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Speech Processors for Auditory Prostheses

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CONTENTS

I. Introduction

The purpose of this project is to design and evaluate speech processors for auditory prostheses. Ideally, the processors will extract (or preserve) from speech those parameters that are essential for intelligibility and then appropriately encode these parameters for electrical stimulation of the auditory nerve. Work in the present quarter included the following:

1. Evaluation of alternative processing strategies in studies with two patients implanted with an initial version of the multichannel cochlear prosthesis developed by the 3M company (these studies were conducted in St. Paul in collaboration with Dr. S.D. Soli of 3M);

2. Further evaluation of alternative processing strategies in follow-up studies with two patients implanted with the four-channel UCSF/Storz cochlear prosthesis (patients HE and MC2);

3. Development of hardware interfaces and software for use of the new laser videodisc materials developed by the cochlear implant team at the University of Iowa (Tyler et al., 1987);

4. Further development of software for feature analysis of results from tests of vowel and consonant confusions;

5. Conversion of the output stage of our wearable speech processor (Finley et al., 1987) from one in which voltage drivers are used to one in which current drivers are used;

6. Presentation of project results at the Mayo Clinic Symposium on Continuing Education in Audiology, Feb. 19-20, 1988 (the lectures from this symposium were televised to more than 50 participating clinics and universities via satellite transmission);

7. Preparation of a manuscript, "Present Status and Future Enhancements of the UCSF Cochlear Prosthesis," to be published in P. Banfai (Ed.), Cochlear Implants 1987;

8. Continued collaboration with the UCSF team in the development of the speech processor and transcutaneous transmission system for a next-generation auditory prosthesis.

In this report we will present a review of recent results from the clinical trials of the UCSF/Storz cochlear prosthesis. This review is an expansion of the one presented in the paper of item 7 above, "Present Status and Future Enhancements of the UCSF Cochlear Prosthesis." A complete review and analysis of the results from the clinical trials is necessary for several reasons. First, these results help to define performance levels and principles of design for the "compressed analog" processing strategy used in the UCSF/Storz prosthesis. The major findings include (a) evidence of strong learning effects with this prosthesis, especially for tests of open-set recognition; (b) a high degree of variability in scores across patients, which supports the idea that patient variables play a large role in determining the outcome with cochlear implants; and (c) no significant differences in the means of test scores for groups of patients with 2, 3 and 4 channels of intracochlear stimulation. Among these findings, the last is perhaps the most important in terms of processor design. A full discussion of the implications of this finding is included in the review.

Another reason for our presentation of results from the clinical trials in this report is that six of the patients who participated in the clinical trials also participated in the studies of the present project to evaluate alternative processing strategies (see QPRs 6, 8 and 9, this project, and Wilson et al., 1988b; 1988c). Data from the clinical trials thus provide an important perspective for the interpretation of results from our studies with the six patients.

The activities indicated above in items 1-5 and 8 will be described in future reports.

II. Review of Recent Results from the Clinical Trials of the UCSF/Storz Cochlear Prosthesis

Clinical trials of the UCSF cochlear prosthesis were initiated in February, 1985, under the sponsorship of Storz Instrument Company. This prosthesis was developed by UCSF with support from the National Institutes of Health. Eighteen patients were implanted with the UCSF/Storz device at four hospitals in the United States. Among these patients, two were fitted initially with percutaneous cables for direct electrical access to the implanted electrodes. The remaining sixteen patients were fitted with a four-channel coil system for transcutaneous transmission of stimulus information. All sixteen patients in the second category have received their speech processors and at least an initial evaluation of performance with the prosthesis. Results of these evaluation studies have been presented in detail elsewhere (Schindler and Kessler, 1987; Schindler _et al._, 1986 and 1987). In this report we will describe the device and provide an overview of results from the clinical trials to date.

Device Description

A unique element of the UCSF cochlear prosthesis is its electrode array. This array has eight pairs of closely-spaced bipolar contacts that have an "offset radial" orientation with respect to surviving dendrites of the auditory nerve (Loeb _et al._, 1983). The pairs are spaced 2 mm apart and the electrode array usually is inserted to a depth of 24-26 mm in the scala tympani. In cases of full insertion the positions of the pairs span locations that in the normal ear correspond to a range of place frequencies from about 800 Hz to about 6000 Hz. Close apposition of the electrodes to the medial wall of the scala tympani is achieved with a mechanical memory for the curvature of the medial wall imparted to the electrode array during construction. The offset radial orientation of the electrodes, along with this close apposition, can provide a high degree of spatial selectivity for activation of neurons in ears with good nerve survival (Merzenich and White, 1977; van den Honert and Stypulkowski, 1987). This sector-by-sector control of nerve activity is designed to allow the spectral content of an acoustic input signal to be represented by the place(s) of intracochlear stimulation. That is, high frequency inputs can be coded by selective activation of neurons near the basal end of the cochlea and low frequency inputs can be coded by such activation at more apical locations.

In the clinical UCSF/Storz device alternate pairs of electrodes are stimulated simultaneously with the "compressed analog" (CA) outputs of a four-channel speech processor. The basic functions of this processor are to compress the wide dynamic range of input speech signals onto the narrow dynamic range available for electrical stimulation of the cochlea, and then to filter the compressed signal into individual frequency bands for presentation to each pair of stimulated electrodes. Typical waveforms of the CA processor are shown in Fig. 1. The top trace in each panel is the input signal, which in this case is the word "BOUGHT." The other waveforms in each panel are the filtered output signals for 4 channels of intracochlear stimulation. The bottom left panel shows an expanded display of waveforms during the initial part of the vowel in BOUGHT, and the bottom right panel shows an expanded display of waveforms during the final "T." The lower panels in Fig. 1 thus exemplify differences in waveforms for voiced and unvoiced intervals of speech.

In the voiced interval the relatively large outputs of channels 1 and 2 reflect the low-frequency formant content of the vowel, and in the unvoiced interval the relatively large outputs of channels 3 and 4 reflect the high-frequency noise content of the "T." In addition, the clear periodicity in the waveforms of channels 1 and 2 reflects the fundamental frequency of the vowel during the voiced interval, and the lack of periodicity in the output of any channel reflects the noise-like quality of the "T" during the unvoiced interval. As will be described below, this representation of speech features can support high levels of recognition and understanding for a large percentage of patients implanted with the UCSF/Storz prosthesis.

The remaining component of the clinical device is the transcutaneous transmission system (TTS) for conveying the outputs of the speech processor to bipolar pairs of electrodes in the implanted array (Merzenich, 1985; Merzenich et al., 1984). The TTS has four independent pairs of transmitting and receiving coils. The receiving coils are implanted under a postauricular skin flap at surgery and the outputs of these coils are fed to an internal connector assembly. Within the connector assembly are four receiver modules on a ceramic substrate for demodulation of the radio-frequency signals from the receiving coils. The outputs of the receiver modules are connected to alternate bipolar pairs of electrodes in the implanted array via contact pads held in a Silastic carrier. The outer case of the connector assembly consists of a circular base plate made of titanium and a covering plate also made of titanium. A central screw is tightened to a specified torque to bring these plates together and to compress the contact pads and Silastic carrier. The internal pressure thus obtained also provides a barrier against condensation of water vapor within the connector assembly after it is closed (Merzenich et al., 1984). Finally, the external transmitting coils are held in position against the skin overlying the implanted receiving coils by small magnets placed in the center of each coil. This arrangement allows for easy removal and replacement of the

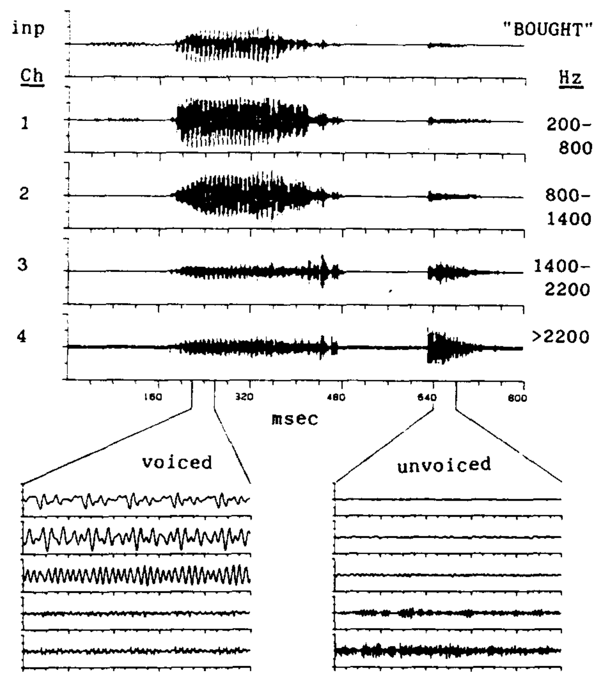

Fig. 1. Waveforms of a compressed analog (CA) processor.

transmitter coils.

Results from the Clinical Trials

In general, results from the clinical trials have been most encouraging. Thirteen of the sixteen studied patients have obtained at least some degree of open-set speech recognition using hearing alone. Most patients have demonstrated significant improvements in the scores of speech perception tests with continued use of the device over time, and all of these patients have experienced substantial increases in their rates of connected discourse tracking when the prosthesis is used in conjunction with lipreading.

The tests administered to assess patient performance in the clinical trials of the UCSF/Storz prosthesis include all tests of the Minimal Auditory Capabilities (MAC) battery (Owens et al., 1985); the Diagnostic Discrimination Test (DDT) of consonant confusions (Grether, 1970); connected discourse tracking with and without the prosthesis (De Filippo and Scott, 1978; Owens and Raggio, 1987); matrix tests of vowel and consonant confusions; and recognition of open-set material presented in a live-voice format. In this report we will restrict our attention to the most recent results (as of August, 1987) from the MAC battery. The interested reader should consult previous publications for earlier results from the MAC battery and for results from the other tests (Schindler and Kessler, 1987; Schindler et al., 1986 and 1987).

Results from the speech perception tests of the MAC battery for patients implanted with the UCSF/Storz prosthesis are presented in Table 1. The immediate impact of device use can be appreciated by comparing the means of the results obtained at the preoperative evaluations with the means of the results obtained at the initial fitting of the prosthesis. Increases in performance are found for every test. Scores for the closed-set tests of prosodic perception (involving timing of syllable boundaries, voice fundamental frequency, and word stress) and of phoneme and word discrimination rose from chance levels for the preoperative evaluations to levels significantly above chance for the initial postoperative evaluations. In addition, some patients achieved a degree of open-set recognition on the first day of device use, as indicated by the non-zero means for recognition of spondees, monosyllabic words, and keywords in the CID and SPIN sentences. This immediate access to speech information with the prosthesis supports the idea that at least some features of normal auditory coding are mimicked with the UCSF/Storz prosthesis (Merzenich, 1985; Merzenich et al., 1984).

Table 1. Results from the Minimal Auditory Capabilities (MAC) battery for patients participating in the clinical trials of the UCSF/Storz cochlear prosthesis[a]

Tests	Chance	Preoperative[b]	Postoperative			
			Initial	6-8 Weeks	6 Months	1 Year
		(N=16)	(N=16)	(N=14)	(N=14)	(N=12)
Prosodic Perception (closed set)						
Question/Statement	50	53	77	86	78	83
Accent	25	32	55	63	66	65
Noise/Voice	50	58	88	91	94	94
Spondee Same/Different	50	59	88	89	93	95
Phoneme & Word Discrimination (closed set)						
Vowels	25	30	44	51	58	62
Initial Consonants	25	30	49	55	62	68
Final Consonants	25	36	54	63	73	71
4-Choice Spondee	25	36	73	81	87	87
Open-Set Recognition						
Spondees		0	9	14	31	41
Monosyllabic Words (NU6)		0	4	8	15	20
Sentences (CID)		0	10	21	32	46
Words in Context (SPIN)		0	2	6	9	14

[a]The results are expressed as the means of the percent correct scores for the indicated numbers (N) of patients.

[b]Seven patients were unable to use a hearing aid and could not be tested. They were assigned chance scores for the closed-set tests.

A pattern of improvements in the scores of speech perception tests after the initial postoperative evaluation is also evident in Table 1. In particular, large improvements over time are found for the tests of open-set recognition while relatively small or no improvements over time are found for the tests of prosodic perception and of phoneme and word discrimination. This pattern is further displayed in Fig. 2 which shows the mean scores of Table 1 plotted along logarithmic scales to depict changes in degree of improvement over time for each test. Although clear increases are seen for all tests of phoneme and word discrimination and for the accent test of prosodic perception, these increases are much smaller than those observed for the open-set tests. Furthermore, scores for the final consonant and four-choice spondee tests plateau after the 6 month evaluation, as do those for the accent test after the 6-8 weeks evaluation. Substantial increases in the scores for all open-set tests are found throughout the measurement period. This pattern of improvement suggests that recipients of the UCSF/Storz device have access to suprasegmental (prosodic perception) and segmental (phoneme and word discrimination) information at an early stage. Experience with the prosthesis may help patients to integrate this information with their knowledge of language and with contextual information provided by speakers. Such integration may be reflected in the long-term improvements found for the scores of the open-set tests.

Additional aspects of prosthesis performance are indicated in Table 2. Specifically, Table 2 presents results from the most recent measures of monosyllabic word and CID sentence recognition for the sixteen patients fitted with the TTS. Also tabulated are (a) months of experience since initial use of the prosthesis and (b) number of available stimulation channels at the time of the measurements. The latter category reflects the fact that many of the patients did not have four functioning channels. As outlined in previous publications (Schindler et al., 1986 and 1987), the UCSF/Storz device had a failure mode that was precipitated by admission of saline or blood into the internal connector assembly during surgery. Although the surgical procedures for implantation have been modified to prevent such failures, most of the patients in Table 2 had been implanted before the problem was evident and before these changes were made. One manifestation of this mode of device failure was loss of individual channels. Among the eight patients in Table 2 with fewer than four channels, five exhibited signs consistent with the failure mode just described. The remaining three patients had fewer than four channels as a result of partial insertion of the electrode array (due to an ossified cochlea) or, in one instance, damage to the electrode array during manipulation at surgery. The usual procedure for dealing with the loss of a channel has been to combine outputs from two speech processor channels into a single channel for intracochlear stimulation. For example, the response

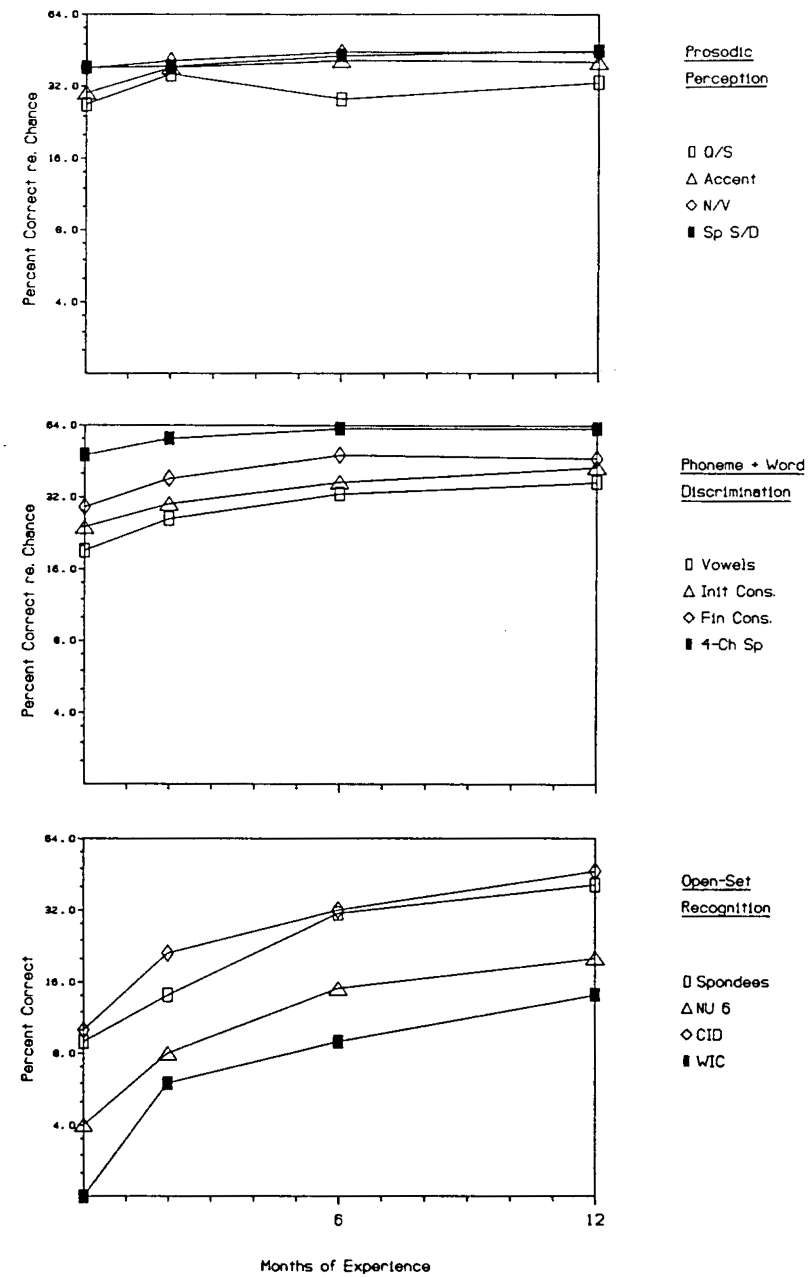

Fig. 2. Plots of the mean scores presented in Table 1 for follow-up evaluations of UCSF/Storz patients. Chance levels are subtracted from the scores of the closed-set tests to indicate actual performance with respect to chance. Abbreviations for the subtests of the Minimal Auditory Capabilities (MAC) battery are Q/S for Question/Statement; N/V for Noise/Voice; Sp S/D for Spondee Same/Different; Init Cons. for Initial Consonant; Fin Cons. for Final Consonant; 4-Ch Sp for Four-Choice Spondee; NU 6 for Northwestern University list number 6 of monosyllabic words; CID for a list of everyday sentences prepared at the Central Institute of the Deaf; and WIC for Words in Context.

Table 2. Results from two open-set tests of the MAC Battery for all sixteen studied patients in the UCSF/Storz clinical trials

Patient	NU6 monosyllabic words[a]	CID Sentences[a]	Months Since Initial Stimulation	Number of Functioning Channels
CR	0	0	2	3
RC	64	95	20	3
CB	4	11	0	3
MW	36	57	12	4
GD	2	25	6	4
MH	8	35	12	2
ET	12	15	24	4
JM	32	38	12	4
MC1	38	89	24	3
HE	8	55	12	4
NL	18	36	12	4
KS	4	4	12	2
RB	4	24	6	4
DP	0	5	12	2
SL	36	67	12	2
MC2	42	90	19	4
Mean =	19.3	40.4		
S. Dev. =	19.4	31.9		

[a]Scores are percent correct.

to a loss of channel 4 in the implanted system would be to sum the outputs of channels 3 and 4 from the speech processor for stimulation of electrode channel 3.

Returning now to the recognition scores presented in Table 2, we note a substantial variability in these scores across patients. The range for recognition of NU6 monosyllabic words is from 0 to 64 percent correct, and the range for recognition of keywords in CID sentences is from 0 to 95 percent correct. The standard deviations are comparable to the means of the results for both tests, which also indicates a high degree of variability in scores across patients. These observations, along with similar observations of high variability for most remaining tests of the MAC battery, suggest that patient variables play a large role in determining the ultimate benefit of the UCSF/Storz prosthesis. In addition to the learning effects described above, such variables might include (a) number of available stimulation channels, (b) electrode insertion depth, (c) the patterns of nerve survival in the implanted ear, (d) the integrity of the central auditory pathways, and (e) cognitive and language skills.

To evaluate the first possibility noted above, we calculated the means and standard deviations of the test scores for the groups of patients with 2, 3 and 4 channels of intracochlear stimulation. The results are presented in Table 3. No significant differences are found among the means of scores for either the NU6 word test or the CID sentence test for the different groups of patients. The hypothesis that the number of available stimulation channels affects performance is therefore not supported by the data from the present population of 16 patients using the UCSF/Storz prosthesis.

Another feature of interest in Table 2 is a high correlation in the scores for the NU6 word and CID sentence tests ($r = .89$; $t = 7.2$; $dF = 14$; $p < 0.001$). This correlation suggests that one of these tests could be safely eliminated in future studies to evaluate open-set recognition of speech.

Finally, we note that the overall levels of performance indicated in Table 2 are excellent. The mean of the scores for the NU6 word test is 19 percent and the mean of the scores for the CID sentence test is 40 percent. In addition, some patients have exceptionally high scores for these tests. These patients include RC (64% on NU6 and 95% on CID), MC1 (38% on NU6 and 89% on CID), and MC2 (42% on NU6 and 90% on CID). The benefits provided by the UCSF/Storz prosthesis are obviously large for such patients.

Table 3. Comparisons of performance in tests of NU6 word and CID sentence recognition for groups of patients with 2, 3 and 4 channels of intracochlear stimulation[a]

		Number of Functioning Channels		
		2	3	4
Number of Patients		4	4	8
NU6	Mean Score	12.0	26.5	19.3
	(Std. Dev.)	(16.3)	(30.3)	(15.5)
CID	Mean Score	27.8	48.8	42.5
	(Std. Dev.)	(29.9)	(50.2)	(24.2)

[a]The test results used for calculating the means and standard deviations (Std. Dev.) for each patient group were obtained from Table 2.

Discussion

Results from the clinical trials establish the efficacy of the UCSF/Storz cochlear prosthesis. Among the sixteen studied patients, thirteen can recognize speech tokens presented in an open-set format as evidenced by scores of 11 percent or better for the CID sentence test. Moreover, all of the patients have experienced substantial increases in their rates of connected discourse tracking when the prosthesis is used in conjunction with lipreading (Schindler and Kessler, 1987).

In addition to a general demonstration of efficacy, the results show significant improvements in the scores of speech perception tests over time. The largest improvements are found for the tests of open-set recognition, and these improvements continue throughout the one-year period of measurements.

Another feature that characterizes results from the clinical trials is the high degree of variability in scores across patients. Such variability is also found for other implant devices (Brimacombe et al., 1988; Gantz, 1987). Apparently, patient variables have a strong influence on the results obtained with cochlear prostheses.

One such variable that might affect the outcome for multichannel devices is the number of available channels for intracochlear stimulation. Depending on the coding strategy used and depending on the isolation among stimulation channels, one might generally expect improved performance as the number of stimulation channels is increased. However, data from the present studies do not support this expectation for the UCSF/Storz prosthesis. In particular, no significant differences are found among the means of test results for the groups of patients with 2, 3 and 4 channels of intracochlear stimulation.

A possible explanation for the lack of correlation between number of channels and performance relates to the type of processing strategy used in the present UCSF/Storz prosthesis. As described above, this strategy delivers "compressed analog" waveforms to the electrode array. It may be that certain patients can make especially good use of such waveforms even in the absence of channel-specific cues. Indeed, the impressive results obtained with SL (2 channels), RC (3 channels), MC1 (3 channels), certain patients in the Vienna series (1 channel; see Hochmair-Desoyer and Burian, 1985; Hochmair-Desoyer et al., 1985) and certain patients in the Symbion series (4 monopolar channels with relatively poor isolation; see Eddington, 1983; Eddington and Orth, 1985; Gantz, 1987) support the hypothesis that the major bearer of information in CA processors is the waveform itself.

Although results from studies conducted at UCSF demonstrate that additional information can be provided with four channels of stimulation using the UCSF electrode array (Ochs et al., 1985; Schindler et al., 1987; White et al., 1985), this additional information obviously is not required for excellent performance in some patients. Most likely, the best results are obtained for patients who have the greatest access to information in the CA waveform(s). These patients might include those with exceptional abilities to discriminate (a) frequencies up through the range of the first formant of speech (Eddington, 1983; Hochmair-Desoyer and Burian, 1985; White, 1983); (b) rapid temporal variations in the envelopes of speech and speechlike stimuli (Hochmair-Desoyer et al., 1985; Soli et al., 1986; Van Tasell et al., 1987); and (c) subtle waveshape changes produced by the addition of frequency components beyond the first formant (Dobie and Dillier, 1985; Hochmair and Hochmair-Desoyer, 1985).

Future Directions

In this report we have outlined the highly positive results from the clinical trials of the UCSF/Storz cochlear prosthesis, and in other reports (Wilson et al., 1988a-c) we have presented results from experimental studies that indicate ways in which the performance of the prosthesis might be improved. The possibilities for improvement include (a) implementation of a wearable processor that will support either the compressed analog (CA) or interleaved pulses (IP) strategies on the same hardware substrate; (b) increasing the number of available stimulation channels, particularly for the IP strategy; and (c) selection of the best processing strategy for each implanted patient. We are now cooperating with UCSF on the development of a next-generation auditory prosthesis based on these principles. The new device will be capable of supporting both the CA and IP processing strategies and also will have a TTS that provides up to eight channels of current-controlled outputs for intracochlear stimulation. A single coil transmitter/receiver system will replace the present four-coil system. We expect that the new device will be available for implantation in the fall of 1988.

Acknowledgments

We are indebted to D.K. Kessler and R.A. Schindler of UCSF for their help in collecting and organizing the data for this report.

III. Plans for the Next Quarter

Our plans for the next quarter include the initial conversion of hardware interfaces and software for use with an 80386-based computer at our cochlear implant laboratory at Duke. This 80386 computer will replace our obsolete and failure-prone Eclipse computer. Use of the 80386 computer also will speed up many of the computational tasks associated with speech processing and with the conduct and analysis of speech perception tests.

An integral element of the new 80386 machine will be a TMS320C25 coprocessor card. This card will be programmed for real-time execution of our "block diagram compiler" software (Wilson and Finley, 1985). Software conversion for the TMS320 system will begin in the next quarter.

In addition the these activities, we have the following plans for the next quarter:

1. Present project results in an invited lecture on "Various Coding Schemes Used," at the Cochlear Implant Consensus Development Conference, National Institutes of Health, May 2-4, 1988;

2. Continue analysis of data from the patient studies mentioned in the Introduction to this report;

3. Begin preparation of two invited papers to be published in J.M. Miller and F.A. Spelman (Eds.), Models of the Electrically Stimulated Cochlea (working titles of the papers are "Comparison of Encoding Schemes" and "3D Finite Element Analysis");

4. Continue ongoing psychophysical and speech perception studies with patient MH (a Duke patient fitted with a percutaneous cable for direct electrical access to her implanted UCSF/Storz electrode array); and

5. Continue our collaboration with UCSF to develop the speech processor, transcutaneous transmission system and clinical fitting system for a next-generation cochlear prosthesis.

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Appendix 1

Summary of Reporting Activity for the Period of
December 28, 1987, through March 25, 1988
NIH Contract N01-NS-5-2396

The following publications and presentations were made in the present reporting period:

Lawson, D.T.: Processing strategies for cochlear implants. Invited faculty lecture, Mayo Symp. on Continuing Education in Audiology, Jacksonville, FL, Feb. 19-20, 1988.

Wilson, B.S., C.C. Finley, D.T. Lawson and R.D. Wolford: Speech processors for cochlear prostheses. Proc. IEEE, in press.

Wilson, B.S., R.A. Schindler, C.C. Finley, D.K. Kessler, D.T. Lawson and R.D. Wolford: Present status and future enhancements of the UCSF cochlear prosthesis. In P. Banfai (Ed.), Cochlear Implants 1987, Springer-Verlag, in press.