds and MCL stimulus amplitudes were used in each case (hence the labels 14n, 53n, and 62n in Table II).

We find that the previous differences among processors 14m4, 53, and 62 seem to have been leveled by SR10's everyday experience with a CIS processor. His current NU6 score with processor 62n represents a substantial improvement over his initial performance with that design in 1993.

III. 22 Electrode Percutaneous Study: results for the first subject

With NIH support, our group is participating with Duke University Medical Center and Cochlear Corporation in a study of patients implanted with a percutaneous research version of the standard Nucleus 22 electrode array. Five patients have been selected thus far and implanted by DUMC surgeon Debara Tucci. It has been agreed that a total of seven patients will be included in the study. Each subject agrees to participate in three two-week research visits to our laboratory. Those studies have begun with four of the patients, and have been completed with the first, NP1, except for a day or two of makeup testing to occur in December before her second surgery at DUMC. At that time she will receive a standard clinical transcutaneous device.

During the percutaneous phase of the studies each patient's everyday processor is a monopolar variation of the standard clinical SPEAK strategy. That processor is fitted and maintained by DUMC audiologist Patricia Roush and evaluated by our group along with various CIS and other research designs. The subjects also participate in our intracochlear evoked potential studies.

A core protocol of processor comparisons is to be carried out with each of the seven subjects. The contents of that protocol have evolved significantly in the course of the early patient visits, as initial results were obtained with each of four subjects. In this report we will outline the final protocol and then briefly present its results for the first subject. It is far too early, of course, to form any general conclusions based on this study.

The fourteen core protocol processors to be compared are outlined in Table III. All of the processors use 33 μs/phase pulses, full wave rectification, twelfth order bandpass filters, fourth order smoothing filters, our normal preemphasis and mapping law. All stimulate chosen intracochlear electrodes monopolarly with respect to a reference electrode in *m. temporalis*. In addition, there are standard settings that are departed from only in processors designed to assess the variation of a single parameter. These standard settings include: positive phase leading in balanced biphasic pulses, a pulse rate on each channel of 833 pps, a staggered order of stimulation within each cycle (e.g. 6,3,5,2,4,1 for a six channel processor), a 200 Hz cutoff frequency for smoothing filters, and a 350 Hz to 5500 Hz overall bandpass range allocated to the channels in logarithmically equal band widths.

Five of the fourteen protocol processors use the standard settings to implement different numbers of CIS channels. These are labeled in Table III, according to the number of channels, as **21std**, **11std**, **8std**, **6std**, and **4std**. Seven processors represent single parameter variations with respect to **6std**. These include **6els** (differing only in that it utilizes a different set of six electrodes), **6ord** (using an apex-to-base rather than staggered order of stimulation), **6sth** (using a 400 Hz rather than 200 Hz smoothing filter cutoff frequency), **6pol** (using balanced biphasic pulses that begin with the negative rather than the positive phase to the active electrode), **6rng** (with frequency bands covering the range of 350 to 9500 Hz rather than 350 to 5500 Hz), **6slo** (with a pulse rate on each channel of 250 pps rather than 833), and **6fst** (with a pulse rate of 2525 pps rather than 833). The remaining two processors are what we call "n-of-m" designs, in which a total of m frequency bands are analyzed and only the n electrodes corresponding to the n highest energy bands are stimulated on a given processing cycle. In this protocol, n will be 6 in every case, while m may vary somewhat depending on each subject's

Table III. Protocol Processor Categories and their Versions for Subject NP1

---------common to all subjects in series-------------							---specific to subject NP1---	
Categ. Name	Chans	Polarity	Rate	Stim. Order	Smooth. Cutoff	Freq. Range	Electrodes	Proc. number
21std	21*	+/-	844 pps	stag	200 Hz	5500 Hz	all but 17	84
11std	11*	+/-	833	stag	200	5500	all even, 2-22	79
8std	8*	+/-	833	stag	200	5500	1,4,7,10,13,16,19,22	81
4std	4*	+/-	833	stag	200	5500	2,10,15,21	75
6els	6	+/-	833	stag	200	5500	*1,5,9,13,18,22	10a
6std	6	+/-	833	stag	200	5500	2,6,10,14,19,21	71
6ord	6	+/-	833	*a-b	200	5500	2,6,10,14,19,21	72
6sth	6	+/-	833	stag	400*	5500	2,6,10,14,19,21	27a
6pol	6	-/+*	833	stag	200	5500	2,6,10,14,19,21	73
6rng	6	+/-	833	stag	200	*9500	2,6,10,14,19,21	74
6fst	6	+/-	2525*	stag	200	5500	2,6,10,14,19,21	76
6slo	6	+/-	250*	stag	200	5500	2,6,10,14,19,21	80
nmslo	6/18*	+/-	250	a-b	200	5500	all but 15,17,21,22	78
nmfst	6/18*	+/-	833*	a-b	200	5500	all but 15,17,21,22	77

Key to Names:
21std, 11std, 8std, 4std, 6std: 21, 11, 8, 6, and 4 channel, standard parameters
6els: 6 channel, alternate electrode choice
6ord: 6 channel, apex-to-base stimulation order
6sth: 6 channel, 400 Hz smoothing cutoff
6pol: 6 channel, reversed polarity
6rng: 6 channel, extended freq range
6fst: 6 channel, fast rate (2525 pps)
6slo: 6 channel, slow rate (250 pps)
nmslo: n-of-m (6-of-18) channel, slow rate
nmfst: n-of-m (6-0f-18) channel, fast rate

number of appropriate electrodes (i.e., the number of intracochlear electrodes that can be stimulated without eliciting non-auditory percepts). For each subject the two processors will be identical except that **nmfst** will have a pulse rate of 833 pps on each stimulated electrode while **nmslo** will have a rate of only 250 pps.

This set of protocol processors has been chosen to support a wide array of comparisons of interest. The effects of varying the number of CIS channels are explored through comparisons among **21std**, **11std**, **8std**, **6std**, and **4std**. The sensitivity of performance to precise choices among available electrodes may be probed by comparing **6std** and **6els**. The effects of various single parameter variations are studied in comparisons of performance between **6std** and, in turn, **6ord**, **6sth**, **6pol**, **6rng**, **6fst**, and **6slo**. The **nmslo** processor is designed to be equivalent in some respects to the clinical SPEAK processor, which also selects a subset of the analyzed bands for stimulation on each processing cycle and stimulates the corresponding electrodes at a variable rate that averages approximately 250 pps. Comparisons are available with a standard six channel CIS processor at the same rate (**6slo**) and an n-of-m processor running at a rate substantially higher than possible for the present SPEAK strategy (**nmfst**). The latter processor also has available for comparison a standard CIS processor running at the same rate (**6fst**). Depending on performance test results with individual subjects, various features of the protocol designs can be combined in additional processors for evaluation. The performance of the monopolar clinical SPEAK processor is tested during each of the three visits to our laboratory, to provide data on learning effects. A bipolar SPEAK processor is fitted early in the last of the three research visits and its performance tested late in that visit after several days of use outside the laboratory.

Table IV summarizes contemporaneous 24 consonant identification data from NP1, the first of seven subjects, for the fourteen protocol processors and the monopolar version of the clinical SPEAK processor she had used daily for approximately one and a half years. [Not all of the subjects have high enough levels of performance to justify use of the 24 consonant tests. 16 consonant tests will be used with some of the other subjects as appropriate.] Results for female and male talker tests are listed separately, in descending order of overall information transmission in each case. Results for two of the processors, **nmfst** and **nmslo**, are marked with asterisks and were obtained for processor implementations now known to be flawed. Corrected versions of those two processors will be tested when the subject returns briefly in December. Percent correct scores also are shown in Table IV. Overall information transmission is generally a more meaningful indicator of processor performance. While overall IT is not a linear function of percent correct, and certainly not every step in this ranking represents a significant difference, one to two percent differences in IT do often correspond to significant differences in percent correct scores.

As one example of the many interesting comparisons embedded in these data, consider the effect of number of channels:

Performance as a Function of Number of Channels

Category Name	Percent Information Transmission Male Talker	Female Talker
21std	83	82
11std	83	82
8std	79	80
6std	77	75
4std	80	73

For this subject and these choices of electrode subsets, the performance of 11 and 21 channel processors are equivalent, both being superior to 8 or fewer channels. While we also have seen advantages of 8 or 11 channel processors over 6 channels for some of the other subjects in this series, we have yet to see any advantage of 21 channels for a CIS processor.

Over the three two-week visits made to our laboratory by each subject, ten to twelve processors

Table IV. Summary of results for protocol processors: Subject NP1

Identification of Medial Consonants: Female Talker

Category Name		% Correct	% Overall IT
6rng		78±2	84
11std		74±2	82
21std		73±2	82
6els		74±2	81
8std		71±3	80
nmfst	*	70±2	79
6ord		68±2	78
6pol		68±3	77
6std		60±3	75
6fst		64±3	74
6sth		67±3	73
4std		63±2	73
SPEAK		61±2	73
6slo		52±2	73
nmslo	*	50±3	69

Identification of Medial Consonants: Male Talker

Category Name		% Correct	% Overall IT
nmfst	*	70±2	84
6rng		68±2	84
21std		67±3	83
11std		65±1	83
4std		64±3	80
6ord		68±3	79
8std		62±2	79
6els		59±3	79
6pol		64±2	78
6std		61±2	77
6fst		61±2	76
SPEAK		60±2	75
6sth		62±2	74
6slo		52±3	71
nmslo	*	45±4	64

(including CIS, n-of-m, and SPEAK implementations) are evaluated with a battery of additional tests. These include identification of eight vowel sounds uttered by male and female talkers (nine presentations of each token in each condition), identification of approximately 200 words in CUNY sentences presented both in quiet and in multitalker babble with a +10 dB signal to noise ratio, identification of fifty monosyllabic words from the CNC lists, and identification of fifty monosyllabic words from selected NU6 lists. Those results for subject NP1 will be presented and discussed in a later report, along with the results for other subjects.

IV. Upward extension of the CIS processed frequency spectrum

One of the parametric studies included in the 22 electrode percutaneous protocol, the potential benefits of extending the overall frequency range represented by CIS processors, also is being investigated with some of our subjects using the Ineraid 6 electrode array. In this report we present results of within-subject performance comparisons involving two subjects from each group: 22 electrode subjects NP1 and NP2 and 6 electrode subjects SR2 and SR3.

The standard frequency range spanned by the channel bandpass filters in our CIS processors has been 350 to 5500 Hz. With these four subjects we have compared the performance of six channel processors using that range with otherwise identical processors spanning the extended range of 350 to 9500 Hz. The performance measure was identification of 24 medial consonant sounds, presented in /a/C/a/ context, by both male and female talkers. The results can be summarized as follows:

24 Consonant Identification, Percent Correct

	Male Talker		Female Talker	
Subject	5500	9500	5500	9500
NP1	61±2	68±2	60±3	78±2
NP2	90±2	90±2	65±2	72±2
SR2			98±1	98±1
SR3	76±3	83±3	53±2	56±2

In each case, extension of the frequency range either improved performance or left it unchanged. This was true both for male and female voices, and over a considerable range of performance with the original frequency range.

With one of the same 6 electrode subjects we performed the same comparison with two 11 channel VCIS processors (6 single electrode channels and 5 channels involving simultaneous in-phase stimulation of pairs of adjacent electrodes, see QPR 6, NIH project N01-DC-2-2401). The results were:

24 Consonant Identification, Percent Correct

	Male Talker		Female Talker	
Subject	5500	9500	5500	9500
SR3	91±2	82±2	77±2	84±2

In this case, while there again was an improvement in identifying female voice consonants, performance with male consonants became worse with processing of the increased frequency range. The net result for this subject was a processor better balanced between its performance with male and female voices.

In general, upward extension of the frequency range does not seem to degrade the overall performance of any of these processors, and in many cases the manipulation produces substantial improvements, especially for the female voice. We will be continuing this study with other Ineraid users as well as the other subjects in the 22 electrode percutaneous series.

V. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. Presentation of project results in invited lectures at the *Thirtieth Anniversary Meeting of the North Carolina Chapter of the Acoustical Society of America*, to be held in Blowing Rock, NC, November 2-3, 1995 (Lawson) and at the *International Course on Hearing Aids, Vibrotactile Devices and Cochlear Implants in Profound Hearing Loss in Children*, to be held in Bolzano, Italy, December 13-16, 1995 (Lawson).
2. Initial studies with the fifth of seven patients in the Nucleus percutaneous series (NP-5, January 15-26, 1996) and completion of studies with the second patient (NP2, November 6-17, 1995). Studies with NP5 will include evaluations of CIS and SPEAK processing strategies. Studies with NP2 will include repeated measures with the SPEAK strategy, detailed evaluation of CIS processors using more than six channels, and measures of intracochlear evoked potentials, as indicated for subject NP1 in the Introduction to this report (under point 3 on page 3).
3. Continued studies with Ineraid subjects SR3 and SR10, primarily to extend the range of stimuli used for recordings of intracochlear evoked potentials. In addition, speech processor studies will be conducted with both subjects and further evaluation of possible learning effects with extended use of a portable CIS processor will be conducted with SR3.
4. Construction of two new laboratories for patient testing at RTI. One laboratory will be devoted to speech reception studies and the other laboratory will be devoted to evoked potential studies. We expect that the laboratories will be available for the upcoming studies with subjects SR3, SR10 and NP5. Studies with subject NP2 will be conducted in the laboratory at Duke University Medical Center, as before.
5. Initial work to develop new speech test materials. We plan to schedule simultaneous visits by our two consultants with special expertise in this area, Bill Rabinowitz and Sig Soli, to review our proposed design for new test materials. Their comments and suggestions will be used to refine or alter the design, as appropriate. Recording of the test tokens will begin once the design is in its final form. We hope to complete the development of new test materials either in Quarter 2 (the next quarter) or Quarter 3 of the project, so that they will be available for use in the remainder of the project.
6. Continued analysis of speech reception and evoked potential data from prior studies, and continued preparation of manuscripts for publication.

VI. Acknowledgments

We thank subjects SR2, SR3, NU4 and NP1 for their participation in studies conducted this quarter.

VII. Announcements

We are pleased to announce that Chris van den Honert, Ph.D., will become a member of the RTI team for this project on November 1, 1995. Dr. van den Honert is an internationally recognized authority on cochlear prostheses. His prior work has included recording of single unit responses from the electrically stimulated auditory nerve in cats, recording of brainstem responses to electrical stimuli in implant patients, modeling of neural responses to intracochlear electrical stimulation, and design of the speech processor for the experimental multichannel prosthesis developed at the 3M Corporation. He served as the elected General Chair for the *1993 Conference on Implantable Auditory Prostheses*. We look forward to having him as a member of our team.

We also are pleased to announce that Charles Finley, Ph.D., was elected by his peers to become the Co-Chair for the *1997 Conference on Implantable Auditory Prostheses*. He will be working closely with the Chair, Margaret Skinner, Ph.D., in the design of the program for that meeting.

Appendix 1

Summary of Reporting Activity for the Period of

August 1 through October 31, 1995

NIH Project N01-DC-5-2103

Reporting activity for the last quarter included the following presentations:

Wilson BS: Speech processors for auditory prostheses. Invited lecture, *26th Annual Neural Prosthesis Workshop*, Bethesda, MD, October 18-20, 1995.

Finley CC: Spatial recruitment of neurons with monopolar and bipolar electrical fields. Invited lecture, *1995 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 20-24, 1995.

Wilson BS: Temporal representations with cochlear implants. Invited lecture, *1995 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 20-24, 1995.

Wilson BS (Chair): Focus group on speech processing. *1995 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 20-24, 1995.