RESEARCH TRIANGLE INSTITUTE

TECHNICAL PROPOSAL

Speech Processors for Auditory Prostheses

Submitted in response to NIH RFP No. NIH-NINCDS-88-04

April 18, 1988

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CONTENTS

I. Introduction

The Research Triangle Institute (RTI) is pleased to submit this proposal in response to RFP No. NIH-NINCDS-88-04, "Speech Processors for Auditory Prostheses." In this proposal we will review results and achievements from our current project supported by the Neural Prosthesis Program (NIH project N01-NS-5-2396, same title as above), and we will outline our plan for continued work. The plan for continued work includes efforts directly related to (a) further development of a laboratory-based speech processing system, (b) evaluation of different speech processing techniques in tests with implanted human subjects, and (c) design and fabrication of wearable speech processors.

II. Background

In this section we will present reviews of the major activities and studies of our current project. These activities and studies touch on many areas related to the design and evaluation of speech processors for auditory prostheses. In particular, we will describe our work to (a) compare analog and pulsatile coding strategies for multichannel cochlear prostheses; (b) design and evaluate a two-channel, "Breeuwer/Plomp" processor; (c) characterize aspects of pitch and loudness perception with cochlear implants in directed psychophysical studies; (d) develop and apply a wearable speech processor for multichannel auditory prostheses; and (e) collaborate with investigators at the University of California at San Francisco (UCSF) in the development of the speech processor and transcutaneous transmission system for a next-generation auditory prosthesis. In addition to the descriptions of these activities, we will outline other important collaborations we have established during the course of our current project, and we will describe our experience with different types of implant patients.. A review of key studies conducted in our previous "speech processors" project for the Neural Prosthesis Program (NIH project N01-NS-3-2356) is presented in this proposal as one of the supporting documents (section X.D).

II.A. Direct Comparisons of Analog and Pulsatile Coding Strategies

The design of speech processors for cochlear prostheses is a multifaceted activity. At the most basic level such processors must extract or preserve from speech those parameters that are essential for intelligibility and then encode those parameters for electrical stimulation of the auditory nerve. Areas of knowledge necessary to the informed design of speech processors for cochlear prostheses include electrical engineering and the speech and hearing sciences. The range of options for processor design is quite large, and this latitude is reflected in the many approaches that have been taken in the design of clinically applied devices (Millar et al., 1984; Moore, 1985; Parkins, 1986; Pfingst, 1986).

A remarkable finding from evaluations of these approaches is that each of several distinctly different processing strategies can produce high levels of speech perception in some patients. Unfortunately the converse is also true, in that poor levels of performance are found for other patients using the same strategies. This heterogeneity of outcomes may result from differences among patients in (a) patterns of nerve survival in the cochlea; (b) the integrity of the central auditory pathways; or (c) cognitive ability and language acquisition. The likely influence of patient variables on outcome obviously complicates comparisons aimed at identifying the best types of electrode and speech processor designs for cochlear prostheses. Indeed, such comparisons are not meaningful when small populations of subjects are used for the evaluation of each system, or when test procedures used at the various laboratories involved in the evaluation of individual systems are different.

Recognition of the problem just described helped to initiate two major studies in which relatively large populations of patients implanted with different devices will be tested in a uniform and consistent manner. One of these studies is a cooperative effort among VA medical centers (N. Cohen, PI) and the other study is being conducted at the University of Iowa (B. Gantz, PI; see Gantz, 1987 and Gantz et al., 1987). Results from these studies should be of great value in establishing expected levels of performance for contemporary cochlear prostheses.

A complementary method for the comparison of prosthesis systems is to evaluate different processing strategies and electrode coupling configurations in tests with individual implant patients. An important advantage of such tests with individual patients is that controls are provided for patient variables. Thus, for a given patient with a fixed pattern of nerve survival and fixed levels of cognitive skill, etc., the performance levels of different speech processors can be directly compared.

In recent studies conducted in collaboration with investigators at UCSF and Duke University Medical Center (DUMC), our team has compared a wide variety of processing strategies in tests with each of eight patients implanted with the UCSF/Storz electrode array. Some of the largest differences in performance among processing strategies were found in comparisons between the compressed analog (CA) processor of the present UCSF/Storz prosthesis and a type of "interleaved pulses" (IP) processor which delivers pulses in sequence to the different channels in the implanted electrode array. To emphasize how the design of the processor can affect the outcome for individual patients, we will restrict ourselves here to brief descriptions of tests related to these two types of processor. Detailed descriptions of these tests, along with the results obtained with other processing strategies, are presented elsewhere (Wilson et al., 1985; 1986; 1987b; 1988a; 1988b; 1988c).

Processing Strategies

In the clinical UCSF/Storz device alternate pairs of electrodes are stimulated simultaneously with the compressed analog 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. II.A-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. II.A-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 has been described elsewhere (Schindler and Kessler, 1987; Schindler et al., 1986a; 1986b; 1987; Wilson et al., 1988c), this

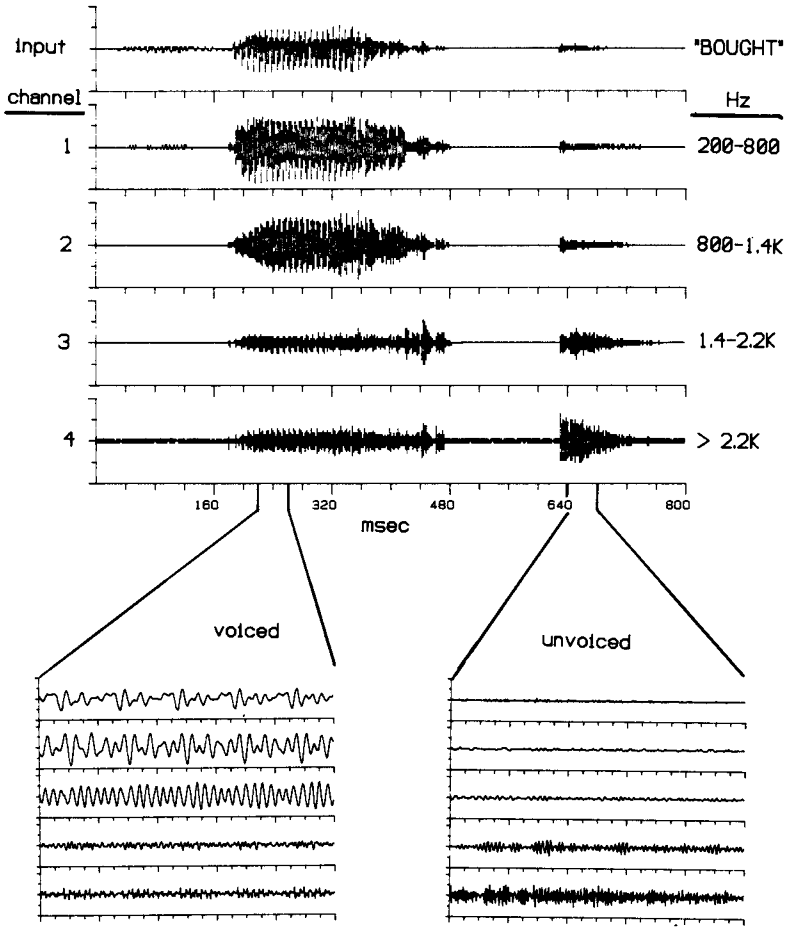


Fig. II.A-1. Waveforms of a compressed analog (CA) processor.

representation of speech features can support high levels of recognition and understanding for many (but not all) of the patients implanted with the UCSF/Storz prosthesis.

To introduce the design of the IP processor, we note that it is intended to solve a potentially serious difficulty with multichannel CA processors -- the problem of channel interactions. Simultaneous stimulation of more than one channel with continuous waveforms results in summation of the electric fields from the individual bipolar pairs of electrodes. This summation can exacerbate interactions among channels, especially for patients who require high stimulation levels. Summation of stimuli from multiple channels also depends on the phase relationships among the waveforms. Because these relationships are not controlled in a multichannel CA processor, representation of the speech spectrum may be further distorted by continuously changing patterns of channel interaction. A reduction of channel interactions might increase the salience of channel-related cues for implant patients.

The problem of channel interactions is addressed in the IP processor of Fig. II.A-2 through the use of nonsimultaneous stimuli. There is no temporal overlap between the stimulus pulses so that direct summation of electric fields produced by different electrode channels is avoided. The energy in each frequency band of the input signal is coded as the amplitude of the pulses delivered to the corresponding stimulus channel. Distinctions between voiced and unvoiced segments of speech are represented by the timing of cycles of stimulation across the electrode array. In this particular processor stimulation cycles are timed to begin in synchrony with the detected fundamental frequency for voiced speech sounds and at the maximum rate (with one stimulation cycle immediately following its predecessor) for unvoiced speech sounds. The timing of stimulation cycles for voiced and unvoiced intervals can be seen in the lower panels of Fig. II.A-2.

Comparison of Figs. II.A-1 and II.A-2 shows large differences in the stimuli presented for the CA and IP processing strategies. One might expect that the CA processing strategy would provide the greatest benefits to patients who could appreciate details in the stimulus waveforms (see discussion below) and who have low thresholds of stimulation. In contrast, the IP processing strategy might be expected to provide superior performance for less fortunate patients who cannot appreciate such details in CA stimulus waveforms and who have high thresholds of stimulation. We note that high thresholds of stimulation and high levels of measured channel interactions with simultaneous stimuli are both regarded as signs of poor nerve survival in the implanted ear (Gardi, 1985; Merzenich _et al._, 1978; Pfingst and Sutton, 1983; White _et al._, 1984). Thus, application of an IP

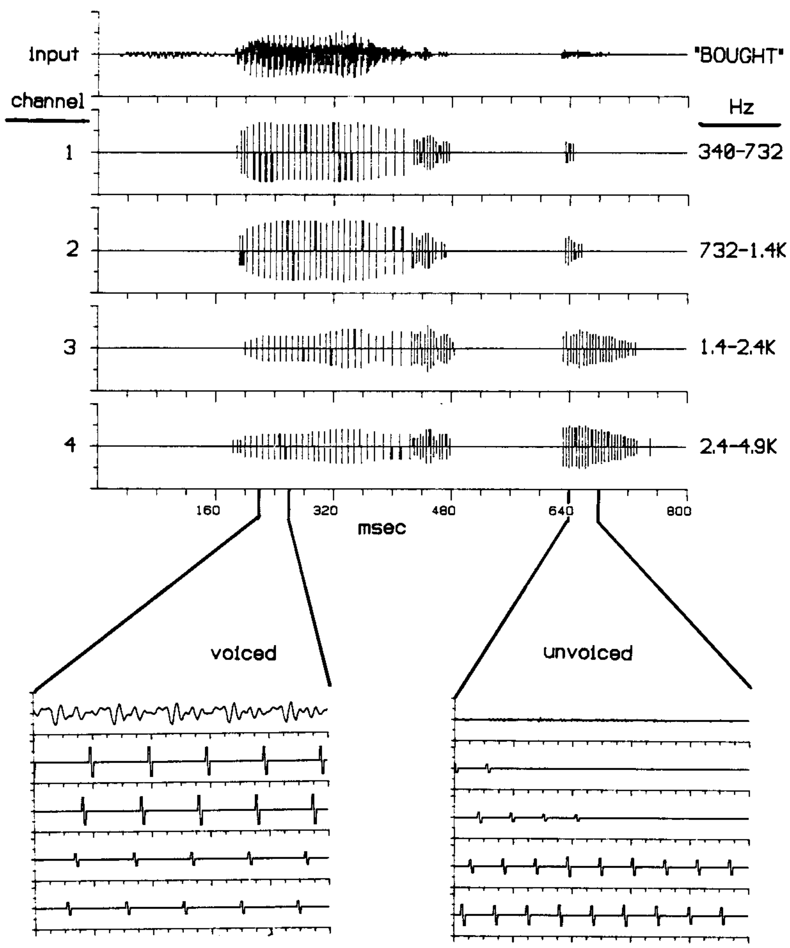


Fig. II.A-2. Waveforms of an interleaved pulses (IP) processor.

processor may confer special benefits for patients with poor nerve survival.

Methods

All eight patients participating in our studies had been implanted with the UCSF electrode array. The first two patients were fitted with percutaneous cables and the remaining six with the four-channel transcutaneous transmission system (TTS) of the UCSF/Storz prosthesis. Use of the cable allows direct access to all 16 electrode contacts in the array (usually configured as eight bipolar pairs) and direct control over the current or voltage waveforms of the stimuli. In contrast, alternating bipolar electrode pairs are assigned to the four channels of the TTS, and the current and voltage waveforms are complex functions of the nonlinear impedances of the electrodes and the limited frequency response of each TTS channel.

Because the cable allowed a much greater degree of stimulus control, many different processing strategies were evaluated in the studies with the first two patients (LP and MH). The performance of each strategy was measured with confusion matrix tests. The confusion matrix for vowels included the tokens "BOAT," "BEET," "BOUGHT," "BIT," and "BOOT," and the confusion matrix for consonants included the nonsense tokens "ATA," "ADA," "AKA," "ASA," "AZA," "ANA," "ALA," and "ATHA." The tokens in the vowel matrix were selected to measure the ability to perceive differences in the formant frequencies of the vowels, and the tokens in the consonant matrix were selected to measure the ability to distinguish the nonvisible consonants that have the greatest frequency of occurrence in spoken English (Schubert, 1985).

Among the processing strategies evaluated with these first two patients, the IP approach achieved the best results. To assess further the performance of this strategy vis à vis the standard CA strategy of the UCSF/Storz prosthesis, an extensive series of standard tests was designed for the remaining six patients (all of whom were fitted with the TTS). In addition to the vowel and consonant confusion tests just outlined, this series included: all subtests 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); and the Iowa test of medial consonant identification with lip-reading cues (Tyler et al., 1983). In this proposal we will review briefly the results from the vowel and consonant confusion tests for all patients, and from the MAC and Iowa tests for the six patients fitted with the TTS. Results for the various patients will be compared for each individual test. Because of the highly varied nature of the MAC subtests, any attempt to analyze performance across tests would necessarily involve arbitrary assumptions about the relative weights of the subtest results. Detailed reports of the evaluation studies are available elsewhere (Wilson et al., 1985; 1986; 1987b; 1988a; 1988b; 1988c).

Results for Patient LP

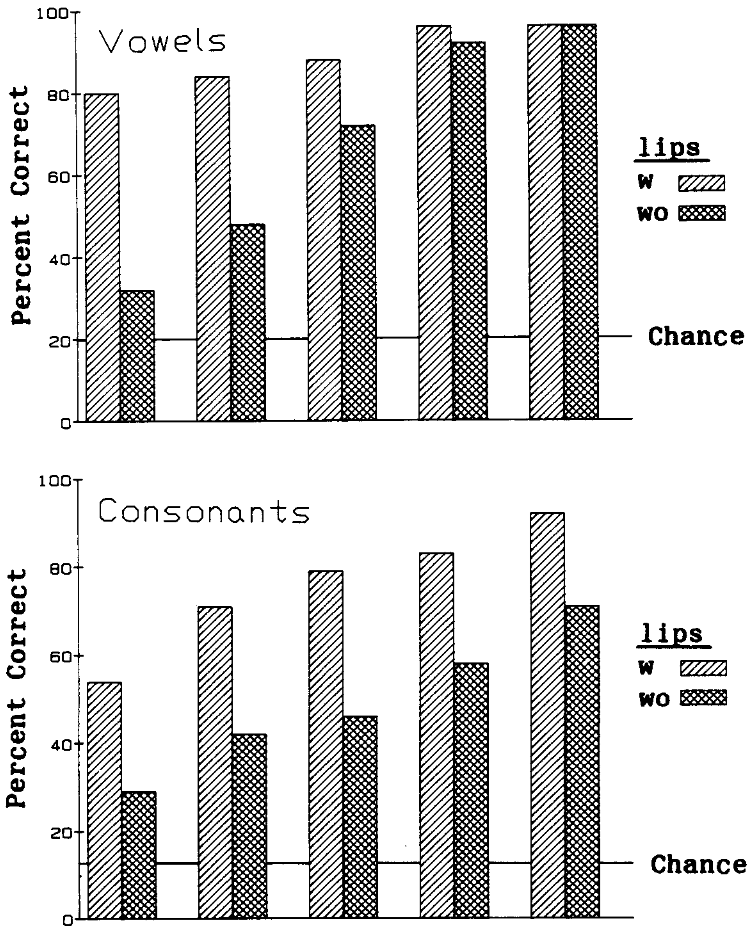
The first patient (LP) had a most discouraging picture of psychophysical performance. He had extremely severe channel interactions and high thresholds for bipolar electrical stimulation. His case was further complicated by extraordinarily narrow dynamic ranges and lability of thresholds and loudness levels both within and between testing sessions. LP's psychophysical findings of severe channel interactions, high thresholds and narrow dynamic ranges were all consistent with a picture of very poor survival of neurons in his implanted ear (Gardi, 1985; Merzenich et al., 1978; Pfingst et al., 1985; Pfingst and Sutton, 1983; White et al., 1984; Wilson et al., 1988a).

As might be expected, LP received no benefit from the CA processor used in the standard UCSF prosthesis. Indeed, he refused to describe any of the percepts produced with this processor as speech-like.

The first application of a 6-channel, IP processor immediately moved LP into the speech mode of auditory perception (Wilson et al., 1985; 1988a). Of the eleven speech tokens initially presented to LP using the IP processor, seven were spontaneously recognized as the correct words or syllables. Although his performance declined when the number of channels was reduced from 6 to 4, formal tests with vowel confusion matrices indicated that LP could perform at a level significantly above chance ($p < 0.01$) even with a reduced 4-channel version of the IP processor (Wilson et al., 1985). A medical complication required surgical removal of LP's implant, ending our study of him with these very encouraging preliminary results.

Results for Patient MH

With the second patient we were able to evaluate differences in processor performance in much greater detail. This patient also had psychophysical manifestations of poor nerve survival (Wilson et al., 1986; 1988a). The results presented in Fig. II.A-3 show her levels of performance



Proc:	CA	IP	IP	IP	IP
Chans:	4	4	4	6	6
FO, v/uv?	NA	N	Y	N	Y
Overall %	49	61	71	83	89

Fig. II.A-3. Results of vowel and consonant confusion tests for patient MH. Diagonally-hatched bars indicate results obtained with lipreading and cross-hatched bars indicate results obtained without lipreading. The table at the bottom of the figure indicates the type of processor used (abbreviations are CA for "compressed analog" and IP for "interleaved pulses"); the number of stimulation channels; whether voicing information was explicitly coded for the IP processors; and the overall percent-correct scores from the four test conditions for each processor. The horizontal line in each panel shows the level of chance performance for that test. All of the scores are significantly above chance at the $p < 0.01$ level, except those for the compressed analog processor tests without lips.

in tests of vowel and consonant recognition. The diagonally hatched bars show her performance with lipreading, and the cross-hatched bars without. The chance levels of performance are indicated by the horizontal lines in each panel. Different processors are represented by different sets of bars. The characteristics of each processor are indicated in the labels at the bottom. For example, the leftmost set of bars shows the scores for a 4-channel CA processor. The remaining sets of bars show the scores for four variations of IP processors. These variations were produced by manipulating (a) the number of stimulation channels and (b) the way in which the beginnings of stimulus sequences were timed. In one approach stimulation cycles were timed to start in synchrony with the fundamental frequency for voiced speech sounds and at randomly-spaced intervals during unvoiced speech sounds. This constituted explicit coding of fundamental frequency and voiced/unvoiced distinctions. In the other approach stimulation cycles were timed to follow each other as rapidly as possible, providing no explicit coding of voicing information. In all, the results shown in Fig. II.A-3 allow direct comparisons of (a) a 4-channel CA processor vs. a 4-channel IP processor; (b) 4- vs. 6-channel IP processors; and (c) IP processors with and without explicit coding of voicing information. The comparisons indicate that:

1. Performance is markedly improved when a 4-channel IP processor is used instead of a 4-channel CA processor;

2. Scores are <u>much</u> higher in all categories except vowel identification with lipreading (where scores are about the same) when a 6-channel IP processor is used instead of a 4-channel IP processor; and

3. Explicit coding of voicing information improves the performance of IP processors, particularly in the categories of vowel identification without lipreading (4-channel processor), consonant identification without lipreading (6-channel processor) and consonant identification with lipreading (both processors).

Good test/retest reliability was thoroughly demonstrated for MH. When retested with a processor that had produced low scores on a previous occasion, MH always would obtain low scores again, and when repeating a test with a processor that earlier had performed well she always would repeat her high scores. The standard deviation of overall percent correct scores from seven repeated trials of the last (rightmost) processor shown in Fig. II.A-3, for example, was slightly less than three percent. All scores presented in Fig. II.A-3 are significantly above chance ($p < 0.01$) except for those of the two hearing-alone conditions for the CA processor.

Results for Patients Fitted with the TTS

The studies with the two percutaneous cable patients demonstrated that (a) different processing strategies can produce widely different outcomes for individual patients and (b) IP processors are far superior to the tested alternative processors for at least two patients with psychophysical signs of poor nerve survival. With these observations in mind, we were most interested in comparing the IP and CA strategies in extensive tests with a larger population of patients. We wondered, for example, how the IP processor would perform for successful users of a CA processor, and whether the potential advantages of the IP processors could be realized in patients with four or fewer channels of stimulation.

As mentioned above, six patients fitted with the 4-channel UCSF/Storz TTS participated in the follow-up studies. Each patient was studied for a one-week period in which (a) basic psychophysical measures were obtained on thresholds and dynamic ranges for pulsatile stimuli, (b) a variety of IP processors (with different choices of processor parameters) was evaluated with tests of vowel and consonant confusions, and (c) the best of these IP processors was further evaluated using a broad spectrum of speech tests.

Before presenting the results obtained from the evaluations of the CA and IP processors, it is important to note several factors that favored the CA processor in comparisons of processor performance. First, all six patients entered our studies with substantial experience using the CA processor. We expected that the learning effects of such experience would strongly favor the CA processor in the comparisons (further discussion on this point is presented in Dowell et al., 1987; Tyler et al., 1986; Wilson et al., 1988c). In a typical case, experience with the CA processor would approximate one year of daily use, while experience with the real-time implementation of the IP processor would be between 15 and 30 minutes before formal testing. Therefore, the information provided by an IP processor would have to be immediately accessible to the patient in order for the results to be at all comparable to those obtained with the CA processor.

An additional factor weighing against the IP processor in these performance comparisons was the use of the 4-channel TTS. The principal limitations of that system for IP processors are (a) inadequate levels of voltage compliance for stimulation with short-duration pulses, (b) the small number of channels, and (c) lack of current control in the stimulus waveforms. Half of the patients in this study were further limited by having even fewer than four functional channels available for stimulation.

The loss of one or two channels in each of these cases has been attributed to fluid or particulate contamination admitted to the connector assembly of the implanted portion of the TTS during surgery (Schindler et al., 1986b). Although the problem of contamination has since been solved by modifying the surgical procedure, most of these six patients were implanted before the problem was evident and before these revisions had been made.

Extensive evaluation (with patient MH; see Wilson et al., 1986; 1988a) of variations in performance with parametric manipulations among IP processors suggested the following five criteria for fitting such designs, in approximate order of decreasing importance:

1. Total number of channels (large increases in performance are found when the number of channels is increased from 2 to 4 and from 4 to 6);

2. Number of channels updated per stimulation cycle, if fewer than the total number of available channels (performance in tests of consonant identification declines precipitously if the number of updated channels falls below 4);

3. Total duration of each stimulation cycle (performance gets better as duration is decreased, and is markedly better when the duration is less than 4-5 msec);

4. Time between sequential pulses (performance improves as the time between pulses is increased, up to the point at which the total duration of the stimulation cycle begins to exceed 4-5 msec); and

5. Explicit coding of voicing information (performance is better with explicit coding of voicing information, and the percepts elicited with processors that use such coding generally are described as more natural and speech-like).

Notice that the small number of channels and limited voltage compliance of the TTS place severe restrictions on meeting criteria 1-4 above. Also, the lack of current control introduces distortions in stimulus waveforms that may require greater separation of pulses in order to avoid channel interactions.

The parameters selected for the IP processors of these six TTS patients are presented in Table II.A-1. The best fulfillments of the five criteria were obtained for patients HE and MC2. Each had the use of all four

TABLE II.A-1. Parameters of Real-Time IP Processors.[a]

patient	channels	pulse widths/ phase (msec)	pulse sep. (msec)	cycle time (msec)
MC1	3	0.5	0.5	4.5
HE	4	0.5	0.5	6.0
JM	3	1.0	0.1	6.3
RC	2	0.5	0.1	2.2
ET	4	1.0 1.0 0.5 0.5	0.1	6.4
MC2	4	0.3 0.7 0.3 0.3	0.5	5.2

[a]All six processors used symmetric biphasic pulses with positive phase leading and with the channels stimulated in base-to-apex order. Stimulation cycles were presented at the fundamental frequency for voiced intervals and at maximum rate (period equal to cycle time) during unvoiced intervals.

stimulation channels and the time between sequential pulses was a relatively long 0.5 msec for both patients. In addition, the stimulation cycle time for MC2 was almost within the 5.0 msec criterion for this parameter.

In contrast, relatively poor sets of parameters had to be used for the remaining patients. Patients MC1 and JM had only three usable channels and patient RC only two. The cycle times remained excessive for patients JM and ET, even with the times between pulses compromised down to only 0.1 msec.

The results of processor comparisons are presented in Figs. II.A-4 to II.A-8. Fig. II.A-4 shows performance levels for the tests of vowel and consonant identifications. Solid black bars represent the scores for lipreading alone, dotted bars for the CA processor alone, and cross-hatched bars for the CA processor with lipreading. Vertically-lined bars represent the scores for the IP processor alone and horizontally-lined bars for the IP processor with lipreading. Chance levels of performance are indicated by the horizontal lines in each panel and, as is the case in subsequent figures, any results that do not significantly exceed chance are noted in the figure captions.

Performance in the tests of vowel identification is quite high for both processors. All patients have scores of 80% correct or better for both processors with lipreading and 68% or better without lipreading. The means of the results for the two processors are not significantly different for either condition.

In contrast to the apparent equivalence of processors for the vowel test, the scores for the consonant test without lipreading are significantly higher for the IP processor ($p < 0.05$, paired t test). All patients except JM obtained higher scores using the IP processor for this condition. The difference between the means for the "with lipreading" condition is not significant. Analysis of specific confusions across patients for the two processing strategies is under way and will be presented elsewhere.

An indication of superior consonant recognition with the IP processor is also seen in the results for the Iowa test of medial consonant identification with lipreading cues. These results are presented in Fig. II.A-5. Every patient except MC2 has substantially higher scores with the IP processor. However, the difference in the means of the results for the two processors is not statistically significant. It is important to note that our procedure for administering this test was designed to confer any benefits of learning on the CA processor. The order of testing was to measure performance first with the IP processor plus lipreading, then with lipreading alone, and finally with the CA processor plus lipreading.

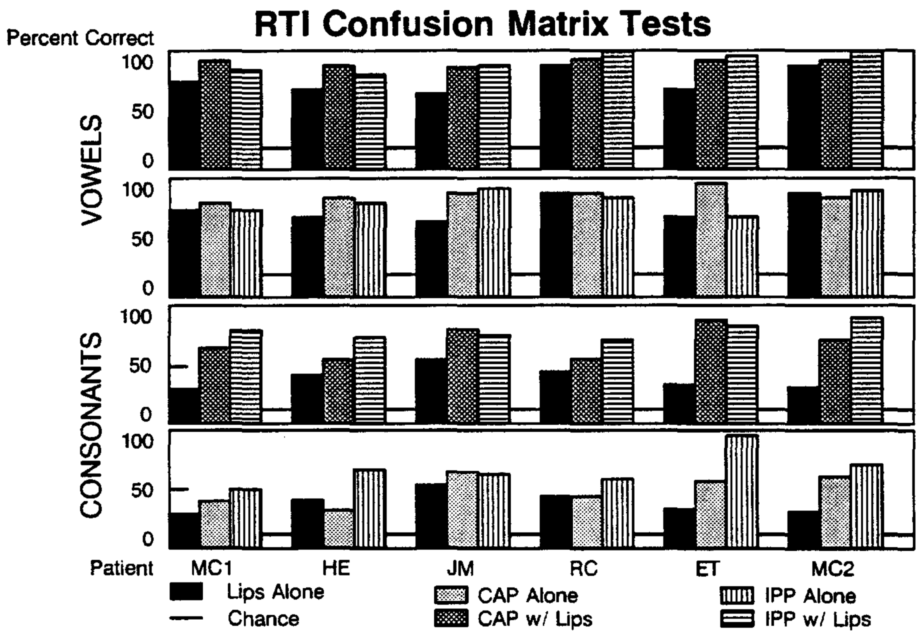


Fig. II.A-4. Results of vowel and consonant confusion tests for six patients fitted with the 4-channel UCSF/Storz transcutaneous transmission system. All of these scores are significantly above chance at the $p < 0.01$ level, except for some scores for the consonant tests with lips alone.

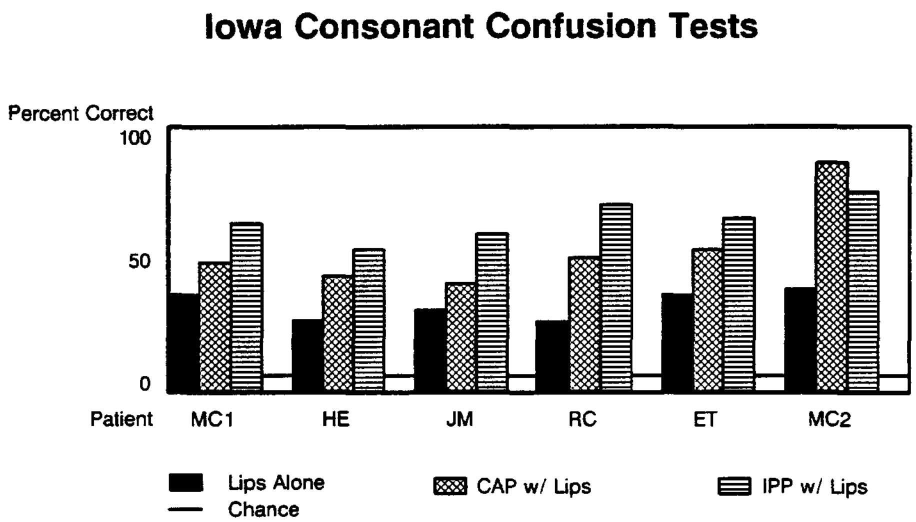


Fig. II.A-5. Results from the Iowa test of medial consonant identifications with lipreading cues. The patients are those described in the caption of Fig. II.A-4. All of these results are significantly above chance at the $p < 0.01$ level.

In addition to paired t tests, a Wilcoxon test (see Hollander and Wolfe, 1973) of nonparametric ranking of results across the six patients was applied to all measurements of this study. Only two sets of measurements emerged from the Wilcoxon analysis as indicating significant improvement with the use of one processor over the other. Both the RTI consonant confusion test without lipreading and the Iowa test of medial consonant identification with lipreading indicated better performance with the IP processor at a significance level of $p < 0.05$ (Wilcoxon $T^{+} = 20$, $p = 0.03$).

The remaining results presented in Figs. II.A-6 to II.A-8 are those from the MAC battery. Results from the subtests of prosodic perception (timing of syllable boundaries, voice fundamental frequency and word stress) are shown in Fig. II.A-6. These results demonstrate that, in general, these subtests are too easy for the patients and processors under study. The scores for the noise/voice (N/V) and spondee same/different (Sp S/D) tests are very high for all patients and for both processors. The accent test is a more sensitive indicator of performance. Scores for this test show clear differences among patients, but relatively modest differences between processors. Three patients did moderately better with the IP processor on this test, (RC, ET, and MC2) and two patients did moderately better with the CA processor (MC1 and JM). Finally, for the Question/Statement (Q/S) test one patient did much better with the CA processor (MC1), three patients did somewhat better with the IP processor (HE, JM and RC) and two patients obtained identical scores with the two processors (ET and MC2). None of the differences in the means of the results for the two processors is statistically significant among the prosodic subtests of the MAC battery.

Results from the phoneme and word subtests of the MAC battery also demonstrate a general equivalence of the processors for the conditions of our study. These results are presented in Fig. II.A-7. Again, none of the differences in the means of the results for the two processors is statistically significant. Patients HE and MC2 have somewhat higher or equivalent scores on all four tests (including vowel, initial consonant, final consonant, and four-choice spondee) with the IP processor, and patients MC1 and RC have somewhat higher or equivalent scores with the CA processor.

Finally, results from the subtests of open-set recognition are shown in Fig. II.A-8. Once again, none of the differences in the means of the results for the two processors is statistically significant. Patient MC2, however, has higher scores for the IP processor for all four subtests of spondee recognition (Sp), recognition of monosyllabic words (NU6), recognition of CID sentences (CID), and recognition of words in context

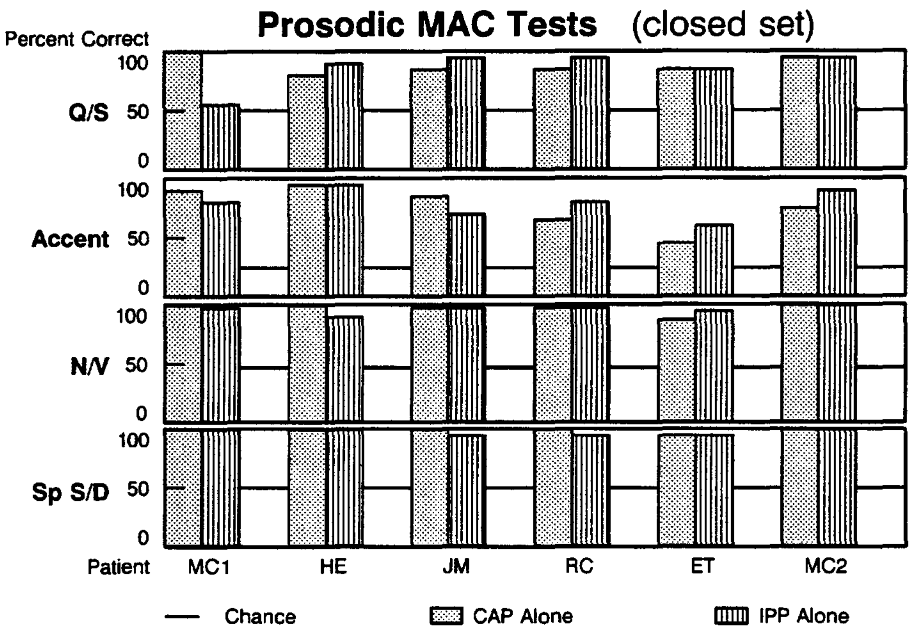


Fig. II.A-6. Results from subtests of the Minimal Auditory Capabilities (MAC) battery designed to evaluate perception of prosodic elements in speech. Abbreviations for the subtests are Q/S for Question/ Statement; N/V for Noise/Voice; and Sp S/D for Spondee Same/Different. The patients are those described in the caption of Fig. II.A-4. All these results are significantly above chance at the $p < 0.01$ level except MC1's score for the Q/S test with the IPP and ET's score for the Accent test with the CAP.

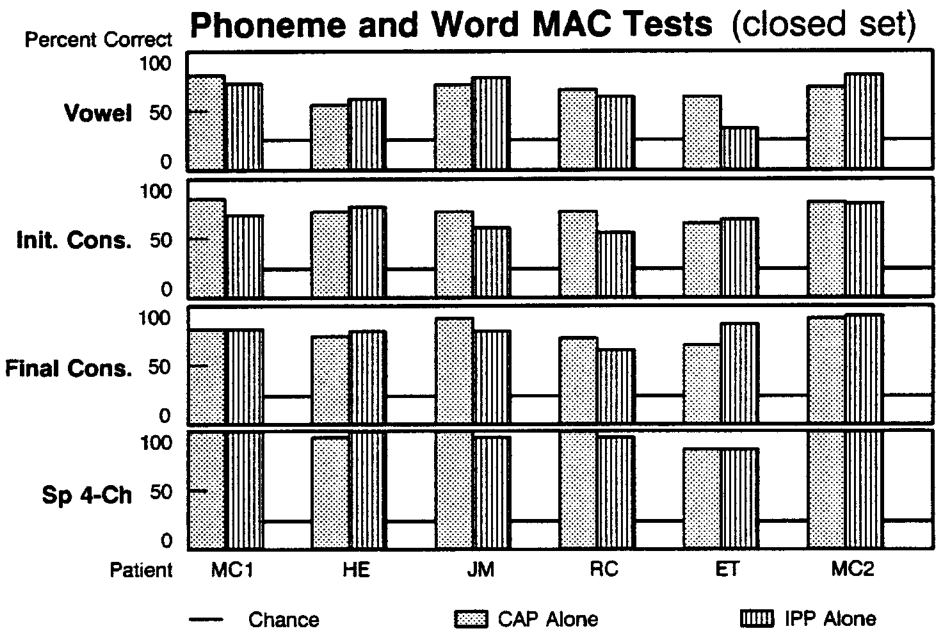


Fig. II.A-7. Results from subtests of the Minimal Auditory Capabilities (MAC) battery designed to evaluate perception of phonemes and words in speech. Abbreviations for the subtests are Init. Cons. for Initial Consonant; Final Cons. for Final Consonant; and Sp 4-Ch for Four-Choice Spondee. The patients are those described in the caption of Fig. II.A-4. All these results are significantly above chance at the $p < 0.01$ level except ET's score for the Vowel test with the IPP.

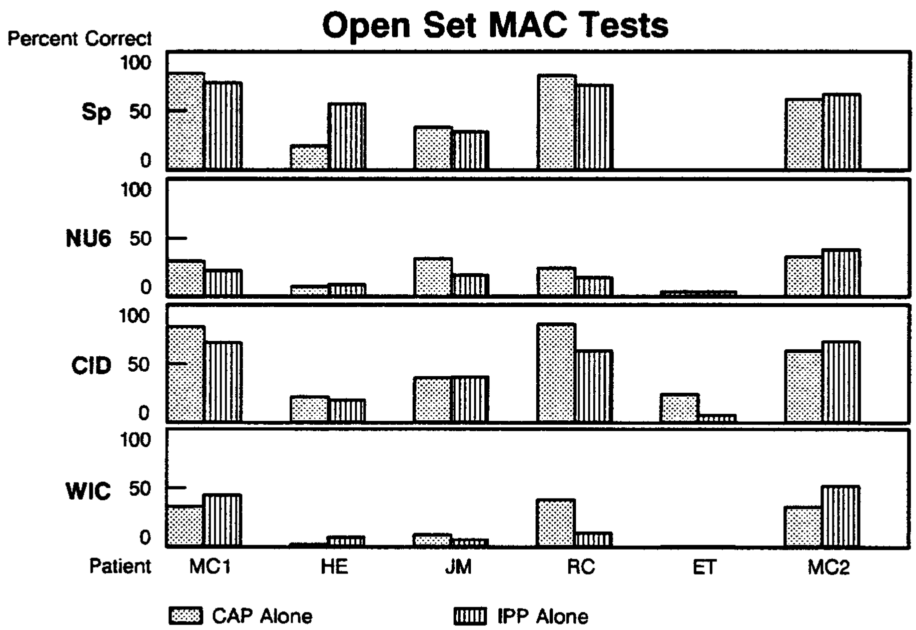


Fig. II.A-8. Results from subtests of the Minimal Auditory Capabilities (MAC) battery designed to measure open-set recognition of speech. Abbreviations for the subtests are Sp for Spondee recognition; NU6 for recognition of monosyllabic words from Northwestern University list six; CID for recognition of everyday sentences from lists prepared at the Central Institute for the Deaf; and WIC for recognition of Words in Context. The patients are those described in the caption of Fig. II.A-4.

(WIC). In addition, patient HE has much higher scores with the IP processor for the tests of spondee recognition and of words in context. On the other hand, patient RC has higher scores with the CA processor on every open-set test, and patients MC1 and ET show generally superior performance with the CA processor for the open-set tests.

Summary of Results

In the studies with the two percutaneous cable patients, each of whom had a bleak psychophysical picture consistent with poor nerve survival, the IP strategy produced much better results than the CA strategy. We believe this improved performance with the IP processor is attributable in part to the sizable reduction in channel interactions afforded by the use of nonsimultaneous stimuli. The studies with the cable patients further demonstrated a very strong correspondence between number of stimulation channels and performance. In the studies with patients fitted with the TTS, the IP and CA processors were compared under conditions of substantial experience with the CA processor, generally high levels of performance with the CA processor, and severe restrictions imposed by the TTS for implementing optimized versions of the IP processor. Despite these limitations, two patients in this second series <u>immediately</u> had better performance with the IP processor (patients HE and MC2) and three had similar or slightly inferior levels of performance with this processor (patients MC1, JM and ET). Only one patient (RC) had clearly superior performance with the CA processor. This patient also happened to have the highest level of performance among the six studied patients with the CA processor and, with only two functioning channels, afforded the poorest fulfillment of our IP processor fitting criteria.

These results suggest that (a) most patients are likely to obtain at least equivalent results if an IP processor is used instead of a CA processor; (b) patients with psychophysical signs of poor nerve survival are likely to obtain better results with an IP processor; and (c) use of a TTS designed to support an IP processor (e.g., a TTS with eight channels of current-controlled outputs) is likely to produce results that are better than those obtained with the limited TTS of the present studies.

Discussion

A key finding of the studies reviewed here is that substantial gains in speech perception can be made by selecting an appropriate processing strategy for each patient. In our two series of patients RC obtained clearly superior results with the CA processing strategy while LP and MH obtained clearly superior results with the IP processing strategy. These results demonstrate that access to a variety of alternative strategies may be required for optimizing the outcomes across a population of patients.

The patient who obtained superior results with the CA processor (RC) had only two functional channels of intracochlear stimulation. This number of channels is certainly too few for even a gross representation of the speech spectrum with an IP processor. The relatively poor performance of the IP processor therefore could be attributed to a poor fulfillment of its fitting criteria.

Another possible explanation for RC's superior performance with the CA processor is that he made especially good use of the information present in the compressed analog waveforms. Indeed, the impressive results obtained with RC (two channels), MC1 (three channels), certain patients in the Vienna series (one channel; see Hochmair-Desoyer and Burian, 1985; Hochmair-Desoyer et al., 1985) and certain patients in the Symbion series (four 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 speech-like stimuli (Hochmair-Desoyer et al., 1985; Soli et al., 1986); 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).

If this second interpretation is pertinent to RC's case, then patients with such special abilities might be best served with a CA processor. Optimal implementations of such a processor would provide any additional information the patient might be able to utilize in multiple channels of stimulation. The maximum number of useful channels is likely to be limited, however, by the severe interactions that can occur between closely spaced electrodes when simultaneous stimuli are used.

In contrast, patients with a psychophysical picture consistent with poor nerve survival (i.e., severe channel interactions, high thresholds, narrow dynamic ranges, and perhaps limited abilities to discriminate frequencies and other stimulus attributes) are likely to receive greater benefit from an IP processor. For two such patients in our initial series large increases in performance were obtained when the number of stimulus channels was increased from 2 to 4 and from 4 to 6. Paradoxically, then, multichannel implants may provide relatively greater benefits to patients with signs of poor nerve survival than to patients without these signs.

To summarize the comparisons made above, Table II.A-2 lists characteristics of the CA and IP processing strategies. Briefly, the CA strategy may be superior for patients with good nerve survival because such patients may perceive substantial temporal and frequency information in analog waveforms and because the lower stimulus intensities required for these patients, along with survival of neural elements over the active electrodes, can greatly minimize channel interactions produced by simultaneous stimulation. On the other hand, the IP strategy may be superior for patients with poor nerve survival because isolation between channels for such patients is tremendously improved with the use of nonsimultaneous stimuli.

Finally, we note that these comparisons between processors suggest possibilities for further improvements in performance. One such improvement might be made by combining the best features of the CA and IP approaches in "hybrid" strategies. For a good nerve survival case, for example, the main benefits of the CA strategy might be realized with a single channel of stimulation. This would leave the remaining channels for the representation of frequency components in speech above the first formant. The excellent results obtained in the present studies with all eight patients using the IP processor (especially patients HE, MC2 and MC1) indicate that interleaved stimuli are likely to enhance speech representation even for patients with good nerve survival (presumably through further reduction of interactions between adjacent channels). The combined use of the CA and IP strategies therefore might confer in an optimal way the benefits of waveform discrimination and multichannel stimulation to fortunate patients with good nerve survival. Similarly, for cases in which nerve survival is patchy, psychophysical or electrophysiological tests might be conducted to identify areas of good survival. A bipolar pair of electrodes adjacent to one of these areas could be selected for compressed analog stimulation. This electrode channel would have low threshold and suprathreshold stimulus levels relative to electrodes adjacent to poor survival areas. Such low levels might allow the remaining electrode channels to receive IP stimuli with only minor channel interactions.

TABLE II.A-2. Characteristics of Processors.*

ANALOG	PULSATILE
continuous waveforms, presented simultaneously	non-simultaneous pulses
severe interactions between channels for patients with poor nerve survival	improved channel isolation, especially for patients with poor nerve survival
in some patients, continuous waveforms can provide good temporal and frequency information (F0, voice/unvoice distinctions, F1, possibly F2)	limited transmission of temporal and frequency information (F0, voice/unvoice distinctions)

*Symbols used in this Table are F0 for the fundamental frequency of voiced-speech sounds, F1 for the first formant frequency of speech, and F2 for the second formant frequency of speech.

Potential applications of hybrid processors, along with the choices posed by the existing CA and IP strategies, emphasize the need for flexibility in the fitting of speech processors to individual patients. We believe further significant advances in the development of speech processors for cochlear prostheses will result from (a) an improved understanding of the electrode-nerve interface, especially as it relates to the pattern of nerve survival, and (b) design and application of better psychophysical and electrophysiological tests to infer the pattern of survival in the implanted ear.

Conclusions

The results obtained from our studies, to compare analog and pulsatile coding strategies for multichannel cochlear implants, are consistent with the following conclusions:

1. Different processing strategies can produce widely different outcomes for individual implant patients;

2. IP processors are far superior to the tested alternative processors for at least two patients with psychophysical signs of poor nerve survival;

3. The performance of IP processors strongly depends on the selection of processor parameters;

4. Use of a TTS designed to support an IP processor (e.g., a TTS with eight channels of current-controlled outputs) is likely to produce results that are better than those obtained with the limited TTS of the present studies;

5. Processors other than the IP processors can be superior for patients with psychophysical signs of good nerve survival and who cannot be fitted with an optimized IP processor;

6. One such processor is the CA processor of the present UCSF/Storz cochlear prosthesis; and

7. Substantial gains in speech understanding can be made by (a) selecting the best type of speech processor for each patient and (b) using implanted and external hardware capable of supporting a wide range of different processing strategies.

II.B. Design and Evaluation of a Two-Channel, "Breeuwer/Plomp" Processor

In a recent paper Breeuwer and Plomp described a speech processor which was particularly effective as an aid to lipreading (Breeuwer and Plomp, 1984). The supplementary signal provided by this processor consisted simply of acoustic representations of the root-mean-square (RMS) energies in a pair of octave bands centered at 500 and 3160 Hz. To evaluate the processing strategy, Breeuwer and Plomp measured the number of correctly perceived syllables in short Dutch sentences presented to 18 listeners with normal hearing. The test conditions included lipreading only, lipreading plus acoustic supplement, and acoustic supplement alone. The results were impressive. The percentage of correctly perceived syllables jumped from 23% correct for lipreading only to 87% correct for lipreading plus the processed speech supplement, a score fully consistent with substantial open-set recognition of speech.

These results inspired a study just completed in our laboratory to evaluate the "Breeuwer/Plomp" strategy in tests with cochlear implant patients (Wilson et al., 1987a). One motivation for this study was to determine the efficacy of the Breeuwer/Plomp strategy in situations allowing the use of only a few channels of electrical stimulation. Such situations are surprisingly numerous and include (a) the use of electrode placements or configurations with inherently poor isolation between channels, as in extracochlear auditory prostheses; (b) the use of two-electrode devices, as is presently the case for stimulation of the cochlear nucleus (Eisenberg et al., 1987); and (c) cases in which only a few channels of stimulation in a multichannel intracochlear device can be perceived independently due to poor survival of cochlear neurons, device failure (see section II.A of this proposal and Wilson et al., 1988c), or partial insertion of the electrode array.

Patients

Five cochlear implant patients participated in this study as part of an extensive series of tests to compare alternative processing strategies for auditory prostheses. These patients included subjects MC1, HE, RC, ET and MC2 from the studies described in section II.A of this proposal. As indicated in that section, each of these patients was implanted with the UCSF/Storz electrode array and was fitted with the four-channel UCSF/Storz system for transcutaneous transmission of stimulus information across the skin. Patient JM was unable to participate in the evaluations of the Breeuwer/Plomp processor due to lack of time.

Processing Strategy

Our application of the processing strategy described by Breeuwer and Plomp consisted of mapping the RMS energies of the two octave-wide bands into the dynamic range of electrically evoked hearing for two channels of intracochlear stimulation. The stimuli were interleaved pulses derived in a manner identical to that described in the previous section (section II.A). The only differences between the two-channel Breeuwer/Plomp processors of the present section and the three- or four-channel IP processors of the previous section were (a) the use of two octave-wide bands for the Breeuwer/Plomp processor, as opposed to contiguous bands spaced along a logarithmic scale for the IP processors, and (b) the lower number of stimulation channels for the Breeuwer/Plomp processor.

Typical waveforms for our implementation of the Breeuwer/Plomp processor are shown in Fig. II.B-1. The top trace in each panel is the processor input and the remaining traces are channel outputs. The input is the word "BOUGHT." The initial consonant occurs at about 180 msec and the vowel follows immediately thereafter. An expanded display of waveforms well into the vowel is shown in the lower-left panel. The /t/ burst begins slightly before 640 msec, and an expanded display of waveforms beginning at 640 msec is shown in the lower-right panel.

In the particular variation of Brēeuwer/Plomp processors presented in Fig. II.B-1, balanced biphasic pulses are used, and voicing information is explicitly coded. During voiced speech the stimulation cycles are timed to begin in synchrony with the detected fundamental frequency, while during unvoiced speech the stimulation cycles are initiated as rapidly as possible (with one stimulation cycle immediately following its predecessor). The pulse sequence in each stimulation cycle is such that the more basal electrode channel is stimulated first.

Methods

The parameters selected for the Breeuwer/Plomp processors used in this study are presented in Table II.B-1. The electrode channels chosen for each subject provided distinct "place pitch" percepts (i.e., differences in timbre or pitch for loudness-balanced stimuli allowed reliable discrimination of the selected channels for all subjects). In addition, the processors for all subjects used explicit coding of voicing information. Stimulation cycles were initiated at the maximum rate during unvoiced intervals for subjects MC1, HE, RC and ET, and stimulation cycles were initiated at randomly-spaced intervals for subject MC2.

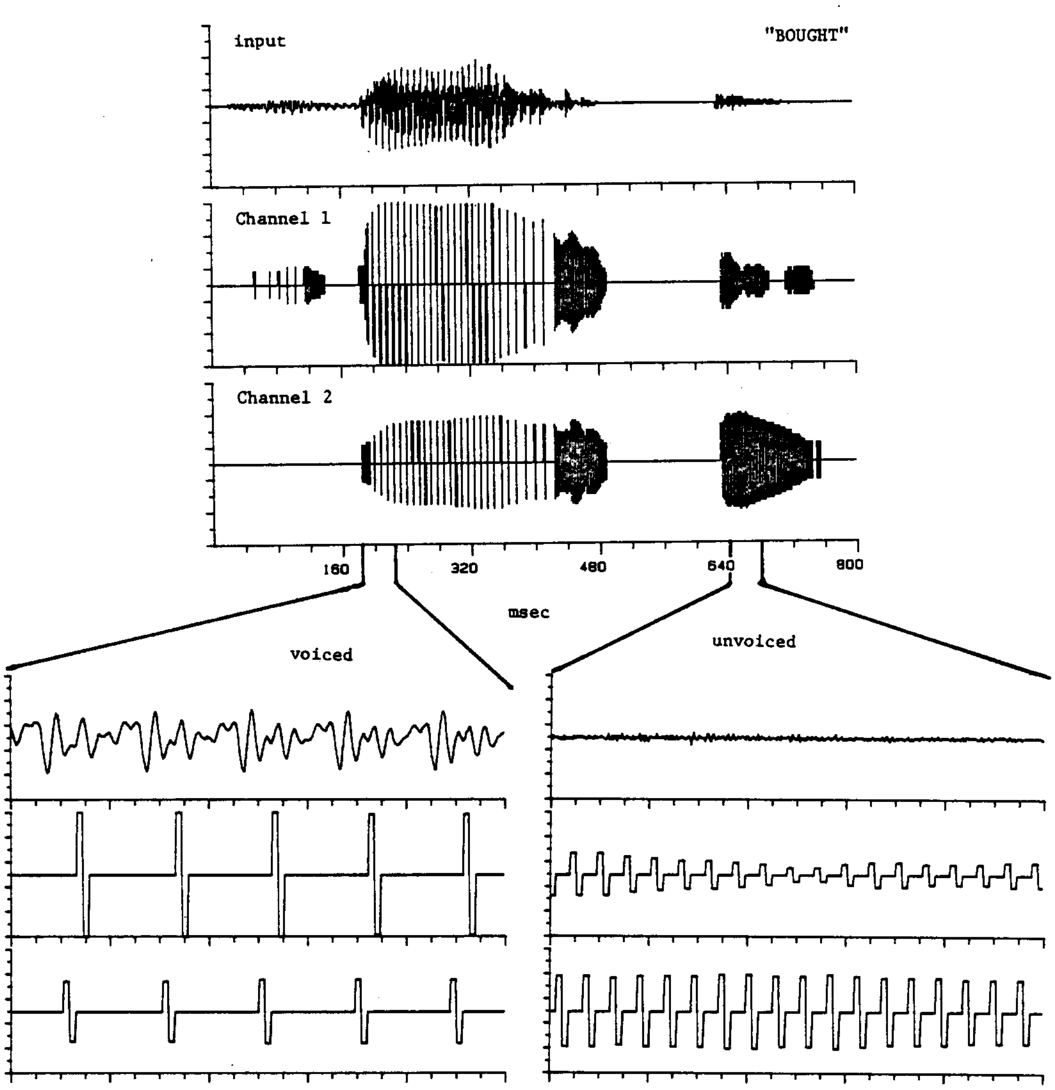


Fig. II.B-1. Waveforms of a two channel, "Breeuwer/Plomp" processor. The top trace in each panel is the input to the processor and the remaining traces are channel outputs. The input is the word "BOUGHT." An expanded display of waveforms during the initial portion of the vowel is shown in the lower left panel and an expanded display of waveforms during the "T" is shown in the lower right panel.

TABLE II.B-1. Parameters selected for Breeuwer/Plomp processors.

subject	channels[a]	pulse duration/ph[b]	pulse sep.[b]	cycle time[b]	Max Rate or Jittered
MC1	1,5	0.5	0.5	3.0	MR
HE	1,7	0.5	0.5	3.0	MR
RC	5,7	0.5	0.1	2.2	MR
ET	1,7	0.5	0.5	3.0	MR
MC2	1,5	0.3	0.5	2.2	J

[a]Channels are numbered in ascending order from the apical end of the electrode array. Channel 1 corresponds to bipolar electrode pair 1+2, and channel 8 to bipolar electrode pair 15+16.

[b]Times are in milliseconds.

Tests of vowel and consonant identification were conducted for all five subjects. These tests were identical to those described above for the comparisons of the CA and IP processing strategies (see section II.A).

In addition to the vowel and consonant tests, the Breeuwer/Plomp strategy was further evaluated with an extensive battery of speech perception tests for one of the subjects. These tests included all subtests of the Minimal Auditory Capabilities (MAC) battery (Owens et al., 1985), connected discourse tracking with and without the processor (De Filippo and Scott, 1978; Owens and Raggio, 1987), and the Iowa test of medial consonant identification with video presentations of the speaker's face (Tyler et al., 1983).

Results

Results from the tests of vowel and consonant identifications are presented in Fig. II.B-2 in the form of confusion matrices. The responses from all five subjects are combined in the matrices for each condition. A significant improvement in consonant identification is produced when the auditory cues from the Breeuwer/Plomp processor are added to the visual cues provided by lipreading ($p < 0.002$, paired t test). Especially impressive is the improvement in the identification of the consonants that are least visible on the lips. Examination of the matrix for consonant identification with lipreading only shows that "l" and "th" are highly visible on the lips while the other consonants are not. The percentage of correctly identified consonants other than "l" and "th" is 22% for lipreading alone and 75% for lipreading plus processor. This improvement clearly demonstrates the potential utility of the Breeuwer/Plomp processor as an adjunct to lipreading.

In addition, the Breeuwer/Plomp processor produced high vowel and consonant recognition scores with hearing alone. Specifically, the overall scores in these categories for the five subjects in this series were 76% correct for vowels and 62% correct for consonants. These scores are surprisingly good in view of Breeuwer and Plomp's report of 27% correct recognition of syllables for the hearing-only mode (Breeuwer and Plomp, 1984). The better results in our series might be attributable to the explicit coding of voicing information in our implementations of a modified "Breeuwer/Plomp" processor or to the relatively-small numbers of tokens used in the vowel and consonant tests. In either case it is noteworthy that the average scores for both vowel and consonant identifications with hearing alone are not statistically different from the scores obtained with lipreading alone.

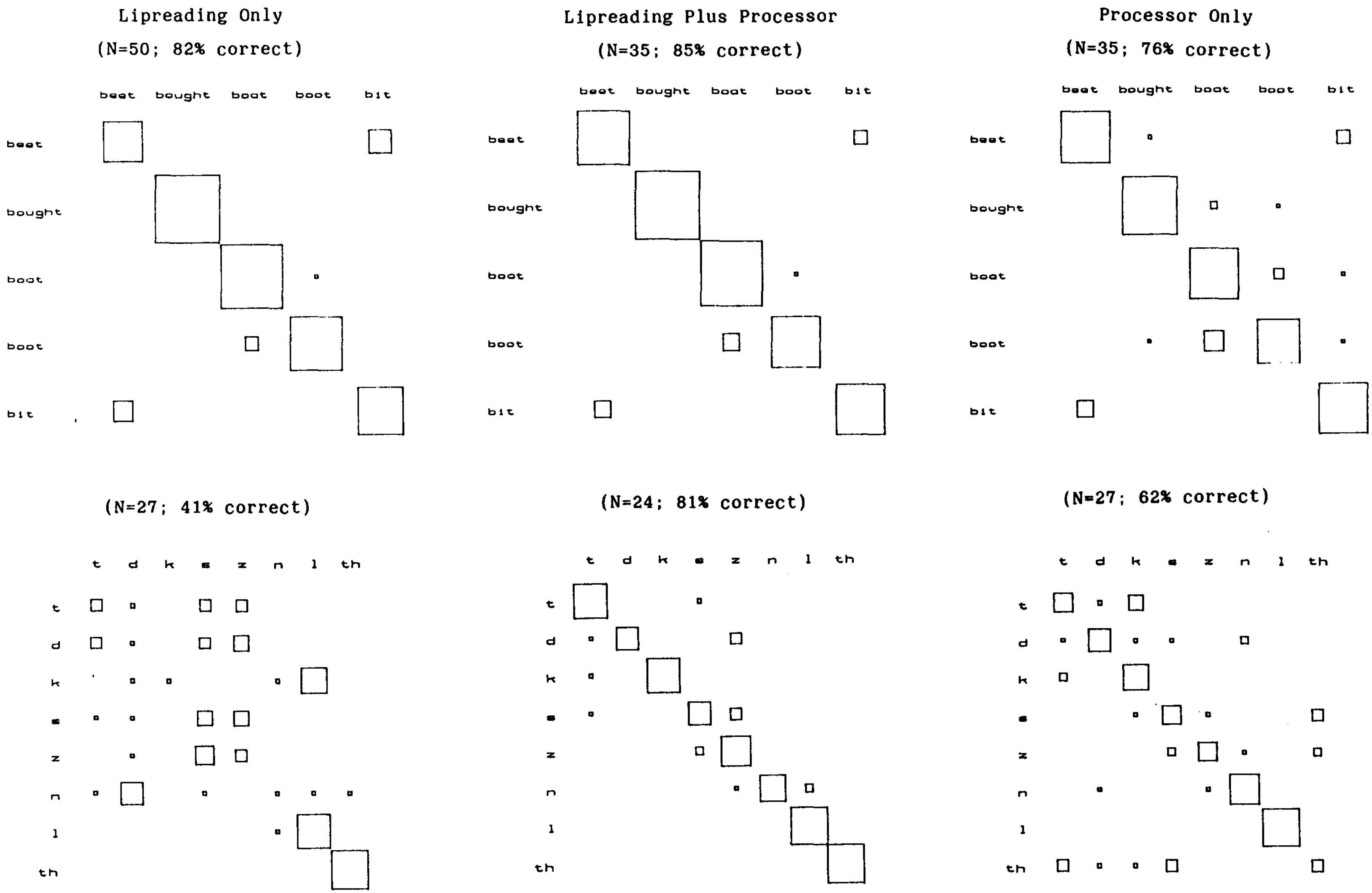


Fig. II.B-2. Results the of vowel and consonant identification tests. The lengths of the sides of each square represent the averages of results obtained with two channel, Breeuwer/Plomp processors across all five subjects. Rows in the matrices represent stimuli and columns the responses. The total number of stimulus presentations and the percentage of correct responses are indicated in the parentheses above each matrix.

The results from the additional studies conducted with one of the subjects are presented in Fig. II.B-3 and Table II.B-2. Fig. II.B-3 shows confusion matrices from the Iowa test of medial consonant identification with lipreading cues. As with the previous consonant identification tests, the consonants are presented in an /aCa/ context (e.g., "AFA"). Unlike the previous tests, though, the lipreading cues are completely controlled in the Iowa tests in that these cues are presented from a videotape recording of the speaker's face. Also, many more consonants are included in the Iowa test (i.e., 14 vs. 8).

The results from the Iowa test are consistent with the previous results from the eight-token consonant identification test. Patient RC obtained a score of 26% correct for lipreading alone on the Iowa test and a score of 71% correct for lipreading plus processor, an almost three-fold improvement in consonant identification. Moreover, the pattern of errors in the lipreading plus processor condition suggests that even better results could be obtained with a modest amount of training or learning. In particular, "t" was always perceived as "k" but never vice versa, and "g" was always perceived as "dh" but never vice versa. These asymmetries in the errors indicate that information is available to make the distinctions, but is not being used by the subject.

Results from the tests of connected discourse tracking further confirm the findings of improved performance when the processor is used in conjunction with lipreading. RC's scores on the tracking tests were 4 words/minute for lipreading alone and 44 words/minute for lipreading plus processor. The additional auditory cues provided by the processor thus bring RC from a poor level of performance to a moderately good level of performance. In fact, his tracking rate with the processor is about half of the average rate obtained in tests with normal-hearing subjects (Owens and Raggio, 1987).

The remaining tests conducted with RC were those of the full MAC battery. The results, presented in Table II.B-2, indicate substantial access to speech information in the hearing-only mode. All scores from the closed set tests of prosodic information and of phoneme and word discrimination are significantly above chance ($p < 0.01$). Indeed, the scores on the Question/Statement, Noise/Voice, Spondee Same/Different and 4-Choice Spondee tests are all 95% correct or better. Surprisingly high scores also are obtained for the Accent (80% correct), Vowel (62% correct) and Final Consonant (63% correct) tests. These high scores are unexpected inasmuch as the Breeuwer/Plomp processor was specifically designed merely to present supplementary cues for lipreading.

Lipreading Only
(26% correct)

Lipreading Plus 2-Channel,
Breeuwer/Plomp Processor
(71% correct)

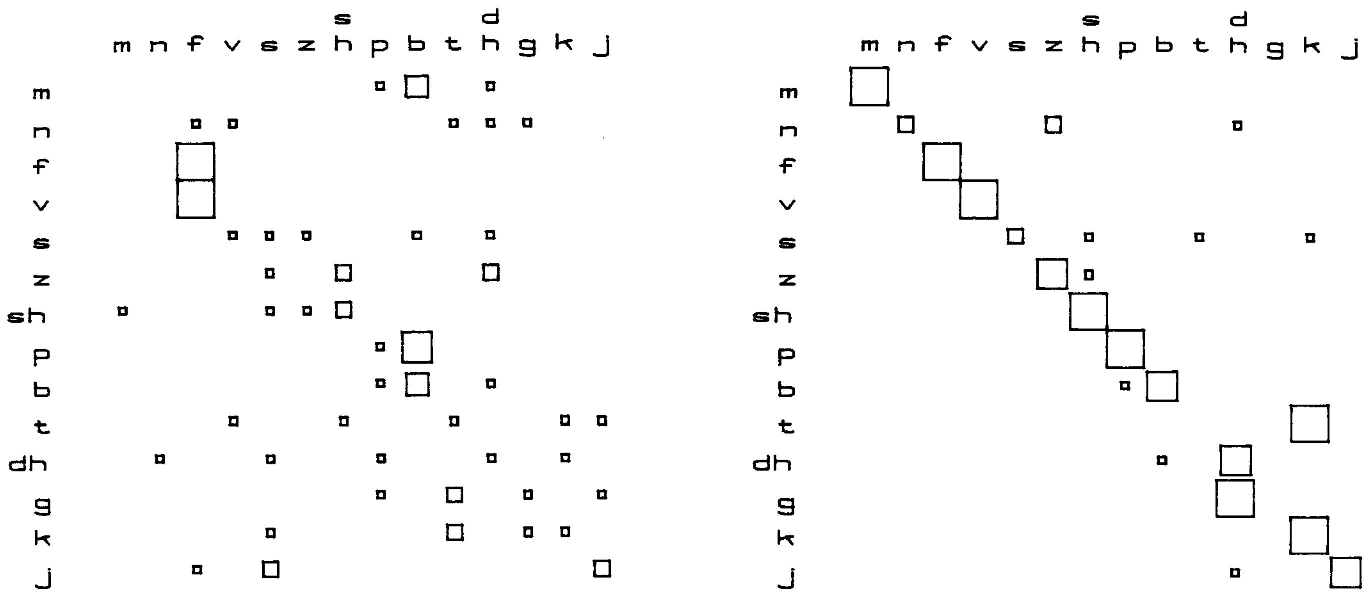


Fig. II.B-3. Results from IOWA tests of consonant identification with visual cues. The matrix on the left shows the performance of patient RC for lipreading only, and the matrix on the right shows his performance for lipreading plus the auditory input provided by a two-channel Breeuwer/Plomp processor. Rows in the matrices represent stimuli and columns the responses. Each token was presented five times in each test.

TABLE II.B-2. Results from the Minimal Auditory Capabilities (MAC) battery for subject RC.

Tests	Chance (%)	Score (%)[a]
Prosodic Perception (closed set)		
Question/Statement	50	95
Accent	25	80
Noise/Voice	50	98
Spondee Same/Different	50	95
Phoneme & Word Discrimination (closed set)		
Vowels	25	62
Initial Consonants	25	55
Final Consonants	25	63
4-Choice Spondee	25	95
Open-Set Speech Recognition		
Spondees		72
Monosyllabic Words (NU 6)		16
Sentences (CID)		61
Words in Context (SPIN)		12

[a]All scores for the Prosodic Perception and Phoneme & Word Discrimination tests are significantly above chance ($p < 0.01$); any score above zero is regarded as significant for the Open-Set Speech Recognition tests.

Finally, the results from the tests of open-set recognition further indicate that the Breeuwer/Plomp processor can provide useful information even when the visual cues from lipreading are not available. In particular, high levels of performance are demonstrated in the tests of spondee (72% correct) and sentence (61% correct) recognition, and good levels of performance are demonstrated for the more difficult tasks of monosyllabic word recognition (16% correct) and recognition of single words in context (12% correct). These scores are comparable to the best results reported for open-set recognition using any type of auditory prosthesis (see, e.g., Gantz et al., 1987). We note, however, that scores on open-set tests are likely to reflect the characteristics of the subject as well as the quality of input provided by the speech processor. The present open-set scores therefore should be regarded as an indication of the potential of the Breeuwer/Plomp processor in the hearing-only mode. That is, the information provided by this processor is adequate to support high levels of open-set recognition; however, all implant patients may not be able to utilize this information as effectively as RC.

Conclusions

The results of this study confirm and extend the findings of Breeuwer and Plomp. In particular, the present results from our evaluation of the "Breeuwer/Plomp" processors for cochlear implants are consistent with the following conclusions: (a) the Breeuwer/Plomp processor can act as a powerful adjunct to lipreading, as evidenced by large improvements in consonant identification seen for five subjects and in connected discourse tracking for a single subject; (b) this processor can produce fairly high levels of vowel and consonant identification with hearing alone; and (c) the performance with the one subject tested with the MAC battery further indicates that the Breeuwer/Plomp processor can provide useful information even when visual cues from lipreading are not available. These observations should encourage consideration of the use of a Breeuwer/Plomp processor in auditory prostheses whenever the number of channels available for distinct stimulation is restricted.

II.C. Experience with Different Types of Implant Patients

An important contributor to our perspective on the design and evaluation of speech processors for auditory prostheses is our experience with different types of implant patients. Some of this experience, outlined in section II.A above, emphasized the likely importance of patient variables on the results obtained with cochlear implants. Also, this experience demonstrated the need for different kinds of processors for different patients.

Another aspect of our experience with implant patients is indicated in Table II.C.1. This table presents the characteristics of patients who have participated in our studies. These characteristics include the type of implant device used by each patient; the primary (or sole) electrode coupling configuration used; whether a percutaneous or transcutaneous system was used for transmission of stimulus information; the number of functioning stimulation channels for each patient; and the clinical center at which the device was implanted. As is evident from the table, we have worked with a number of cochlear implant devices (UCSF experimental, UCSF/Storz, 3M/Vienna and 3M experimental), electrode coupling configurations (radial bipolar, monopolar and longitudinal bipolar), and number of functioning channels (from 1 to 8). In addition, we have worked with a variety of percutaneous and transcutaneous transmission systems. This experience with different types of auditory prostheses has provided important insights into prosthesis design that would have been totally missed if our work was dedicated to evaluations of patients with a single implant system. Further work with groups of patients using different prostheses will build on this experience and is expected to provide additional insights into the relative importance of different electrode coupling configurations, speech processing strategies, numbers of functioning channels, etc. As outlined in section III.B of this proposal (see subsection on "patients"), we plan to broaden the range of studied prosthesis systems to include the Symbion device (four channels, monopolar, percutaneous connector), the Nucleus device (21 lateral bipolar pairs of electrodes, transcutaneous transmission system) and the new generation of the UCSF device being developed by MiniMed Technologies (8 radial bipolar or 16 monopolar stimulus channels, highly flexible speech processor, highly transparent transcutaneous transmission system, see Wilson *et al.*, 1988c, for details).

TABLE II.C-1. Characteristics of Patients Studied by the RTI Team.

Patient[a]	Device	Electrode Coupling Configuration[b]	Transmission System	Number of Functioning Channels[c]	Implant Center[d]
LP	UCSF (experimental)	radial bipolar	percutaneous	8	UCSF
SG	UCSF/Storz	"	"	"	DUMC
MH	"	"	"	7	"
MC1	"	"	transcutaneous	3	UCSF
HE	"	"	"	4	"
JM	"	"	"	3	"
RC	"	"	"	2	"
ET	"	"	"	4	"
MC2	"	"	"	4	New Haven
HP	3M/Vienna (extracochlear)	monopolar	transcutaneous	1	WUMC
GL	3M (experimental)	longitudinal bipolar	percutaneous	6	UMMC
JS	"	"	"	7	"

[a]Patients are listed in chronological order of the major studies conducted with them.

[b]The primary coupling configuration is listed; other coupling configurations can used for studies with patients fitted with percutaneous connectors.

[c]Number of functioning channels refers to the number of available electrode stimulation channels for the listed coupling configuration. The number of functioning channels can be less than the maximum number provided by a given prosthesis due to device failures.

[d]Abbreviations for implant centers are UCSF for University of California at San Francisco; DUMC for Duke University Medical Center; New Haven for New Haven Ear, Nose, Throat and Facial Plastic Surgery Center; WUMC for Washington University Medical Center; and UMMC for University of Minnesota Medical Center.

II.D. Psychophysical Studies

In this section we will (a) describe the software and hardware we have developed for a broad range of psychophysical studies and (b) indicate the types of studies that have been conducted to date.

Software and Hardware for Psychophysical Studies

All stimuli for psychophysical and speech perception studies are delivered through an eight-channel stimulus isolation unit (Wilson and Finley, 1984). The isolation unit is designed to provide current-controlled outputs for stimulation with patients fitted with percutaneous cables. Outputs on each of the eight channels can be simultaneously updated under computer control every 50 μsec, and the linear resolution of these outputs is 12 bits (-2048 to +2047). The clock rate of updates can be increased to 60 kHz (from 20 kHz for 50 μsec updates) if the number of simultaneous updates is reduced to two. The bandpass of each channel extends from approximately 40 Hz to 30 kHz. Attenuation of frequency components below 40 Hz provides an additional safeguard (beyond the safeguards provided by the controlling software) to ensure charge balancing of stimuli delivered to the electrodes.

The stimulus isolation unit is also used for studies with patients fitted with a transcutaneous transmission system (TTS). For these studies voltage outputs are generated by placing appropriate load resistors across the current sources of the isolation unit. These voltage outputs are then buffered for use as control signals for the modulator circuits of the TTS (for amplitude-modulation systems). Custom interfaces of this kind have been constructed for studies with patients fitted with (a) the four-channel UCSF/Storz TTS or (b) the single-channel 3M/Vienna TTS. The software developed for psychophysical studies allows the specification of a wide range of stimuli and testing procedures. This software is organized around a "shell" structure so that the addition of new types of stimuli and new testing procedures is straightforward. With approximately three years of intense use and development, the original software has grown to be a mature and highly flexible tool.

The types and parameters of stimuli that can now be specified for psychophysical tests are indicated in Table II.D-1. These stimuli include single pulses, multiple pulses, pulse trains, sine bursts and noise bursts. Once specified, the stimuli can be delivered to single channels in a "manual" mode, or they can be delivered to one or more channels under the automatic control of a psychophysical testing procedure.

The procedures implemented to date include the following:

1. A transformed up/down procedure (Levitt, 1971) for converging on the 50.0 or 70.1 percent points of the psychometric function is used for determination of detection thresholds and difference limens (DLs), where tests usually are conducted in a two-alternative, forced-choice format;

2. A magnitude estimation procedure (Stevens, 1956) is used for measures of loudness and pitch (also see Shannon 1983a, 1983b and 1985a; Eddington _et al._, 1978a and 1978b; Geller and Margolis, 1984), with randomized presentations of the different stimuli in a given test;

3. A ranking procedure similar to the ones described by Eddington _et al._ (1978a and 1978b) and Townshend _et al._ (1987) is used for measures of channel discrimination and ranking, with randomized presentations of the different stimuli in a given test;

4. A loudness summation paradigm, using a magnitude estimation procedure to obtain the loudness judgments, is used for measures of simultaneous and nonsimultaneous channel interactions (see Shannon, 1983b and 1985a); and

5. Direct estimation of complete psychometric functions, with randomized presentations of stimuli across the anticipated range of a given function, for certain studies of frequency and intensity discrimination.

Psychophysical Studies Conducted to Date

The psychophysical studies conducted to date have been aimed at (a) obtaining threshold and loudness data required for the specification of speech processor parameters, (b) obtaining indirect indications of the extent and pattern of nerve survival in the implanted ear, and (c) characterizing patterns of pitch and loudness perception with monopolar and radial bipolar configurations of intracochlear electrodes. The studies to obtain threshold and loudness data for specification of processor parameters have been conducted with all patients in our series, and the studies to obtain indirect indications of nerve survival have been mainly limited to patients with percutaneous access to their implanted electrodes. These latter studies have included the following measures:

1. Simultaneous and nonsimultaneous channel interactions, providing information about the spread of intracochlear excitation. The amount and pattern of interaction across electrode combinations are functions of electrode geometry, distance between stimulating electrodes and excitable tissue, nerve survival, and variables (such as impedance changes at fluid/bone interfaces) that affect the distribution of stimulus currents within the cochlea. Correlations between measured channel interactions and nerve survival have been discussed by Gardi (1985), Merzenich _et al_. (1978), Merzenich and White (1977), Shannon (1983b, 1985a), and White _et al_. (1984).

2. Thresholds to low frequency (e.g., 100 Hz) and high frequency (e.g., 1000 Hz) sinusoids. Both thresholds to low frequency sinusoids and the ratio of the two thresholds (as expressed by the difference in dB between the thresholds) have been correlated with survival of spiral ganglion cells in the ears of test monkeys implanted with intracochlear electrodes (Pfingst _et al_., 1985). We have used the ratio measure because it provides a control for factors not related to nerve survival (e.g., electrode placement) that can affect the absolute threshold at a given frequency.

3. Dynamic ranges between threshold and uncomfortable loudness levels for sinusoidal and pulsatile stimuli. Low dynamic ranges have been correlated with poor survival over the stimulating electrodes in the studies of Pfingst _et al_. (1981, 1985) and Pfingst and Sutton (1983).

4. Differences in thresholds for monopolar and radial bipolar stimulation with the UCSF electrode array. This difference is likely to be large (e.g., greater than a factor of three) in cases of poor survival over a pair of radial bipolar electrodes (Merzenich _et al_., 1978; Merzenich and White, 1977). That is, the difference in current levels required for stimulation of nearby and distant neurons is much greater with the spatially-selective radial bipolar configuration than with the far less selective monopolar configuration (Merzenich and White, 1977; van den Honert and Stypulkowski, 1987). Therefore, the difference in thresholds obtained with these two electrode configurations is probably a good indicator of local survival in that small differences may reflect good survival near the radial bipolar pair and large differences may reflect poor (or no) survival locally.

Finally, as mentioned above, a third group of psychophysical studies was aimed at characterizing patterns of pitch and loudness perception with different electrode coupling configurations. These studies were conducted with one of our percutaneous cable patients (MH) and the results demonstrated some striking differences in the patterns of pitch percepts reported by this patient under conditions of monopolar and radial bipolar stimulation with the UCSF electrode array. In particular, the repetition frequency of pulsatile stimulation was a much more salient cue for pitch with the monopolar coupling configuration than with the bipolar configuration, while the site of intracochlear stimulation generally had only minor effects on pitch judgments. The latter cue did affect pitch judgments--in a complex way--for selected channels among the bipolar electrodes. Judgments of pitch also were strongly dependent on the intensity of stimulation for certain electrode channels and stimulation frequencies for both coupling configurations. In fact, the intensity of stimulation in many cases was a more salient cue for pitch than either the stimulation frequency or the site at which the stimuli were delivered. In all such cases increases in stimulus intensity produced increases in perceived pitch. This "covariance" between intensity (or the percept of loudness) and pitch has been noted by other investigators (e.g., Simmons et al., 1979). It presents an obvious problem for speech processors that attempt to represent the frequency content of an acoustic input by the frequency and/or site of intracochlear stimulation. Clearly, this representation will be distorted for patients who perceive large changes in pitch when the intensity of stimulation is varied.

A complete discussion of the implications of these findings for processor design is presented in the fifth quarterly progress report for our current project (Wilson et al., 1986b). Details of the experimental methods and all results are also presented in this report. Results from preliminary studies with other patients suggest that the apparent dependence of pitch on intensity of stimulation is highly variable across patients (and across electrode channels within patients). Indeed, some patients have moderate decreases in pitch with increases in intensity and some patients have stable pitch percepts over the entire useable range of intensities (i.e., these patients exhibit no covariance between pitch and intensity). We plan a systematic investigation of the dependence of pitch on the intensity, frequency and site of intracochlear stimulation in greater detail and with more patients as part of the proposed project. We also plan to investigate in greater detail the large differences in the patterns of pitch percepts obtained under conditions of monopolar and radial bipolar stimulation. These latter studies will of course require patients implanted with devices that allow such manipulations in the coupling configuration.

Table II.D-1. Basic stimuli produced by the psychophysical test software.

Stimuli	Adjustable Parameters
single pulses	- waveshape (balanced biphasic pulses, with either polarity leading; or charge-balanced, "monophasic-like" pulses, with a short duration, high intensity initial phase and a long duration, low intensity second phase) - duration (duration of either phase can be adjusted between 0.033 and 10.0 msec; the durations of both phases are of course equal for balanced biphasic pulses) - amplitude (can be adjusted between 0.0 and 1.0 mA, with a linear resolution of 11 bits)
multiple pulses	- waveshape, duration and amplitude of the individual pulses, as above - number of pulses in the sequence (minimum is 2) - duration of the interpulse interval (can range from 0.033 to 100.0 msec)
pulse trains	- waveshape, duration and amplitude of the individual pulses, as above - pulse repetition frequency, between 1.0 Hz and the reciprocal of the total duration of both phases of the individual pulses - duration of the pulse train (range is between the duration of a single pulse and 660 msec) - rise/fall time of the leading and trailing portions of the pulse burst envelope (a raised cosine window is used, and the rise/fall time can range from zero to half the duration of the pulse burst)
sine bursts	- peak amplitude (between 0.0 and 1.0 mA) - frequency of the sinusoid (between 10 Hz and 10 kHz) - duration of the sine burst (from the duration of one sinusoidal cycle to 660 msec) - rise/fall time (from zero to half of the burst duration)
noise bursts	- peak amplitude (between 0.0 and 1.0 mA) - frequency content (pink or white noise can be specified, and this noise can be optionally filtered with low pass, high pass or band pass filters of adjustable frequencies) - burst duration (up to 660 msec) - rise/fall time (from zero to half of the burst duration)

II.E. Development of a Real-Time Bench Processor for the Cochlear Implant Laboratory at Duke

Our ability to study a patient in our laboratory, evaluate his or her performance with a wide range of different processing strategies, approach optimal configurations for the most promising such strategies, and evaluate their performance in some detail--all during a single week's visit--is the result of two distinct devices developed by us under previous NINCDS contracts.

These devices are: (1) a highly general Block Diagram Compiler that can be configured rapidly for practically any definable processor design and used to preprocess recorded speech samples for patient testing, and (2) a Real-Time Bench Processor that can realize a range of processors within a particular limited class of designs and allow live voice testing as well as the use of extensive recorded materials without any delay for preprocessing.

The block diagram compiler can make available limited testing material, vowel and consonant confusion tokens for instance, with delays after conception of a processor design ranging from half an hour to several hours, depending on design complexity. Different processor configurations presently can be developed, tested, and verified for the real-time bench processor within a few hours. Such configurations are purely in the form of software and, once prepared, can be substituted in the real-time processor hardware within a few seconds.

The block diagram compiler, the earlier of these two crucial devices to be developed in our laboratories, has been described in detail in a progress report under NIH project N01-NS-3-2356 (Wilson et al. 1985a). Details on the evolving architecture and capabilities of our real-time bench processor, beyond the outline to follow, may be found in progress reports under our present NIH project N01-NS-5-2396 (Finley et al. 1986,1987).

General design criteria for the real-time bench processor have included the following:

(a) full implementation of interleaved-pulses processing strategies, including those that code explicit voicing information;

(b) broad flexibility that accommodates a wide range of processor designs, both parametrically and architecturally;

(c) functional approximation to what would be expected for a final portable design;

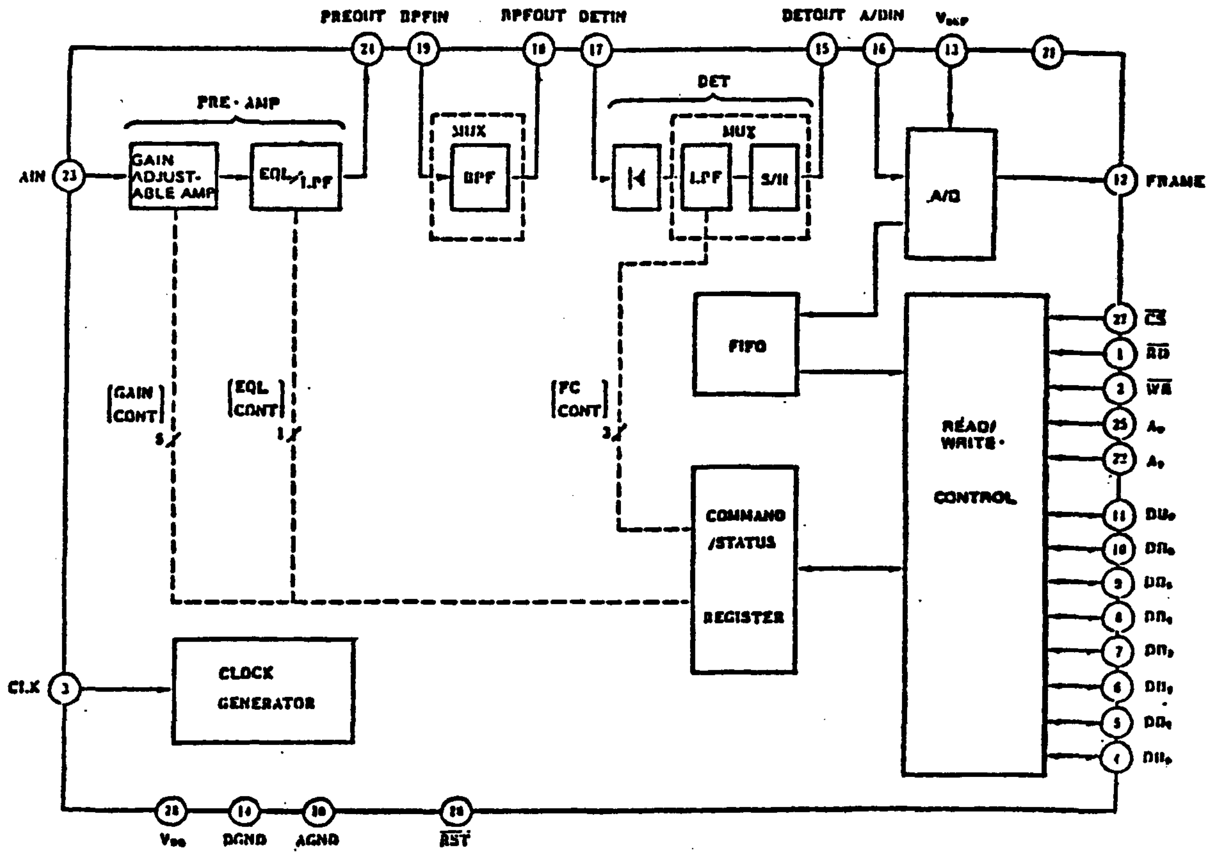
(d) electrical specifications including a minimum of 8 bits of stimulus resolution, 100 usec temporal resolution, current driver outputs with + and - 10 volts voltage compliance;

Of course, safety concerns are of extreme importance. At all levels of hardware and software design and construction safety and reliability have been emphasized.

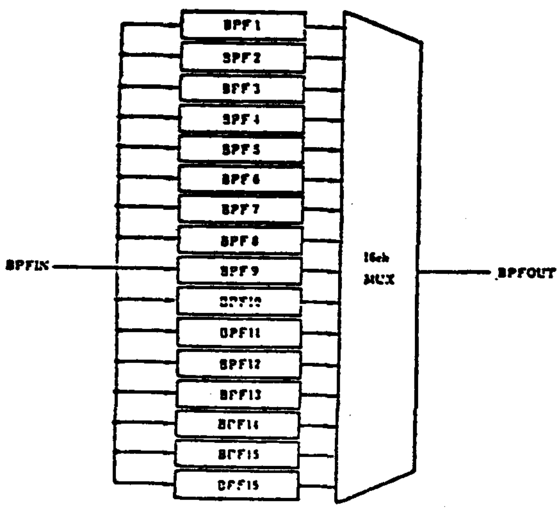
Specialized Hardware

Only in recent years has the state of the art of electronics developed to a point where portable, battery-operated implementation of complex signal processing strategies, such as the interleaved-pulses processor, has been feasible. This is largely due to development of large scale integrated circuits which utilize fast, low-power CMOS technology. Two circuits incorporating these advances were selected for this device. One is a microprocessor-compatible speech analysis chip for speech recognition systems that features a band-pass filter bank with RMS outputs. The other is a high speed programmable microprocessor that implements the post processor logic. Each of these devices is described briefly below.

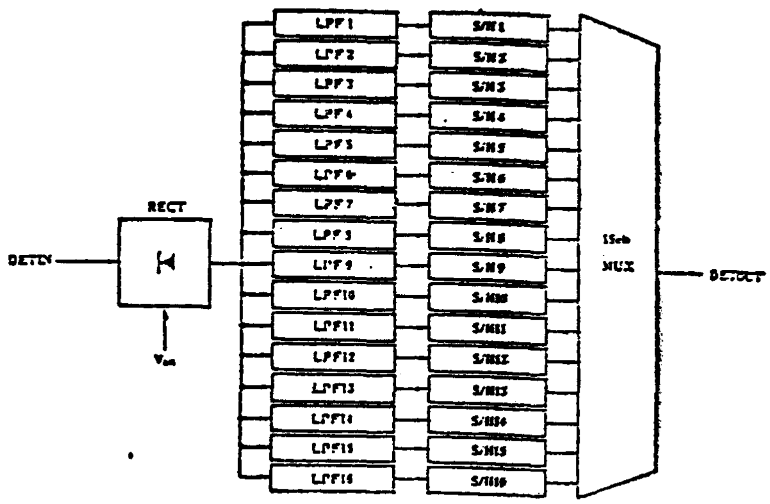
Filter bank analysis with RMS outputs is achieved with a single uPD7763D NEC speech analysis chip designed for speech recognition systems (Figure II.E-1a). The uPD7763D incorporates a programmable pre-amp with optional equalizer, a 16-channel switched-capacitor band-pass filter bank (Figure II.E-1b), a multiplexed rectifier with switched-capacitor low-pass filters and sample and hold (S/H) outputs (Figure II.E-1c), and an 8-bit analog to digital (A/D) converter in a single LSI/CMOS 28-pin package. The uPD7763D has a general purpose microprocessor interface which provides access to a first-in, first-out (FIFO) buffer containing digitized RMS outputs of band energies. Pre-amp gain (-13.5 dB to +33.0 dB), equalizer ON/OFF, analyzed frame period (1-32 msec) and low-pass filter cut-off frequency (12.5 Hz - 400 Hz) are controlled via the microprocessor interface. Analysis proceeds on a frame-by-frame basis with RMS levels for each band-pass during the previous frame being available in a FIFO buffer. A frame period signal is available as an external interrupt signal to the



(a) Block diagram of uPD7763D NEC speech analysis chip.



(b) Switched-capacitor filter bank with multiplexed output.



(c) Multiplexed RMS extractor featuring rectifier, low-pass filters and multiplexed S/H buffered outputs.

Figure II.E-1. Functional components of NEC uPD7763D speech analysis circuit.

post-processor, which may then read the memory-mapped FIFO buffer. The uPD7763D typically consumes 175 mWatts of power (350 mWatts maximum). It offers in a compact package a remarkably powerful set of speech analysis resources that would otherwise take considerable effort and expense to develop.

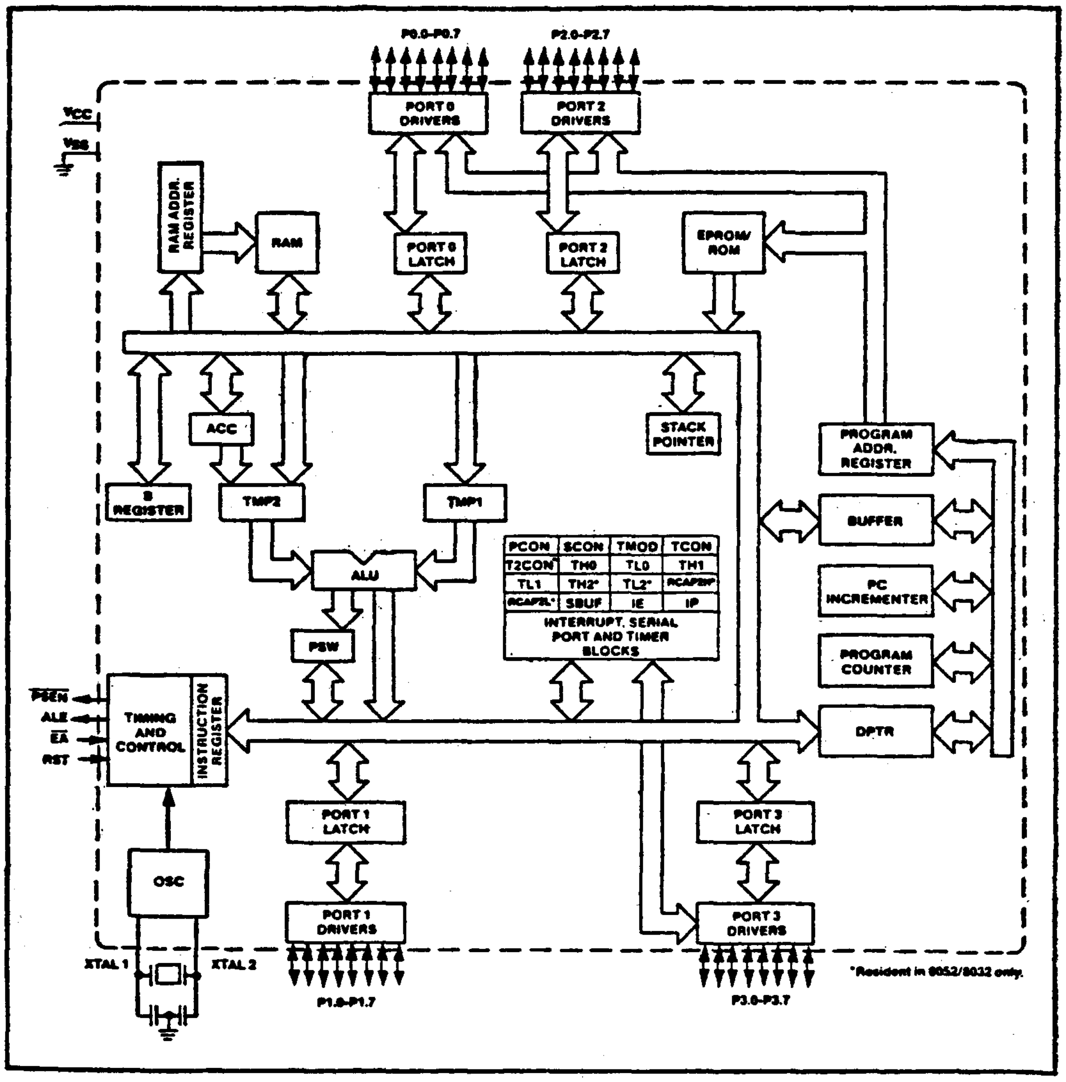
The post-processor is an Intel 8031 8-bit microprocessor (Figure II.E-2). This device features two 16-bit programmable timers with interrupt capability along with two external interrupt lines. The 8031 has 128 bytes of onboard RAM and can address 64k bytes of external program memory and 64k bytes of external data memory. Thirty-two programmable I/O lines and an asynchronous serial port are available. A hardware multiplication and Boolean processing capability are also provided. This processor is available in CHMOS technology as the 80C31. The 80C31 additionally offers two software selectable power down/idle modes for minimization of power consumption. In the powerdown mode the processor clock is turned off, whereas in the idle mode the interrupt, asynchronous serial input, and onboard timer operations continue to function. At 12 MHz clock operation (1 usec instruction period, typical), the 80C31 consumes 80 mW of power at full operation and 22.5 mW of power when idled.

POST PROCESSING AND SOFTWARE ARCHITECTURE

Software Organization

Post-processor functions for the six-channel, interleaved-pulses processors include:

- read the RMS energy estimates for the sixteen frequency bands from the filter bank FIFO levels;
- appropriately scale RMS energy estimates as implementation of the front-end, 1200 Hz high-pass filter;
- condense these sixteen band energies down to the required six band energies for the six-channel processor;
- determine if unvoiced speech energy is present;
- sort the six band energies into rank order by energy;
- sort the four maximum energy ranked channels into specific base-to-apex order for cyclic stimulation;
- construct stimulation cycle output buffer information by defining temporal and amplitude stimulus features for each channel from a previously-defined lookup table;
- output the current stimulation cycle information based on the presence of voiced or unvoiced energy;



- **Power Control Modes**
- **128 x 8-Bit RAM**
- **32 Programmable I/O Lines**
- **Two 16-Bit Timer/Counters**
- **64K Program Memory Space**
- **High Performance CHMOS Process**
- **Boolean Processor**
- **5 Interrupt Sources**
- **Programmable Serial Port**
- **64K Data Memory Space**

Figure II.E-2. Block diagram of INTEL 80C31 8-bit microcontroller.

- perform pitch extraction doing peak-picking detection of voiced energy;

Post-processor software organization has been structured to take advantage of the hardware interrupt and timing features of the 80C31 microprocessor. Two independent timers are used to drive interrupt service routines which operate at different priority levels. Figure II.E-3 summarizes the software organization and subsequent sections describe each software activity in more detail.

At first (highest) priority is the Stimulus Output Interrupt Task driven by timer 0 at 100 usec intervals. This task controls the loading of the output channel DACs with appropriate stimulus level information at appropriate times as defined by the stimulation cycle buffer. Software flags from the pitch extractor and the unvoiced speech energy detector are used to determine when to initiate a stimulation cycle. The DAC buffers are latched, permitting the service routine to encode only changes in the output data, thereby greatly reducing software overhead and freeing computing resources for lower priority tasks.

At second priority is the Pitch Extraction Interrupt Task driven by timer 1 at 500 usec intervals. This task performs peak picking of F0 frequency information to detect pitch pulses. If a pitch pulse is detected, the Stimulus Output Interrupt Task is informed by the setting of a software flag.

All remaining processing is done on a background, non-interrupt basis. After an initial setup phase to establish the interrupt structure and preset required variables, the background task operates in a fast loop, checking for a frame signal from the NEC chip. If a NEC frame signal is detected, the NEC Service Routine is called which (1) reads current spectral information from the NEC chip, (2) determines if unvoiced speech energy is present, (3) computes the stimulation cycle information and stores it in an external RAM buffer, and (4) at the appropriate time loads the new stimulation cycle information into an internal RAM buffer for fast output by the Stimulus Output Interrupt Task.

Spectral Energy Estimation

The basic computation for spectral energy estimation consists of adding together RMS energy estimates for various combinations of bands from the NEC speech analysis chip. As described previously, the NEC chip performs analysis across sixteen bands, spaced roughly as adjacent critical bands for

SOFTWARE ORGANIZATION

Start up

- set stack pointer
- zero DACs
- do self check

- setup timer 0
- setup timer 1
- setup NEC chip

- preset miscellaneous flags

Background Task

- check for FRAME signal from NEC
  if so, call NEC Service Routine

  otherwise, loop back

Stimulus Output Interrupt Task

Priority 1 interrupt driven by timer 0
(100 usec service interval, 10 kHz)

- checks Stimulation Cycle timing and drives channel DACs with information in Stimulation Cycle Data Buffer in internal RAM

Pitch Extraction Interrupt Task

Priority 2 interrupt driven by timer 1
(500 usec service interval, 2 kHz)

- performs peak picking of F0 frequency information to detect pitch pulses

NEC Service Routine

effectively Priority 3, called by Background Task after FRAME signal from NEC chip is detected (8 msec interval)

- computes current spectral information
- makes voice/unvoiced interval determination
- orders all 6 channels by energies
- orders max 4 energy channels by channel
- computes pulse heights, channel nos., duration and real-time timing for next Stimulation Cycle and loads data buffer in external RAM

- waits for current Stimulation Cycle to end and then transfers external RAM buffer to internal RAM buffer
- return

Figure II.E-3. General software organization for post processor.

normal hearing. However, the interleaved-pulses processors require energy estimates from a smaller number of logarithmically spaced bands. Figure II.E-4 shows the -3 dB break frequencies for the sixteen NEC analysis bands that span the spectrum from 146 Hz to 5756 Hz. Band 1 (146 - 340 Hz) is not used in the spectral analysis since energy in this band is predominately fundamental voicing energy, F0. Therefore, only outputs from 340 Hz to 5756 Hz, bands 2 through 16, are used from the NEC chip. Figure II.E-4 also shows the desired frequency breaks for speech processors using from two to eight logarithmically spaced bands between 340 and 5756 Hz. Shown in parentheses beneath the frequency breaks for each processor are the NEC bands combined to approximate each processor band. While the NEC band combinations do not produce exactly logarithmically spaced bands, the approximations are fully adequate.

In combining the energy estimates across several NEC analysis bands, attention must be given to the possibility of roll-over of the eight bit registers during addition. Scaling of individual energy estimates prior to addition is presently being used to avoid roll-over and maximize speed. Double precision addition with post division is more accurate, but is computationally more involved and therefore slower. Future versions will probably use the latter approach.

Detection of Unvoiced Speech Energy

During each frame period while reading new spectral data from the NEC chip, a test is performed to determine whether unvoiced speech energy is present. This test requires computation of the ratio of high frequency energy (1560 - 5756 Hz) to low band energy (340 - 732 Hz) and comparison of the result to a preset threshold level. If the computed ratio exceeds the reference level, unvoiced speech sounds are considered to be present thus triggering either maximum rate or jittered rate presentation of the stimulation cycles. Since the stimulation cycle output codes the current spectral information onto the output channels, abrupt increases in the output frame rate simply accentuate the high frequency spectral information associated with the unvoiced components of speech. Brief maximum rate bursts are often perceived as noise-like as well, which is consistent with the classical vocoder technique of injecting noise instead of voicing energy during unvoiced speech intervals.

High band energy is computed by combining NEC band energies 8 - 16. Low band energy is computed by combining NEC band energies 2 and 3. The ratio test is implemented by a look-up table which is precomputed assuming a fixed threshold ratio. In using the table, the high band energy value is

NEC band	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
-3 dB freq Hz	146 340 536 732 927 1146 1366 1560 1780 2049 2366 2683 3073 3512 4073 4878 5756
8 band processor	340 484 690 982 1399 1992 2838 4041 5756
	(2) (3) (4) (5-6) (7-9) (10-12) (13-14) (15-16)
7 band processor	340 509 763 1143 1712 2565 3842 5756
	(2) (3) (4-5) (6-8) (9-11) (12-14) (15-16)
6 band processor	340 545 873 1399 2242 3592 5756
	(2) (3-4) (5-6) (7-10) (11-13) (14-16)
5 band processor	340 599 1054 1856 3269 5756
	(2) (3-4) (5-8) (9-12) (13-16)
4 band processor	340 690 1399 2838 5756
	(2-3) (4-6) (7-12) (13-16)
3 band processor	340 873 2242 5756
	(2-4) (5-10) (11-16)
2 band processor	340 1399 5756
	(2-6) (7-16)
NEC band	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Figure II.E-4. NEC Bandpass Break Frequencies showing band combinations for eight to two band interleaved-pulses processors.

used as the table index. The corresponding table entry is the low band energy value required to achieve the threshold ratio. The current low band energy value is compared to the value returned from the table. If the current low band energy is less, then unvoiced speech energy is detected and a flag is set. The actual stimulus output due to the detection of the unvoiced speech energy does not begin until (1) the current stimulation cycle is completed, (2) the latest stimulation cycle information has been loaded into the internal RAM output buffer, and (3) the Stimulus Output Interrupt Task has recognized the unvoiced speech energy flag in that order.

The ratio value presently used for unvoiced speech energy detection is 1.0, given that the NEC gain block equalization is enabled. Of course a ratio of 1.0 makes the ratio comparison trivial, not requiring the look-up table operation described above. The ratio test originally was designed for speed, to avoid a time consuming division procedure and yet provide for fine resolution of threshold ratio values. The present ratio value of 1.0 provides for unvoiced speech energy detection for a male speaker in the absence of background noise. Further ratio evaluation is needed for female and young speakers, as well as for noisy conditions.

Stimulus Train Generation

Generation of the output stimulus train is a two stage process. First is the calculation of the stimulus features of the stimulation cycles, based on spectral information from the NEC chip during the current cycle period. Second is the utilization of the stimulation cycle information to generate the output stimulus sequence on the appropriate output channels.

To facilitate discussion, the characteristics of the stimulation cycles are described now in greater detail. Figure II.E-5 shows a single stimulation cycle for an interleaved-pulses processor. This particular stimulation cycle is one that typically might be used for a patient who has good neuronal survival, manifested by low electrical thresholds and low channel interactions. Charge-balanced, biphasic pulses are used for each channel. In this case the biphasic pulses are short duration (200 usec/phase) and are temporally staggered across channels with short delays (100 usec interpulse time). In general, the pulse durations are chosen to be as short as possible yet maintain a stimulus amplitude within the operating limits of the output driver stage that can produce a MCL level percept with a 100 Hz rate, 300 msec duration pulse train. Pulse durations may differ between channels. Timing delays between pulses delivered across channels is a function of the temporal interaction time constants of the channels. Optimal times are 100 usec but can range out to 1.0 msec in poor

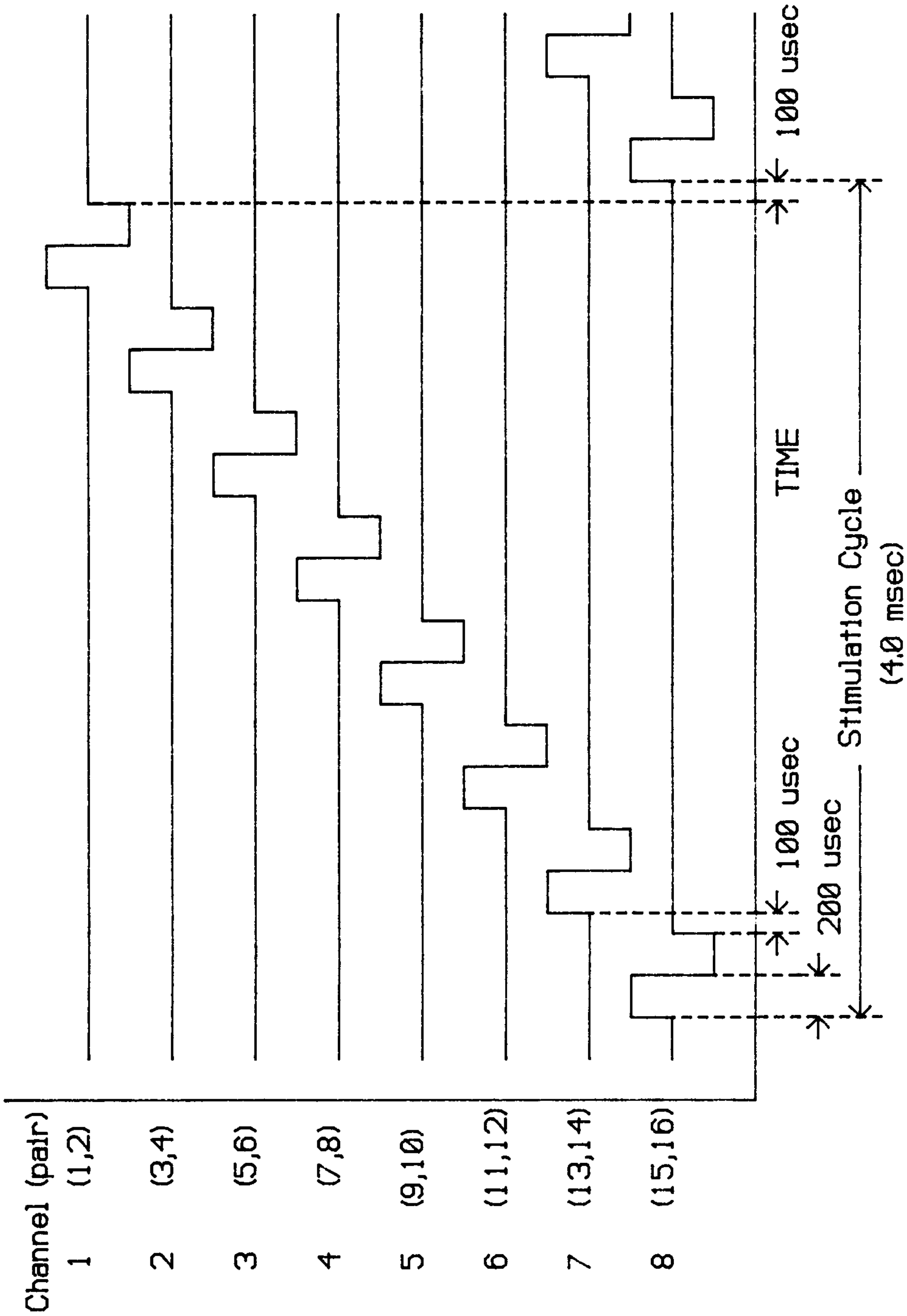


Figure II.E-5. Output timing sequence for one stimulation cycle using short duration, biphasic pulses on all eight channels.

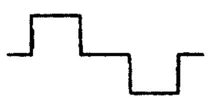
cases with very interactive channels. As seen in Figure II.E-5, eight channels are stimulated in a base-to-apex order (electrode pair [15,16] is the most basal bipolar pair with pair [1,2] being the most apical pair). The stimulation cycle shown in Figure II.E-5 describes a relatively simple set of stimulus characteristics that would be used with an uncomplicated, good neuronal survival patient.

The stimulation cycle characteristics can change significantly for poor survival patients. These patients typically have high electrical thresholds, large channel interactions and often experience pain in conjunction with their auditory percepts. Generally high electrical thresholds force selection of long duration stimulus pulses to obtain the desired MCL level percepts. Large channel interactions lead to selection of long interpulse intervals to obtain release from interactions. Finally, in order to avoid painful stimulation and to further reduce channel interactions, manipulation of pulse wave shapes and polarities often is required.

Candidate waveshapes must maintain charge balancing. The following pulse types are prime candidates for use in interleaved-pulses processors:

balanced biphasic

asymmetrical, balanced biphasic



split, balanced biphasic

split, asymmetrical, balanced biphasic

Not shown are the reversed polarity conditions of each pulse shape. Wave shape and timing selection are made on a channel-by-channel basis and thus may differ among channels. No effort is made at this point to discuss the physiological basis for selecting a particular stimulus shape or timing. The purpose here is to show the diversity of the stimulus characteristics that may be needed among patients using interleaved-pulses processors.

Further complicating the design of a stimulation cycle is the experimental observation that interleaved-pulses processors produce better constant confusion matrix scores if the total stimulation cycle duration is held to 4 - 5 msec. This is achieved easily for the good survival patient; however, it is not achievable directly for the poor survival patient whose stimuli must be generally of longer duration. To accommodate this requirement the stimulation cycle design is further modified in two ways to minimize the total cycle duration.

The first method is to re-evaluate interaction characteristics once channel pulse shapes have been selected based on MCL measures and freedom from painful stimulation. Experience has shown that with selection of asymmetrical, balanced biphasic pulses, channel interactions may be dramatically reduced. This may make it possible to present stimulation on adjacent channels simultaneously, thus reducing the stimulation cycle duration.

The second method is to stimulate only the channels which at that point in time contain the maximum RMS spectral energies. In this manner, each cycle may represent only 7 of 8 or 4 of 6 (as in Fig. II.E-3) or any such combination of channels with maximum RMS energies. The combination of selected channels may change dynamically from cycle to cycle.

Pulse amplitudes are specified on a channel-by-channel basis from a logarithmic mapping law of the form:

for RMS level > or = to RMS_{thres}

pulse amplitude = A x Log(RMS level) + k,

otherwise,

pulse amplitude = 0

where the parameters "A", "k" and "RMS_{thres}" have been specified for each channel according to the threshold, MCL levels and noise levels for each channel.

Once the characteristics of a stimulation cycle have been defined, its presentation to the electrodes must be executed. This requires identifying when output of a stimulation cycle should begin, followed by the generation of the specified waveforms on the appropriate channels. In all cases, once the presentation of a stimulation cycle has been initiated, it is always fully presented across all appropriate channels at the specified timing. At that point, another decision may be made as to the timing of the next stimulation cycle presentation. In the case of the interleaved-pulses processor that codes voicing explicitly, this decision is two-fold. Stimulation cycles are timed to start in synchrony with the fundamental frequency (F0) during voiced speech sounds and at either randomly-spaced or maximum-rate intervals during unvoiced components of speech.

The real-time speech processor software accomplishes the tasks of defining the stimulation cycle and then outputting it by exploiting the interrupt structure of the microprocessor. The background NEC Service Routine computes the stimulation cycle characteristics every 8 msec and buffers the results temporarily in the external RAM. The NEC Service Routine then pauses until the Stimulus Output Interrupt Task has completed presentation of the current stimulation cycle, at which point the Service Routine transfers the external RAM buffer into an internal RAM (on-chip) buffer and signals that the internal RAM buffer has been loaded. The NEC Service Routine then returns to the Background Task. Once the internal RAM buffer has been loaded, the Stimulus Output Interrupt Task, operating at highest priority with 100 usec interrupts driven by timer 0, outputs the stimulation cycle information to the appropriate channels. Figure II.E-6 outlines the organization of the Stimulus Output Interrupt Task.

Specification of stimulation cycle characteristics in the buffers is greatly simplified by the use of latched DAC's on the output drivers for each channel. This allows coding only of changes in the data to each channel. Each stimulus change is fully specified by giving the channel number, the amplitude value to change to and the time at which the change is to occur. Timing information is specified relatively in 100 usec intervals since the last stimulus change. The timing information is used simply to load an interval counter that is decremented once for each 100 usec interrupt. If it reaches zero, the appropriate channel is set to the specified level and the counter is again loaded to begin timing out the next interval. Upon reaching the end of the stimulation cycle, stimulus outputs are stopped, unless unvoiced components of speech have been detected. If so, the interval counter is loaded with zero to initiate maximum-rate stimulation or with a random table value to initiate jittered-rate stimulation depending upon the processor design.

Pitch Extraction

The extraction of voice pitch is a basic problem for all speech processors that explicitly encode voicing. Although useful solutions to this problem have been demonstrated, many of the methods employed for pitch extraction are too complex for analysis of speech in real-time devices. Included among these methods are (1) identification of high-frequency peaks in cepstrum representations of speech, (2) identification of periodic peaks in the autocorrelation function of speech that has undergone "spectral

<u>Stimulus Output Interrupt Task</u>

priority 1 interrupt driven by timer 0
(100 usec service interval, 10 kHz)

- if within stimulation cycle, continue with stimulation cycle service
- if internal RAM data buffer is being loaded, then **<u>EXIT with no output</u>**
- if UNVOICED speech energy flag is set, then check if it's time to start a new stimulation cycle.
  If not time, <u>EXIT with no output</u>.
- if PITCH PULSE FLAG set, then clear PITCH PULSE FLAG and reset begin a stimulation cycle immediately
- otherwise, <u>EXIT with no output</u>.

<u>Stimulation cycle service</u>

- decrement timer counter
- if it is time for next event then
  write DAC value to appropriate channel
  and load timer counter with counts to
  next event in stimulation cycle.
- if it is end of stimulation cycle, then reset for new start
  otherwise, **<u>EXIT without change in output conditions</u>**.

Figure II.E-6. Stimulus Output Interrupt Task Organization flattening," and (3) identification of pronounced discontinuities in the residual error after linear predictive analysis of speech signals.

One attractive variation of the autocorrelation method is the Average-Magnitude Difference-Function (AMDF) which can be implemented in real time (Ross et al., 1974; Un and Yang, 1977). The AMDF algorithm is a robust approach and offers good performance in poor signal to noise ratio environments (Paliwal, 1983).

For the present design, however, an alternative approach using an analog, peak-picking strategy was taken. It was felt that the the analog approach could be implemented more quickly than the AMDF approach. The analog approach also would conserve the 80C31 microprocessor computation resources for the needs of the post-processor until more experience could be gained with the interleaved-pulses strategy itself.

The analog pitch extractor relies on a relatively simple method of nonlinear processing to accentuate and then detect recurring peaks in the waveforms of speech. In any periodic waveform there exists, by definition, one highest peak that is repeated in each period. If the peak is sufficiently large compared to other peaks in the period, it is possible to accentuate and then detect this peak with nonlinear shaping and analysis of the speech signal (Dolansky, 1955; Filip, 1969; and Gruenz and Schott, 1949). The circuit used for nonlinear processing of speech is illustrated in highly schematic form in Figure II.E-7a. Waveforms present in two stages of nonlinear processing are shown in Figure II.E-7b. for typical inputs of voiced speech. As can be appreciated from Figure II.E-7, an input signal will charge capacitor C_1 when the diode of the input circuit is forward biased. When the magnitude of the input signal falls below the voltage present across the capacitor, the diode is reverse biased and ceases to conduct the input signal to the capacitor. During this period the capacitor will discharge through the low impedance path of R_1. This exponential decay of charge is shown in Figure II.E-7b as the dashed lines that are superimposed on the input waveforms (panels a and c), and as the outputs of the first and second "detectors" (panels b and d). The process of charging and discharging capacitor C_1 is repeated every time the voltage at the input exceeds the voltage across the capacitor. Thus, for the input waveforms shown, there are two charge-discharge cycles per period for "low-pitch" waves where a strong second harmonic is present, and one charge-discharge cycle per period for "high-pitch" waves where the second harmonic is relatively small.

Additional processing of the signal is performed by the differentiating circuit of C_2 and R_2. This circuit emphasizes the peaks extracted by the

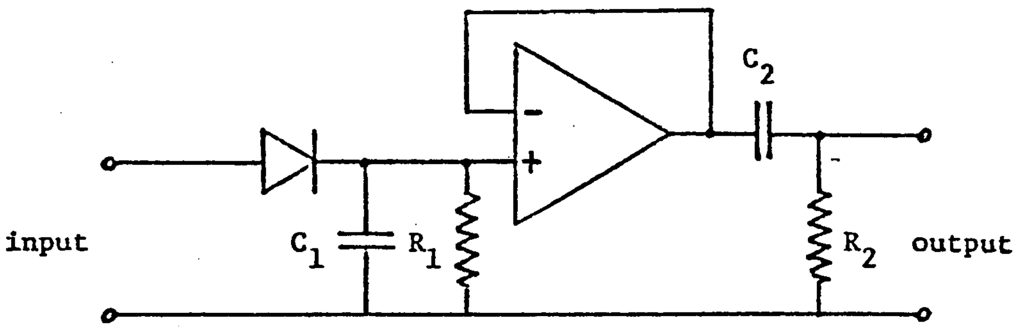


Figure II.E-7a. Circuit used for nonlinear waveshaping.

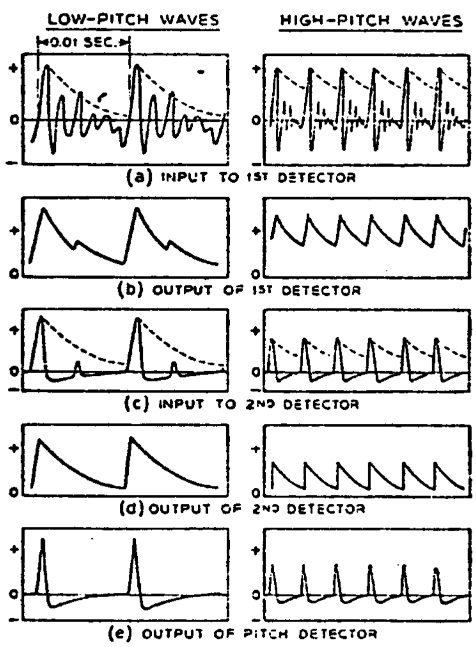


Figure II.E-7b. Steps in the detection of periodic peaks in speech signals (taken from Gruenz and Schott, 1949).

input circuit and removes the dc component from the signal across C_1. Typical results of wave shaping by C_2 and R_2 are shown in Figure II.E-7b as the input to the second detector (panel c) and as the output of the pitch detector (panel e). The unity-gain amplifier in Figure II.E-7a provides isolation between input and output circuits.

Two problems associated with this general method of pitch extraction are that "major" peaks in the quasi-periodic waveforms of voiced speech are rarely equal in height and that "minor" peaks often take on major proportions. False indications of voice pitch can be minimized, however, by careful selection of the time constants for the integrator and differentiator circuits, by cascading pitch extractors as shown in Figure II.E-7b, and by analyzing both the positive and negative halves of the speech wave for periodicity detection (Filip, 1969). The optimum time constant for the integrator is a function of the expected range of voice pitch and the relative magnitudes of major and minor peaks in the speech waveform. If the time constant is too great, the pitch extractor will "skip" major peaks that follow peaks of slightly greater amplitude, and if the time constant is too small, the extractor will fail to discriminate major from minor peaks. Experiments have shown that the optimum time constant for analysis of typical speech waveforms is in the range of 4.5 to 5.0 ms.

The optimum time constant for the differentiator circuit is a function of the maximum slope of the voltage waveform across C_1, noise content of the input waveform, and available gain to offset the attenuation encountered in the process of differentiation. Because the maximum slope and noise content of the signal presented to the differentiator are different in succeeding stages of pitch extraction, the optimum time constant is different for each stage. In general, the optimum time constant for the differentiator is less than the optimum time constant for the integrator.

A pitch extractor using this approach has been included in the laboratory model of a speech-analyzing lip-reading aid for the profoundly deaf (Cornett et al., 1978).

The performance of the pitch extractor has been evaluated using both sinusoidal and speech inputs. The dynamic range of the intensities over which the instrument will reliably extract the fundamental frequencies of sinusoids is a maximum of 26 dB at 65 Hz. False indications of pitch doubling and pitch halving are occasionally found during rapid transitions in voiced speech waveforms. The accuracy and dynamic range of the pitch extractor can be improved by (1) squaring or cubing the input signal (Sondhi, 1968), (2) center clipping the input signal (Sondhi, 1968), (3) adding an automatic gain control, and (4) processing the output signal with error logic.

Implementation of this analog peak-picking strategy has been done by simulating the strategy mathematically in software. The speech signal is low-pass filtered at 400 Hz and sampled at a 2 kHz rate. The signal is then center clipped and squared (Sondhi, 1968). Then, two-stage peak picking, as described above, is applied to the positive and negative signal peaks separately. Positive and negative peak information is then combined and further processed to eliminate frequency doubling. Whenever a pitch pulse (positive or negative) is identified a pitch pulse flag is set and a time-out interval of 2 msec is started and the pitch pulse magnitude is saved. If a second pulse is detected and the time-out interval is in effect, the magnitude of the pulse is compared to the previous pulse magnitude. If the new pulse is larger, then the time-out interval is reset for a full 2 msec again. If the new pulse is smaller, its occurrence is ignored. Once the time-out period expires, the next identified pulse (positive or negative) starts the process over. This post processing forces the pitch extractor to lock temporally to the largest pitch pulse, regardless of polarity.

Stimulation Output

All outputs from the real-time bench processor are delivered to the eight-channel stimulus isolation unit described in section II.D. above (Wilson and Finley, 1984). That unit can provide either current-controlled outputs for direct stimulation via percutaneous cables, or control voltages for the modulator circuits of transcutaneous transmission systems.

II.F. Development and Application of a Portable Speech Processor for Multichannel Cochlear Prostheses

In parallel with our design of a real-time bench processor, as outlined in the previous section, and in the light of our experience with its clinical application, we have developed a Portable Real-Time Processor. Viewed as an intermediate step between the Phase I bench device and an eventual Phase III marketable design, the evolving Phase II device described briefly in this section reflects both our present needs for investigational flexibility and our anticipation of future constraints on packaging size, power consumption, *et c.* More detailed information regarding this device may be found in a project progress report (Finley *et al.*, 1987).

The portable speech processor, as an intermediate step between the bench-level real-time processor and the final optimized portable processor, is both a prototype for the final processor and a research tool for testing advanced speech processor designs in the context of the daily activities of the patients. Since its design is closely related to that of the real-time bench processor described in section II.E. above, we shall concentrate on the distinctive elements of the portable unit in the present section. In addition to the criteria already listed for the real-time bench processor, the portable device requires:

(e) small package size to be consistent with definition of a portable unit;

(f) low power consumption so that battery size, weight and charging schedule do not interfere with daily use by patient;

(g) ease and simplicity of operation for the patient; and

(h) rapid design and production to make processors available to patients and to broaden the base of experience for the design of more effective speech processors as quickly as possible.

The NEC speech analysis chip typically consumes 175 mWatts of power (350 mWatts maximum). This level of power consumption is higher than what would be desired for a final production unit. However, this circuit is still attractive for use in the initial portable instrument described here.

It offers in a compact package a remarkably powerful set of speech analysis resources that would otherwise take considerable effort and expense to develop. Its power consumption is appropriate for a versatile portable speech processing instrument. Development of similar integrated circuits with lower power consumption may be premature until more is understood about the hardware requirements necessary for better speech processing strategies.

At 12 MHz clock operation (1 usec instruction period, typical), the 80C31 microprocessor consumes 80 mW of power at full operation and 22.5 mW of power when idled.

Figure II.F-1 shows a functional block diagram of the present portable, real-time speech processor. Central to the design is the 80C31 microprocessor that functions as the postprocessor for the system. On a common data bus the controller can access 32k bytes of EPROM and 8k bytes of RAM memory, can both control the state of and read information from the NEC speech analysis chip, and can control eight D-to-A converters for output to the electrodes. Only six output channels are used in the present design for patient MH. In addition, the microprocessor handles signals to and from dedicated hardware circuits for the operation of the automatic gain control and squelch functions and samples running speech to identify glottal pulses during voiced intervals. Finally, the microprocessor monitors the battery status, senses the mode switch position and controls front panel light emitting diode (LED) indicators to show system status. Input signals from the microphone are initially filtered, restricting them to speech spectrum frequencies. Outputs from the processor are transformer-coupled, voltage-controlled drivers instead of the more desirable current-controlled driver stages. The microprocessor operates at a 8.0 MHz clock rate.

The functional structure of both the general interleaved-pulses processor and of this portable hardware implementation may be divided into three rough stages of (i) front-end hardware processing followed by (ii) software-driven post processing culminating in (iii) output stimulation. The implementation of each of these stages in the portable processor is discussed in the following sections. Generally the portable implementation closely follows the design of the interleaved-pulses processor as described in section II.A. There are however a few modifications that have been incorporated into the portable processor design to enhance performance and obtain the same functional design as described in section II.A. These modifications are discussed briefly here.

The first modification is that a front-end 1200 Hz. high-pass filter following the AGC has been implemented in software following the band-pass filter bank. This method adds flexibility in that almost any front-end

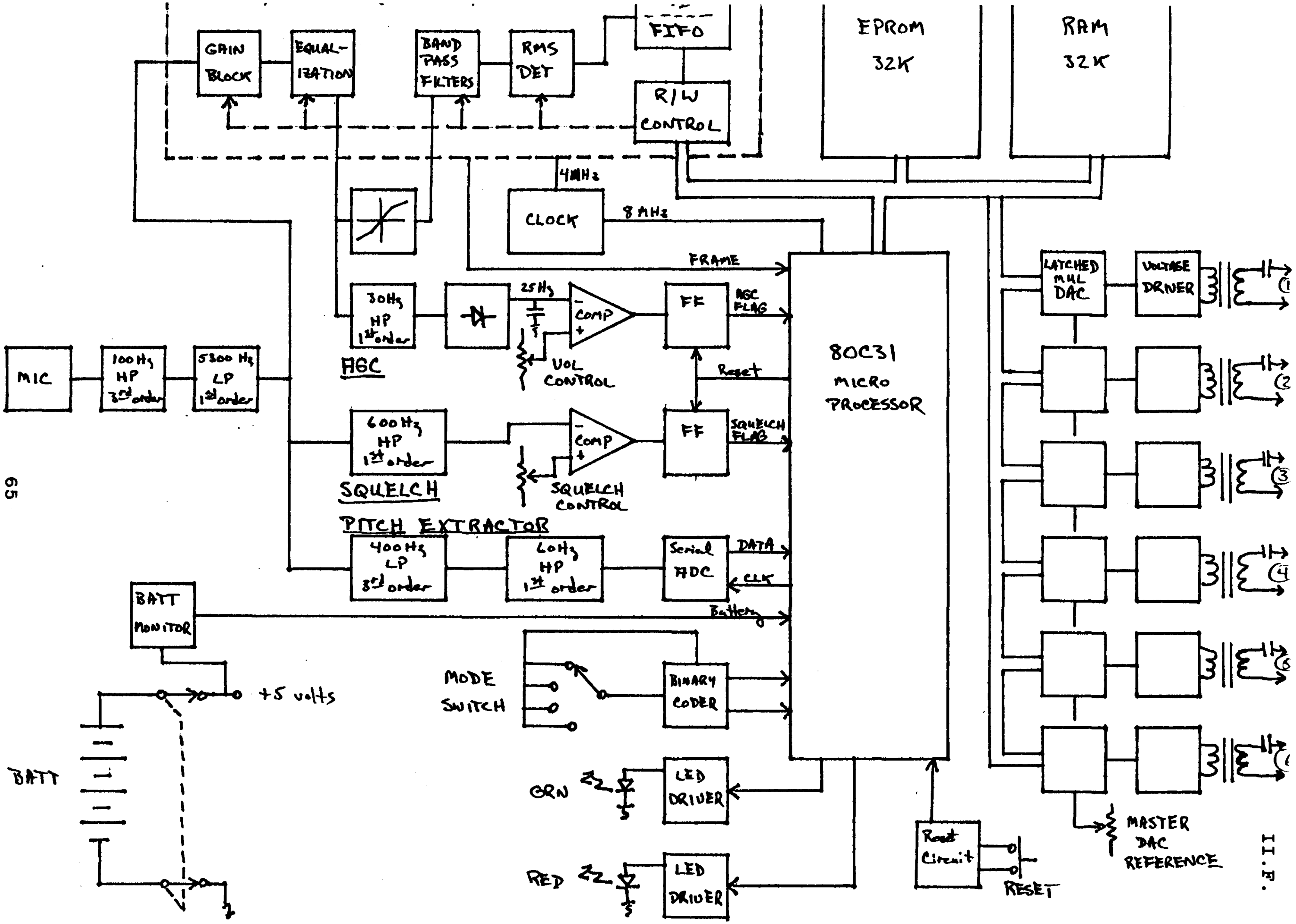


Figure II.F-1. Functional block diagram of portable interleaved-pulses processor.

filter characteristic can be easily specified in software. In addition, separate front-end hardware stages are eliminated thus saving space and reducing power consumption.

The second modification pertains to how stimuli are delivered during nonvoiced portions of speech. In the high accuracy (floating point), low noise block-diagram compiler implementation of the interleaved-pulses processor stimulation cycles are presented continually at either randomly-spaced or maximum-rate intervals during nonvoiced speech. In mapping RMS energy levels to pulse amplitudes, RMS_{thres} levels are selected so that during quiet passages output pulse amplitudes are zero. This is perfectly adequate for low noise speech, producing characteristically sparse output stimulation patterns. In the presence of noise however, continuous presentation of stimulation cycles during nonvoiced speech produces a continual low level of stimulation. When tested with such a stimulus, patient MH reports a smearing or fusion of the discrete speech sounds and consequently scores lower on confusion matrix tests. This phenomenon arises for two reasons. One reason is the higher noise levels associated with the portable processor due to both enviromental sound sources and intrinsic electrical sources within the processor itself (i.e. front end hardware noise, internal NEC chip noise). The other reason is the decreased amplitude resolution associated with 8-bit integer arithmetic of the microprocessor as compared to floating point arithmetic of the block-diagram compiler. When scaled to 8 bits, RMS_{thres} levels are typically smaller than one least significant bit level, making low level RMS band energy mapping coarse at best. To correct this problem, a separate unvoiced speech energy detector was added in software to discretely signal when stimulation cycles should be presented during nonvoiced speech. The net effect is that the portable, real-time processor outputs stimulation cycles only during voicing or when substantial unvoiced speech energy is present. Otherwise, the processor presents no output. This resolves the background noise problem and restores the stimulation cycle structure to its original sparse representation of the speech signal.

The third modification is the addition of a squelch circuit to the processor. This squelch circuit is adjusted by the patient so that noise and speech-plus-noise intervals can be discriminated by the processor. This adjustment is easily done with the patient using her own voice as a test signal. Once set the squelch is rarely adjusted, unless the patient moves into a different environment where the background noise level is substantially different. The squelch circuit makes several useful features possible. One is that it serves as a coarse indicator of when the processor should and should not deliver stimuli to the electrodes. Another is that it allows the microprocessor to exploit its idle down power conservation features during squelched periods to extend battery life. This particular feature has not yet been fully implemented in the portable processor. The final feature the squelch function allows is described in the following paragraph.

The fourth modification also pertains to a noise associated problem. As stated earlier, patient MH utilizes her portable processor in a noisy workplace environment. We have implemented a noise subtraction algorithm which utilizes the processor's squelch circuit to discriminate noise from signal plus noise conditions. The noise is relatively constant compared to the time scale of speech and can be reasonably described by RMS energy estimates during times when the squelch is active. Subtraction of these RMS noise levels from the running speech plus noise RMS estimates improves the performance of the portable speech processor.

FRONT-END HARDWARE PROCESSING

Microphone Input Conditioning

The microphone is a miniature electret device with a frequency response of 50-15000 Hz. Placement of the microphone is discussed below in the context of device packaging.

Signals from the microphone are first high pass filtered at 100 Hz with a 3rd order Butterworth filter, followed by a variable gain stage with a single pole 5300 Hz low-pass cut off. Signals at this point are typically 3.10 V peak-to-peak for loudly spoken voiced sounds.

Spectral Energy Processing

After input conditioning, signals are fed directly to the NEC speech analysis chip. The first processing stage of the NEC device is the programmable gain block. The gain of this stage is set under software control and may vary from -13.5 dB to +33.0 dB. This gain stage is the forward path gain control element for the AGC control loop. Further details of the AGC are discussed below.

Following the gain stage is an optional, software-selectable equalizer. Equalization provides essentially a +6 dB/octave gain slope across the speech spectrum. The equalizer option is utilized in this processor design.

The output from the equalizer is then compressed instantaneously through a piece-wise-linear gain stage. Input-output characteristics for this gain stage are:

$E_{out} = 2 * E_{in}$ for $E_{in} < 0.4$ volts

$E_{out} = E_{in} + 0.4$ for $E_{in} > 0.4$ volts.

This provides an instantaneous compression of high amplitude speech signals and reduces the crest factor (peak to RMS ratio) of the speech signal from 7 to 5. This compression effectively expands the dynamic range of the band-pass filters by allowing higher RMS inputs but avoiding peak clipping. In addition, considerable improvement is made in the signal to noise ratio through the band-pass filters since RMS levels are higher relative to the noise intrinsic to the NEC speech analysis chip itself.

Signals next are routed to the NEC chip's switched-capacitor, band-pass filter set. Here the speech spectrum is divided into sixteen bands, corresponding roughly to adjacent critical bands for normal human hearing. The output from each filter is then rectified and low-pass filtered (50 Hz, single-pole) to produce RMS energy estimates. These RMS energies are then sampled and the values are stored in the FIFO array. This array may be accessed from the microprocessor data bus and appears as a single memory mapped location. Sequential reads from that location pass the band energy information to the microprocessor. Once the FIFO has been loaded, the NEC chip sets the FRAME line to indicate to the microprocessor that more recent spectral information is available. Frame periods are 8 msec long.

It is important to note that the 1200 Hz high-pass filter which reduces F0 and F1 energies is implemented in software. In the frequency domain, this filter produces staggered scaling of the outputs of the band-pass filters which is readily executed in software during reading of the band-pass energies by the post processor. By achieving the desired filter characteristic in this way, a greater degree of flexibility is gained, implementing more complex front end filters without any change in front end hardware.

Squelch

Squelch operation is a simple matter of determining whether or not a signal exceeds a preset threshold level. Speech signals from the microphone preconditioning stages are high-pass filtered (600 Hz, single pole) to diminish F0 energy. The resultant signal's positive phase is then compared to a reference dc level which is set with the front panel squelch control. If the signal level exceeds the reference then a logical flag is set. This logical flag is mapped into the bit space of the microprocessor via port 1 and is readily examined by the software. The microprocessor can issue a signal that clears the squelch flag, (simultaneously clearing the AGC flag as well). The software logic of the squelch function is described below.

Automatic Gain Control

The AGC control loop operates to maintain the average RMS energy of the forward speech signal path near an operating point set by the front panel volume control. The output from the gain/equalization stage of the NEC speech analysis chip is half-wave rectified and low-pass filtered (25 Hz, single-pole). This RMS estimate is then compared to a DC level set by the volume control. If the RMS estimate exceeds the reference level a logical flag is set. This flag is bit mapped into the microprocessor via port 1 and is easily interrogated. It may be cleared along with the squelch flag by the microprocessor. The software logic of the AGC is described below.

Pitch Extraction

Pitch extraction is implemented essentially as a peak-picking software algorithm. At this front end hardware stage, running speech is preprocessed by filtering and then sampled. The microphone preconditioned signal is low-pass filtered (400 Hz, 3rd order Chebyshev, 0.5 dB ripple) to reduce F1 resonance ringing. The signal is then high-pass filtered (60 Hz, single-pole) and finally digitally sampled at a 2.0 kHz rate using a serially interfaced analog-to-digital converter (ADC), TLC548. The ADC communicates with the microprocessor using the 80C31's on-board serial interface operating in mode 0. Chip select for the ADC is controlled by a port 1 line from the microprocessor.

Battery Monitor

The battery voltage monitor is the voltage monitoring circuit built into a Maxim MAX 630 DC-to-DC converter. Reference levels are adjusted so that if the battery terminal voltage drops below 4.5 volts a logical line is cleared to the microprocessor. The microprocessor monitors this line as part of its background processing and will stop speech processing and signal the patient when the battery drops below 4.5 volts. At that point the processor stops all stimulation of the electrodes and begins flashing the red front panel LED at half-second intervals indicating that a battery change is required.

DIGITAL POST PROCESSING FEATURES UNIQUE TO THE PORTABLE UNIT

Noise Subtraction Algorithm

A noise subtraction feature has been added to the processor design in direct response to patient MH's experiences with her portable processor. Patient MH usually wears her processor in a noisy workplace environment. While environmental noise reduction measures have helped to improve the processor's performance, further noise immunity remains a highly desirable feature for the processor.

Since the background noise in this case is due to continuously operating machinery, its spectrum is essentially constant on the time scale of speech processing. It is therefore possible to subtract the pure noise spectral energy estimates from the speech-plus-noise spectral energy estimates to derive spectral energy estimates for speech alone. Pure noise signals are discriminated from speech-plus-noise signals by the squelch feature of the processor. We call this process our noise subtraction algorithm and have implemented it as a mode switch option for MH.

Implementation of noise subtraction in software occurs immediately after the logarithmically-spaced energy band estimates have been obtained. If the noise subtraction mode is selected and the squelch mode is active, the current RMS energy estimates are considered to be pure noise and the current energy values are stored in buffer memory space. Processing continues, but no output is generated since the squelch is active. If the squelch mode is inactive, then the RMS energy estimates are considered to be speech plus noise. At that point, the previously measured noise energies, stored in memory when the squelch was last active, are subtracted from the current RMS band energies. The resultant energies are then passed through subsequent processing stages to generate output stimuli.

This noise subtraction approach, in addition to removing slowly-varying environmental noise contamination, will also remove processor generated steady-state noise and/or DC offsets appearing in the RMS energy estimates. To date evaluation of this feature has been only anecdotal. Patient MH reported an immediate improvement in clarity and naturalness of perceived speech in both quiet and noise on first application of this algorithm. She now reports only minor changes in speech quality and no changes in loudness when workplace-equivalent background noises are turned on and off in the laboratory. In addition, at her work place she had often reported hearing a brief "echo" at the end of a speech signal. This percept arose due to high level background noise mapping through her processor after speech had stopped but before the squelch delay timer had expired. With the noise subtraction algorithm running, this echo effect is eliminated.

For the present portable speech processor design, two improvements are being implemented for noise subtraction. One is to perform the noise subtraction on a band by band basis as data are read from the NEC speech analysis chip before combining data to approximate the logarithmically spaced filters. The other is to compute a running average of the pure noise signal energy estimates, instead of using simply the last noise estimate obtained while the squelch was on. This would help eliminate short term and impulsive perturbations in the background noise estimates.

Formal studies of the noise subtraction algorithm using controlled noise conditions and standard speech reception tests are planned.

Squelch and Automatic Gain Control

Squelch and automatic gain control (AGC) processing are handled as a subtask of the NEC Service Routine because of the convenience of synchronizing AGC forward path gain changes with frame periods (8 msec) of the NEC speech analysis chip. Squelch and AGC processing are discussed separately since they are functionally independent of the spectral analysis functions of the NEC chip.

Squelch and AGC service tasks are executed once every 8 msec. These tasks essentially poll the status of the relevant hardware flags and then reset them.

Squelch processing begins with polling of the squelch hardware flag bit. This bit is mapped into the microprocessor via port 1 and is directly bit addressed by the software. If the flag is set, then an above-threshold signal is present to be processed. A software squelch flag, SQLON, is cleared. This automatically turns on the green LED driver indicating to the patient that a signal has been detected. In addition, a squelch delay counter is activated which forces the squelch function to remain off for about 500 msec after the signal has ceases to exceed threshold. This prevents the squelch from turning on between words during running speech. From this point, AGC processing is begun. If the squelch hardware flag is not set when polled and the squelch function is already activated, then squelch processing is exited. If the squelch hardware flag is not set when polled and the squelch function is off, then the squelch delay counter is decremented and checked for zero. If it is zero, the SQLON is set, activating the squelch function; otherwise, squelch processing is exited. In all cases, exiting squelch processing includes issuing a reset pulse which clears both the squelch and AGC hardware bit flags.

The AGC functions in a conventional manner with fast attack and slow release times. The forward path AGC gain control element is the programmable gain block of the NEC chip. This stage provides a range of 45 dB gain in increments of 1.5 dB.

AGC processing occurs only if the squelch mode is off and begins with polling of the AGC hardware flag which is software addressable via port 1. If the hardware flag is set, then the average RMS energy at the output of the gain block exceeds the reference level set by the VOLUME control. The processing enters the attack mode, decreasing gain at a rate of 6 dB/16 msec or 3 dB/8 msec or two 1.5 dB decrements/one 8 msec frame period. Gain changes are made by modifying a variable, GAIN, always checking to verify that GAIN stays within the acceptable 45 dB range of the NEC chip. Every time a gain decrease is made a counter/timer variable is initialized for timing the gain increments used in the release phase.

Upon polling, if the AGC hardware flag is not set, then the RMS energy at the output of the gain block is lower than the VOLUME control reference level. AGC processing then enters the release mode, increasing gain at a rate of 6 dB/320 msec or 1.5 dB/80 msec or 1.5 dB/ten 8 msec frame periods. Since the minimum gain step is 1.5 dB, long time constants must be spread step-wise across a number of frame periods. As mentioned previously, a timer/counter is initialized during attack phases and decremented once each 8 msec frame period. If the counter had reached zero, it is initialized again and a 1.5 dB gain increment is made. If the counter has not reached zero, then no gain change is made; however, the release phase processing continues.

Once the GAIN value has been chosen for the current frame period, then the gain stage of the NEC chip is adjusted. The final step in AGC processing is issuing a reset pulse which clears both the squelch and AGC hardware bit flags.

Mode Selection

Mode switch settings are read by the background processing task. Four modes are possible. A diode switching matrix codes the four switch positions as a two-bit binary code on the microprocessor port 1. The software reads these bits and compares the new switch data to the previous switch data. If no change has occurred, the background task continues its normal looping. If a change has occurred, then flags are set to indicate the new mode condition, any immediate processing changes are made (i.e., changing parameters or jump commands, etc.) and then normal background processing resumes.

The mode switch option is a valuable feature to have in a microprocessor-based processing system. We utilize this option to provide the patient with a range of operating modes that she may select. In this manner, the patient may directly compare two or more processing strategies in a particular listening situation. Ultimately, we envision that a patient may be fitted with perhaps three distinct speech processing strategies all available in the same instrument -- one optimized for best performance in quiet, one optimized for best performance in noise with lip-reading (e.g. a two-channel Breeuwer/Plomp strategy) and one optimized for conveying the most salient features of that patient's favorite music.

Stimulation Output

The output driver stages of the portable speech processor are transformer coupled voltage sources capable of + and - 10 volts and 20 kHz bandwidth. Six independent channels are presently provided. A driver for a single channel consists of a memory-mapped, latched CMOS DAC (one stage of a quad DAC) feeding a two stage operational amplifier driver that is transformer-coupled to the electrodes. The DAC operates with a unipolar binary code and uses a DC reference source common to all channels. The DC reference level is adjustable with an internal potentiometer and provides a master gain control across all six channels. The electrodes are driven in a bipolar manner and are capacitively-coupled to the transformer output coils. The transformers are the bandwidth limiting elements of the output driver stages with a typical frequency response of 300 - 20 kHz. The 20 kHz upper cutoff provides good rise time characteristics for the pulsatile outputs; however, the 300 Hz lower cutoff contributes substantial decay distortion to the pulse wave forms.

As configured, this output driver stage is the least desirable aspect of the present system. The initial choice to use a voltage-controlled as opposed to a current-controlled output driver was made to expedite the development of the portable processor. The voltage-controlled stages did not require power supply isolation between channels because of the isolation provided by transformer coupling. In contrast, current-controlled drivers require full supply isolation (including grounding) between channels to insure control of the current through the electrodes. Such a design is technically possible, but could not be implemented quickly and yet maintain power consumption requirements consistent with a battery-operated, portable unit. Therefore, the decision was made to begin with the transformer-coupled driver stages and later retrofit the more desirable current-controlled outputs.

Power Consumption

As presently defined the portable interleaved-pulses processor consumes approximately 600 mWatts of power. This roughly breaks down to the following power budget:

NEC speech analysis circuit	250 mWatts;
Output driver board	200 mWatts;
Front-end hardware processing and microprocessor (8 MHz)	150 mWatts.

A single battery pack provides approximately 4500 mWatt-hrs (5 volts x 900 mAmp-hr) of energy, thus allowing six to seven hours of operation on a single battery pack. These figures, although higher than ultimately desired, are consistent with our original design criteria for an initial, portable speech processor that provides full flexibility in implementing interleaved-pulses processing strategies.

Several options exist for reducing power consumption of the present design. One is to replace the switched-capacitor filter bank of the NEC speech analysis chip with a linear, active-filter, band-pass filter bank. Of course, additional electronics must be added for RMS calculation, AGC function and microprocessor interfacing; however, preliminary calculations suggest that these functions combined would require 40 to 50 mWatts at most. The output driver board power consumption can be easily reduced with better transformer selection and reducing operating voltages from + and - 12 volts to 0 to 3.5 or 5 volts. A general redesign of this driver board is underway in any case to provide current-controlled sources. Front-end processing hardware and microprocessor power may be reduced by dropping operating voltages, reducing the microprocessor clock frequency and using the idle down operating feature of the microprocessor in conjunction with the squelch circuit.

Packaging

This section describes the physical package configuration of the portable unit. The package was designed for the specific needs of patient MH. MH presently has a percutaneous cable connection that exits just above her left ear (her right ear is implanted). In the interest of safety and convenience, the processor is packaged in a small plastic case that is placed within a custom designed carrying pouch and strap. The strap of the carrying pouch is worn across the right shoulder and passes across the body to the left hip where the processor pouch is located. Figure II.F-2 shows a patient wearing the processor while making a front control panel adjustment.

The strap is a hollow envelope and contains both the microphone cable and the six-channel (twelve-lead) output cable. As seen in Figure II.F-2, the microphone is located about two-thirds the way up the strap, passing through a slit in the strap itself. Just above the microphone, at about clavicle level is the output cable connector. MH passes her percutaneous cable behind her neck to this output connector. This connector is hidden beneath the strap against the patient's clothing. When connected, the connections lie flat just above the right clavicle, and lie unseen beneath the carrying strap.

Figure II.F-3 is another view of the carrying case showing the access for the rechargeable battery. Battery swaps are made by folding down the large flap that folds over the side of the processor and opening the two thin end flaps. All flaps are held in place using plastic hook-and-loop fastening material. The battery drops out of the bottom of the case, still attached to the power cable. As seen on the diagram drawn on the large side flap, the power cable unplugs from the battery pack. Battery swaps are easily made without removing the carrying pouch and strap from the body. Such swaps require about a minute to complete.

Also seen in Figure II.F-3 are the microphone cable and output cable exiting from the hollow shoulder strap where it attaches to the carrying case. The shoulder-level output connector that is normally concealed beneath the strap during use, may also be seen. The buckle seen in the top of the figure is worn across the back and provides for adjustment of the shoulder strap length.

Figure II.F-4 shows the front view of the processor in its carrying pouch. This is the basic view of the processor that the patient has while wearing the unit. In the center of the front panel are three knobs that are, from left to right, the mode switch, the squelch adjustment and the volume adjustment. To the right of the volume knob is the stimulus output

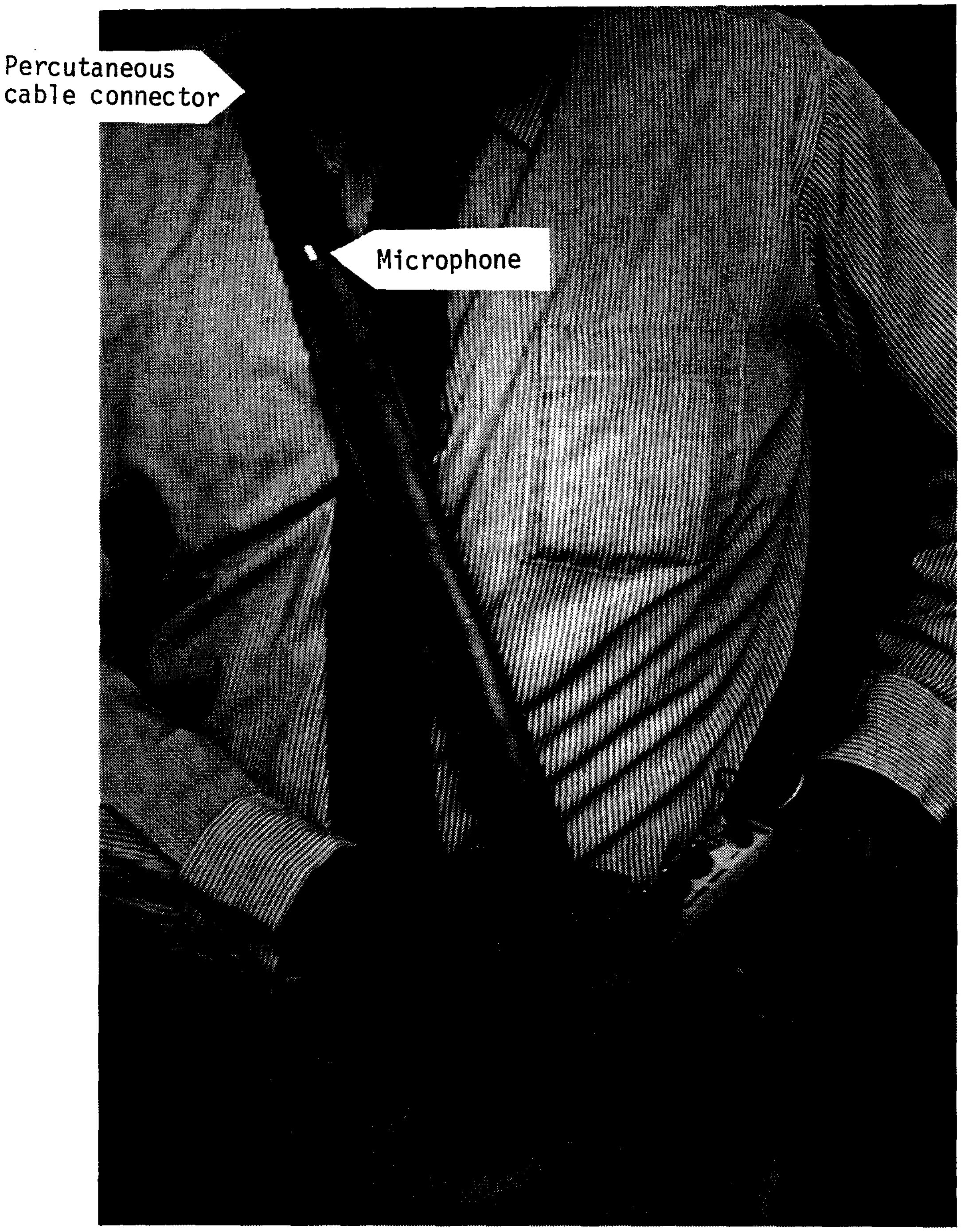


Figure II.F-2. View showing patient wearing the portable speech processor while making a front control panel adjustment.

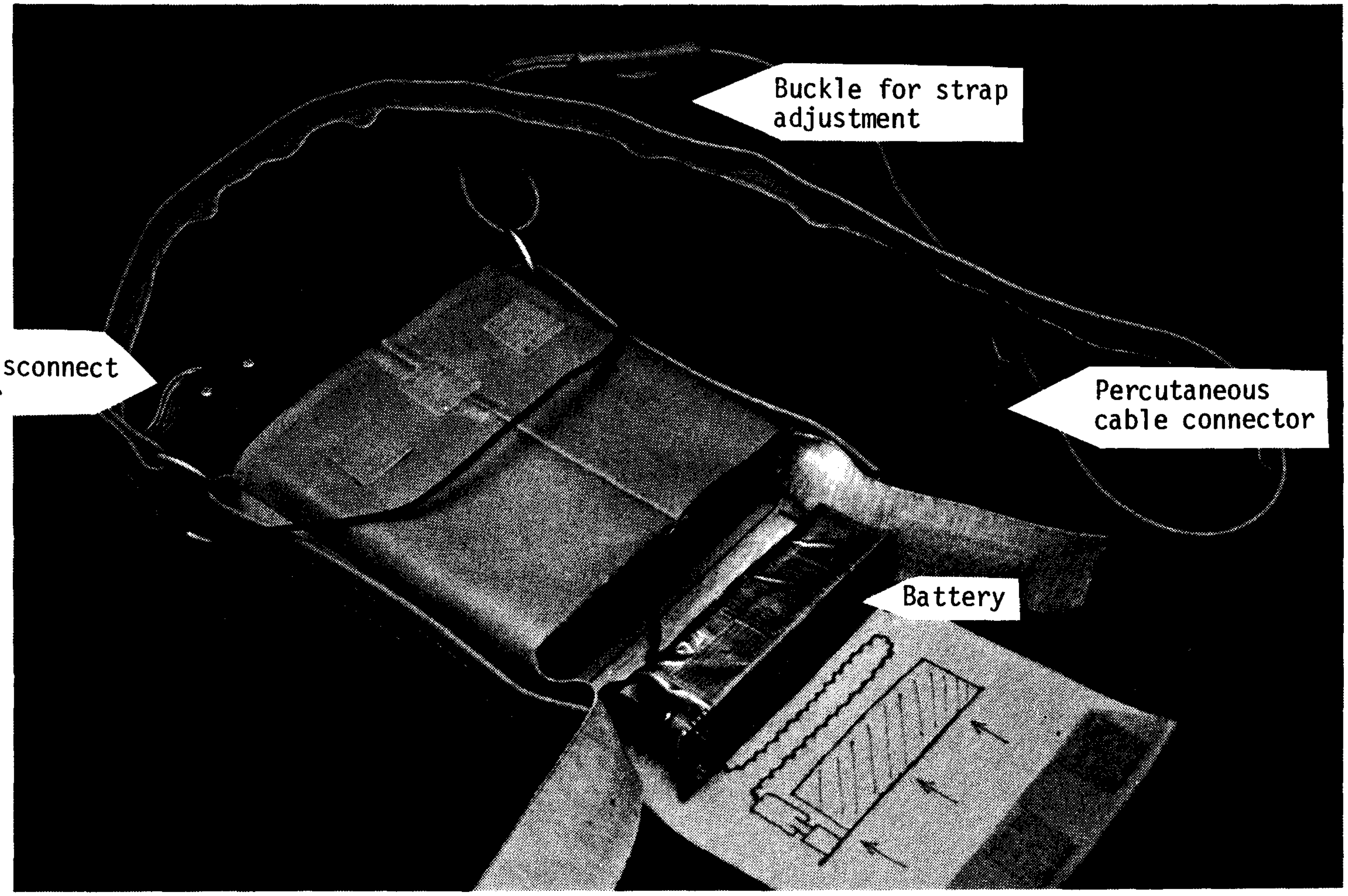


Figure II.F-3. View showing wearable speech processor with access flaps open and battery pack partially removed.

Figure II.F-4. View showing front panel of wearable speech processor with output cable connector removed.

connector. The connector plug for this socket is seen in Figure II.F-3. This large plug provides an easily accessed and quickly removed safety disconnect in the event the patient needs to quickly disable the unit. In addition, this plug is the last to be connected during start up and thus serves to minimize the patient's exposure to start-up transients. Beneath the output connector are two LED indicators. One LED indicator (GREEN) indicates when the squelch circuit is disabled, that is to say that it is on when signals are being processed and stimuli delivered to the patient. This visual LED signal is helpful to the patient in adjusting the squelch circuit threshold. Typically the squelch is adjusted to discriminate the presence or absence of the patient's own voice. The green indicator is wired in series with a normally open push button switch to conserve battery life once the squelch control has been adjusted. The other LED indicator (RED) flashes when the battery terminal voltage had dropped beneath its minimum terminal voltage (4.5 V typically). On power up, both the red and green LED indicators are used to flash a characteristic pattern to affirm to the patient that the processor has passed its own self test and is working properly. At that point, the patient plugs in the electrode cable to the output connector. At the extreme left of the unit are the microphone input connector, a master reset for the microprocessor and the main on/off switch for the battery.

Figure II.F-5 shows the processor turned upside-down and with the bottom case removed. This view shows the compact construction of the unit. Two layers of perforated boards are used, each being hand wired point-to-point. The component sides of the boards are mounted inward. The rechargeable battery pack is seen at the back end of the unit. The connector strip seen at the left front corner of the upper board carries output stimuli down to the front panel output connector. Disconnecting this connector at the edge of the board and removing the battery pack allows the processor boards to be folded open, as seen in Figure II.F-6.

With the board folded open, the board still inside the case and closest to the front panel contains the front-end processing hardware, the microprocessor with memory, and the NEC speech analysis chip. The other board contains the DACs and driver circuitry for generating the output stimuli for six channels.

Figure II.F-7 is a view of the battery charger that accompanies the unit. Four batteries are provided. Each battery pack contains eight AA nicad rechargeable batteries (1.25 volts at 450 mA-Hr.) wired into two parallel stacks of four batteries. Each pack provides typically 5 volts at 900 mA-Hr. Charging is at C/10 rate. Each battery pack provides approximately 6 hours of operation of the processor.

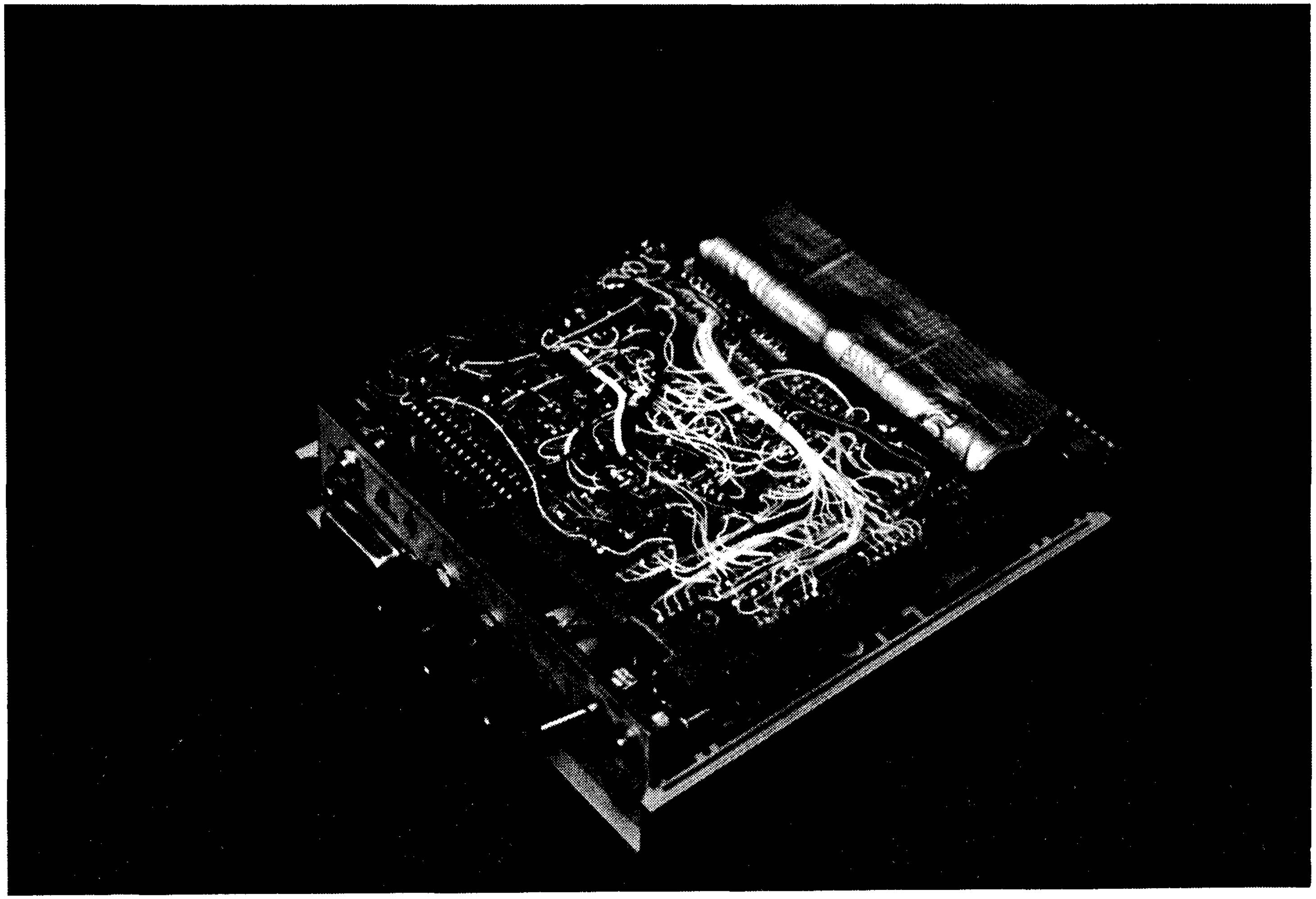


Figure II.F-5. View showing wearable speech processor with case removed. Bottom of output driver board is seen with rechargeable battery pack at back.

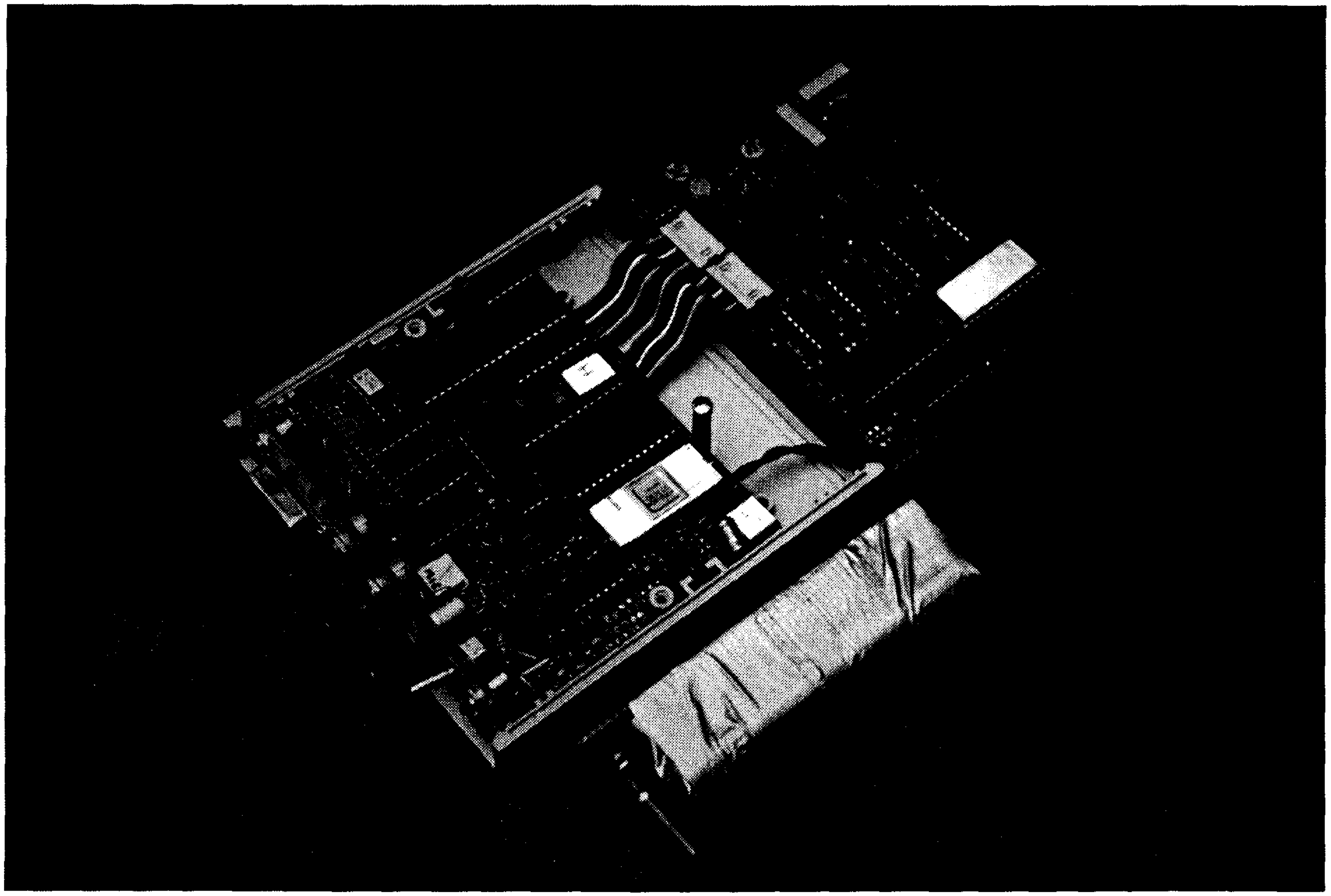


Figure II.F-6. View showing wearable speech processor with output driver board folded to the right, exposing front-end hardware and microcontroller board.

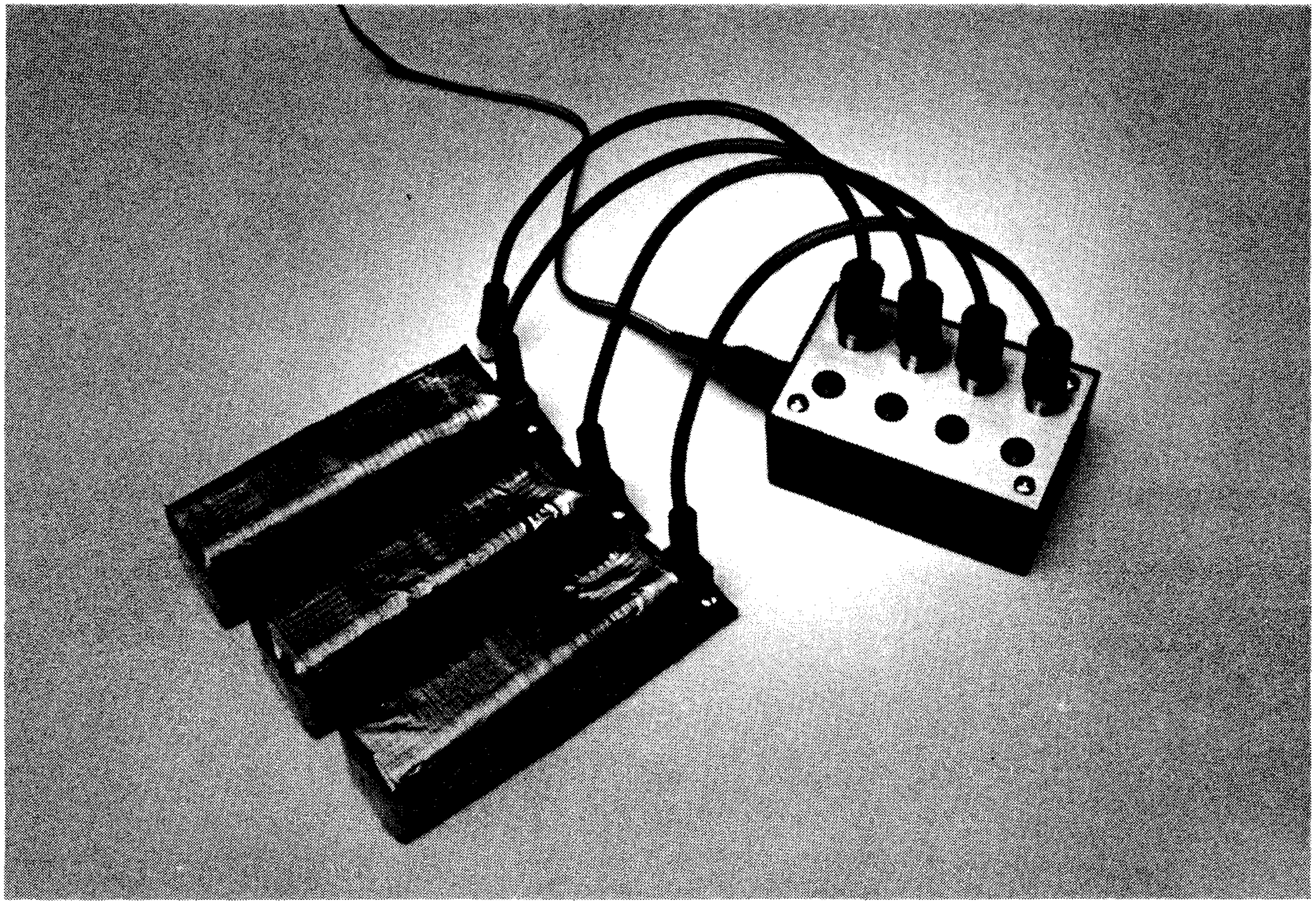


Figure II.F-7. View showing battery charger and three battery packs. Cable at top of figure leads to a 110 V AC to 9 V DC wall plug module.

II.G. Development of a Next-Generation Auditory Prosthesis

We have been collaborating with UCSF in the development of a next-generation UCSF auditory prosthesis. In particular, we have played major roles in the specification and design of the speech processor and transcutaneous transmission system (TTS) for this new device. The design of these two elements of the system is based on the results from our studies comparing analog and pulsatile coding strategies in tests with individual implant patients. As outlined in section II.A of this proposal, the major conclusions from these studies are that

1. Different processing strategies can produce widely different outcomes for individual implant patients;

2. Interleaved pulses (IP) processors are far superior to the tested alternative processors for at least two patients with psychophysical findings consistent with survival;

3. The performance of IP processors strongly depends on the selection of processor parameters;

4. Use of a TTS designed to support an IP processor (e.g., a TTS with eight channels of current-controlled outputs) is likely to produce results that are better than those obtained with the limited TTS of the present UCSF/Storz prosthesis;

5. Processors other than the IP processors can be superior for patients with psychophysical signs of good nerve survival and who cannot be fit with an optimized IP processor;

6. One such processor is the compressed analog (CA) processor used in the UCSF/Storz prosthesis; and

7. Substantial gains in speech understanding can be made by (a) selecting the best type of speech processor for each patient and (b) using implanted and external hardware capable of supporting a wide range of different processing strategies.

The next-generation UCSF prosthesis, to be produced by MiniMed Technologies, will be capable of supporting both the CA and IP processing strategies and will also have a TTS that provides up to eight channels of current-controlled outputs for intracochlear stimulation. In fact, the TTS will have unprecedented flexibility for such a system. The current drivers in the system are fully isolated and can be individually programmed to provide outputs in 3 percent increments between 2 and 2000 μA. The drivers can also be instructed to provide a zero output or negative outputs (the direction of current flow is controlled by a switch matrix). All eight driver outputs can be simultaneously updated every 77 μsec (13 kHz sampling rate) and a smaller number of driver outputs can be updated at higher rates. For example, one channel can be updated every 12.3 μsec (81 kHz sampling rate). This feature permits a mixture of sampling rates for the various stimulation channels which might be most useful for the generation of stimuli for CA processors. In particular, high frequency analog stimuli can be "reconstructed" at high sampling rates for basal electrode channels while low frequency stimuli can be reconstructed. Finally, the outputs of the current drivers can be connected to form a wide range of electrode coupling configurations. Both the monopolar and radial bipolar configurations will be supported, as will "hybrid" mixtures of the two. In addition, a longitudinal bipolar configuration can be implemented if nonsimultaneous stimuli are used. All outputs from the current drivers are capacitively coupled to the selected intracochlear electrodes to ensure charge balancing of the stimuli.

The significance of the new UCSF device for the present project is that we will have access to patients with a highly-transparent TTS. This will allow us to evaluate an extremely wide range of processing strategies and electrode coupling configurations in tests with individual patients without having to use a percutaneous cable. Thus, we will be able to retain most of the flexibility provided by the cable while eliminating the potential complications of cable use.

We expect that the new device will be available for implantation in the fall of 1988. As outlined in section III.B of this proposal, UCSF presently has a backlog of 20 candidates for implants with this device and Duke has 8 candidates for implants with this device or the Nucleus device. All implanted patients among these candidates will be asked to participate in the studies we are proposing.

II.H. Collaborations

In its efforts to develop advanced auditory prostheses, the RTI/Duke cochlear implant team has established a number of important collaborations with other groups having similar objectives. These collaborations have greatly enriched our program here in North Carolina. They also constitute an expression of confidence by distinguished outside investigators in the capabilities of our RTI/Duke team. Our major collaborations at this time are as follows:

<u>University of California at San Francisco (USCF)</u>,
San Francisco, CA

We have collaborated with investigators at UCSF since September, 1982. A primary area of mutual interest is the development and evaluation of advanced speech processors for multichannel cochlear prostheses. UCSF is the named collaborating institution for the conduct of patient studies in the contract for RTI's initial project with the Neural Prosthesis Program, and UCSF and Duke are the named collaborating institutions in our present contract. Investigators at UCSF (primarily M.M. Merzenich, M.W. White, R.V. Shannon, R.A. Schindler, D.K. Kessler, S.J. Rebscher, D. Morledge, D. Wilkinson and L. Vurek) have unselfishly provided advice and insights based on nearly two decades of experience in cochlear implant research and have made available patients implanted with the UCSF electrode array for study by the RTI/Duke group. In addition, UCSF, RTI and Duke have jointly developed a next-generation auditory prosthesis, as described in section II.G above. This collaboration among these three institutions is a wonderful example of synergy and cooperation in the development of a complex medical device.

<u>Washington University Medical Center (WUMC)</u>, St. Louis, MO

Our primary collaboration here is with Dr. M.W. Skinner, Director of Audiology. With our assistance she has constructed a cochlear implant laboratory at WUMC that is functionally identical to the laboratories we have constructed at UCSF and Duke. These laboratories have computers, associated custom software, and associated custom peripherals to support a wide range of psychophysical and speech perception studies with cochlear implant patients. We expect to work with Dr. Skinner in the conduct of such studies at WUMC in the near future now that the laboratory is largely completed.

In addition to the above activities, we have also collaborated with Dr. Skinner in the design and evaluation of speech processing strategies for single-channel cochlear prostheses. This collaboration included joint studies of alternative speech processors for one of Dr. Skinner's patients implanted with the extracochlear version of the 3M/Vienna cochlear prosthesis. Most of these studies were conducted at Duke.

Massachusetts Eye and Ear Infirmary (MEEI), Boston, MA

The collaboration with MEEI is to study four or perhaps five patients implanted with the Symbion multichannel electrode array. In this study members of the Duke/RTI team, in collaboration with Drs. D.K. Eddington and W.M. Rabinowitz of MEEI and MIT, respectively, will evaluate the performance of several alternative speech processing strategies with these patients. The processors to be evaluated will minimally include the interleaved-pulses processor (developed under our present NIH contract) and the compressed analog processor used in the Symbion device. This comparison will complement and extend our previous comparison of interleaved-pulses and compressed analog processors in tests with six patients implanted with the UCSF/Storz electrode array. The results of the planned tests with the Symbion patients should be most informative inasmuch as the design and electrical characteristics of the Symbion electrode array are fundamentally different from those of the UCSF electrode array. All tests with the Symbion patients will be conducted in our cochlear implant laboratory at Duke. Each patient will be studied for a one-week period, as in our previous studies with six UCSF patients. We expect to begin our series with Symbion patients in the summer of 1988.

3M Company, St. Paul, MN

The 3M Company has been involved with the development of a multichannel auditory prosthesis with a unique speech processor and electrode array. Dr. Sigfrid Soli of 3M recently asked the RTI/Duke team to evaluate this processor along with "state-of-the-art" alternative processors in tests with patients implanted with an initial version of the electrode array. Tests with one such patient were conducted at Duke in December, 1987, and follow-up studies were conducted with this patient and another patient at 3M in February, 1988. Results from these studies will be presented in a future progress report for our current NIH project.

Kresge Hearing Research Institute (KHRI), University of Michigan, Ann Arbor, MI

We have several areas of collaboration--ongoing and planned-- with KHRI. One study now in progress is to evaluate and apply a new method for measuring frequency discrimination in psychophysical tests with implant patients. This method was initially developed by Dr. Bryan Pfingst of KHRI in behavioral studies with monkeys (Pfingst and Rush, 1987). Once the method is fully developed for tests with human subjects, we expect that it will provide a powerful means for investigating subtle aspects of pitch and loudness perception by implant patients. Software for the initial evaluation studies is now under development at RTI, and we expect to begin these studies with a Duke patient in the summer of 1988.

In addition to the studies with Dr. Pfingst, we have planned a joint study with Dr. Josef Miller and others at the Institute to evaluate alternative speech processors for patients with lateral wall (extracochlear) implants. This latter study is briefly described in section III.B of this proposal, under the heading titled "Lateral Wall Implants."

Finally, we have proposed studies with KHRI for the design and evaluation of speech processors with stimulating electrodes placed in or on the cochlear nucleus. This project is fully described in one of the supporting documents for this proposal (section X.C) and briefly described in section III.B under the heading titled "Central Nervous System Auditory Prostheses." If approved for funding, the project will support a collaboration among the groups at RTI (B. Wilson, C. Finley and D. Lawson), Duke (R. Wolford and J.H. Casseday), KHRI (primarily D. Anderson and J. Miller), and the House Ear Institute in Los Angeles (primarily D. Nielsen).

Goethe Universität, Frankfurt, West Germany

Rainer Hartmann of the Goethe Universitat has invited B. Wilson to visit his laboratory in Frankfurt as a guest scientist. The basic aim of our collaborative project is to evaluate certain predictions of electro-neural models of implant function with measurements of single unit responses to intracochlear electrical stimuli. Cats will be used for these measurements. Funding for all travel and per diem expenses will be provided by the Deutsche Forschungsgemeinschaft and funding to support Wilson's time will be provided by an RTI Professional Development Award. We expect that the initial experiments will be conducted in Frankfurt in the late summer or early fall of 1988.

Carleton University, Ottawa, Canada

Robert Morris of Carleton University has designed an advanced system for real-time extraction of the spectral envelopes (through computation of linear-prediction coefficients) and fundamental frequencies (through use of the Simple Inverse Filter Tracking algorithm) of speech signals. Inasmuch as such information could be used in various ways to represent features of speech with cochlear prostheses, Dr. Morris has asked us (and others) to evaluate this application of his system. As indicated in section III.A of this proposal, we have agreed to incorporate some essential elements of the system into our facilities for real-time processing of speech signals. We look forward to using Dr. Morris' system in future studies with implant patients, and we are very pleased to honor his request for collaboration.

III. Plan of the Proposed Effort

In this section we will present our plan to meet or exceed all requirements specified in the Statement of Work for RFP No. NIH-NINCDS-88-04, "Speech Processors for Auditory Prostheses."

III.A. Further Development of a Laboratory-Based Speech Processing System

Introduction

As noted in section II.E. above, we have developed and presently have available two highly complementary tools for the rapid and thorough evaluation of patients and selection and optimization of their processing strategies. Each of these devices--the Block Diagram Compiler and the Real-Time Bench Processor--has crucial advantages and significant limitations.

The block diagram compiler offers great power, generality, and flexibility. It allows the preprocessing of speech test materials in emulation of practically any speech processor that is definable. Since it does not operate in "real time", however, its emulations cannot include live speech, and significant delays are involved in preprocessing the extensive speech samples involved in many of the desirable tests.

The bench processor, on the other hand, does function in real time and thus can accommodate live speech and allow testing with speech materials from a variety of media with no preprocessing delay. While allowing rapid configuration to a variety of custom processor designs within a particular class (*viz* interleaved pulse processors) the real-time bench processor does not, however, offer the power, generality, or flexibility available from the block compiler approach.

The ideal clinical instrument would seem to be a fusion of these two devices--a highly flexible real-time processor that could be programmed quickly by a highly flexible block compiler. It is precisely such an instrument that we propose to develop and apply as a second-generation device, making full use of our experience in the development and use of the first-generation parent tools.

Present First-Generation Laboratory-based Speech Processing System

As part of previous contracts from the Neural Prosthesis Program to design and evaluate speech processors for multichannel auditory prostheses, we have developed a computer-based system for the rapid and flexible emulation of promising coding strategies in software. Use of this system has allowed us to make valid comparisons between many different approaches to processor design in tests with single subjects. We refer to this system as the RTI Block Diagram Compiler. The first generation of this system, which is presently in use in our laboratory, has been described in detail elsewhere (Wilson and Finley, 1985; Wilson et al., 1985a).

A brief overview of the presently used system is presented here to establish a foundation for planned improvements to be incorporated in a second-generation system described later in this section. The first-generation block diagram compiler is composed of several interactive program elements that assist the operator through the steps of specifying, simulating, and validating a speech processor design, ultimately leading to the preparation of preprocessed stimulus files for patient testing. A brief description of these software elements may be found on page D-6 of supporting document X.D of this proposal. The key interactive program element DESIGN is the tool used by the investigator to fully specify a speech processor system. The design process consists of the investigator specifying on a block-by-block basis the functional nature of each signal processing element and its connections to other elements in the system. The classes of available elements include standard digital signal processing functions, high level speech analysis tools, a variety of signal sources, standard mathematical operators, and classical circuit functions useful in electrical engineering. Table III.A-1 summarizes the choices available in each class. Once a particular function for a given block has been specified the operator is queried for details on input and output connections and specific functional parameters. The operator may monitor any number of nodes in the system for subsequent display or for analysis of signals from different intermediate stages of the processor. Finally, once the speech processor system is fully specified, files of previously digitized speech material may be processed through the simulated system, thus building a set of stimulus files for presentation to the patient at a later time.

As presently configured the block diagram compiler is a powerful and flexible tool for use in design and evaluation of speech processors for auditory prostheses. Its strength lies in the convenience and generality that it makes available to the investigator for design and simulation of processing strategies.

The one significant weakness of the present configuration of the compiler is that it is not capable of real-time processing of speech materials. Because of this, screening materials for initial processor design comparisons usually have been limited to abbreviated vowel (5 token) and consonant (8 token) confusion matrix tests. Off-line simulations using these materials generally require about 15 minutes of computing time using an Eclipse S/140 minicomputer with a hardware floating-point coprocessor. The speed of this simulation is roughly equivalent to 1/80 to 1/100 of real time. The block diagram compiler alone, then, does not allow live voice

Table III.A-1. Functional Elements Available to Block Diagram Compiler

Module Category	Functions
Digital Signal Processing	Filter FFT Analyzer Cepstrum Analyzer Window
Speech Analysis	LPC Analyzer Formant Tracker Pitch Extractor
Signal Sources	Noise Generator Sine/Cosine Generator Pulse Train Generator Disk File
Mathematical Operations	Summer Multiplier/Inverter Divider Logarithmic Calculator Integrator
Circuit Functions	Compressor Zero-Crossing Counter Peak Detector Window Comparator Level Comparator One Shot (Monostable Multivib.) Flip-Flop Switch Rectifier Unit Delay Operator

processing, and preprocessing of a greater body of speech testing material (e.g. the MAC battery) is achieved only with a considerable time delay.

To alleviate this problem we developed a real-time bench processor system to complement the block compiler. The development of the real-time bench-level processor is described in detail in background section II.E. This processor system provides a microprocessor-based hardware substrate for rapid configuration of real-time versions of speech processor strategies initially designed and tested using the block diagram compiler. At present the bench-level processor is capable only of implementing the broad class of interleaved pulses processor designs that utilize front-end frequency band filtering based on a single bank of band-pass filters. The only speech feature extraction facilities that have been implemented on the real-time bench processor are a variety of detectors for fundamental pitch (F0) and presence or absence of unvoiced energy. The real-time bench processor is used only on an ad hoc basis to allow evaluations of promising speech processor designs with a broader body of test material and/or in the live-voice situation. Working in concert, the block compiler and the real-time bench processor provide the basis for a sophisticated laboratory-based speech processing system that is already in place and available for use.

Background sections II.A and II.B detail previous studies using the block diagram compiler and real-time bench processor to make direct comparisons among a variety of processor designs in individual patients. Having proved the strength of the block compiler approach to speech processor design and evaluation, and observed the advantages of real-time processor testing, we now propose to develop a second-generation system. This new integrated system will build upon the knowledge and experience gained from the present set of complementary devices and will take advantage of recent advances in hardware development for signal processing applications.

Another consideration in our decision to develop a new compiler at this time is the need to replace our aging Data General Eclipse S/140 minicomputer systems. The technology for these systems is based on early 1970's designs. Maintenance and reliability have become major concerns. Recently RTI has agreed to replace these systems, using internal capital equipment funds, with 20 MHz 80386 microprocessor-based personal computers. These new 386 systems complete bench-mark digital filter calculations ten times faster than the Eclipse systems. This enhancement of computing capabilities is one factor influencing our approach to the design of a second-generation block compiler system. The following section describes that proposed system in some detail.

Proposed Second-Generation Laboratory-based Speech Processing System

The second-generation implementation of the RTI block compiler will be a real-time system that incorporates the full flexibility, convenience, and speed of the original compiler for system specification. The addition of real-time processing to the original design offers several very significant advantages. First and foremost is that real-time operation will eliminate off-line preprocessing of speech material prior to testing, allowing continual live-voice interaction with patients and the use of extensive speech test materials without delays. A second major advantage of a block-compiled real-time processing capability is that ad hoc configuring of real-time bench-level speech processors for test comparisons will be eliminated. This will free up more of a professional's time in the first year alone than will be required for design, implementation and validation of the new real-time block compiler.

The new speech processor system will be configured around the TMS320C25 signal processing microprocessor from Texas Instruments (TI). The TMS320C25 is the newest second-generation member of the TI family of TMS320 digital signal processors. Among the many features of the CMOS TMS320C25 are a 100-nsec instruction cycle time, 128K words of total program and data memory, a general purpose on-chip timer, and an expanded instruction set that is upward compatible with the rest of the TMS320 family of processors. This impressive processing capability provides the hardware basis for implementing a software-specified block compiler system in real time.

System Overview

Fig. III.A-1 shows the general organizational plan of the new second-generation system. The layout of this figure reflects the general functional concept of the system, the block compiler functioning as a high-level interface between the operator and the patient. The core of the system is an IBM-compatible 80386 microprocessor-based personal computer (PC). This PC is equipped with a bus-compatible TMS320C25 development system. Real-time speech processor emulations are executed by the TMS320C25 under the control of the PC. The powerful block compiler facility is retained in the software running on the PC. The operator interacts with the compiler software on the PC to specify a speech processor design. When specification is completed, the compiler automatically generates an intermediate TMS320C25 assembly code listing that is cross-assembled by the PC, loaded into the TMS320C25 system, and executed there.

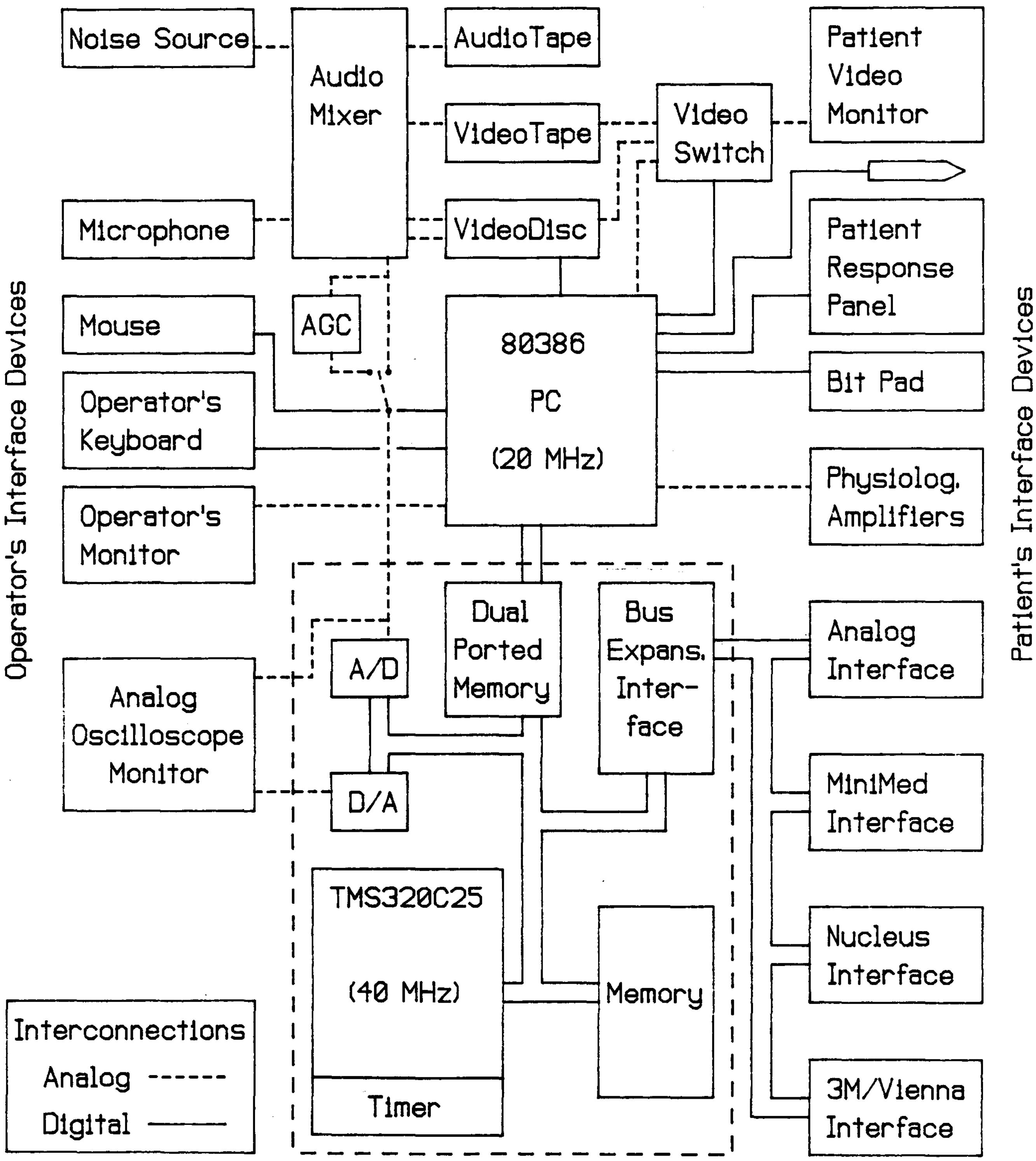


Fig. III.A-1. Real-Time Block Compiler
Speech Processor and Testing System

Once running on the TMS320C25, a block-compiled real-time processor receives its input primarily by A/D conversion of analog signals from any of a variety of sources. Available sources include microphones, video disc, audio tape, video tape, and standard noise generators. All audio signals are controlled and conditioned by an audio mixer. An optional slow-acting automatic gain control (AGC) may be switched into the "front-end" signal path.

Output from the TMS320C25 may be directed to any of several memory-mapped patient interfaces. One is a standard analog interface featuring at least eight channels of optically-isolated current/voltage drivers. This interface will be used with patients who have implanted electrode arrays that are directly accessible percutaneously. The stimulus isolation unit presently in use in our laboratory (see section II.D above) will form the basis for this interface. A second interface is a digital serial interface to the new generation prosthesis being produced by MiniMed Technologies. We have played a major role in the specification and design of both the speech processor and transcutaneous transmission system for this device, as described in section II.G of this proposal. A third interface is a digital serial interface for the Nucleus prosthesis. This device will be based on a custom interface developed recently at Boys Town National Institute (Shannon et al., 1988). We presently are contacting Nucleus Pty., Ltd., directly regarding their assistance in evaluating this interface, as well as seeking their full cooperation in our planned studies. Plans for a fourth interface, to the 3M/Vienna prosthesis, are in a preliminary stage at present. Each of the proposed interfaces will be thoroughly evaluated in our laboratory, of course, before use with patients.

Patients will interact with the system in a variety of ways. The PC will be able to conduct many closed set speech tests with a block-compiled speech processor running in the TMS320C25, and a wide range of psychophysical tests by loading appropriate test stimulus modules to run, like processors, in the TMS320C25. A video monitor with light pen accessory is provided for presentation of video test material and automatic collection of certain types of patient responses. A response panel with pushbuttons and knobs, and an x-y digital bit pad also will be available for patient response input. The PC will be interfaced as well to a system for making electrophysiological measurements.

TMS320C25 Real-Time Processor--Hardware Considerations

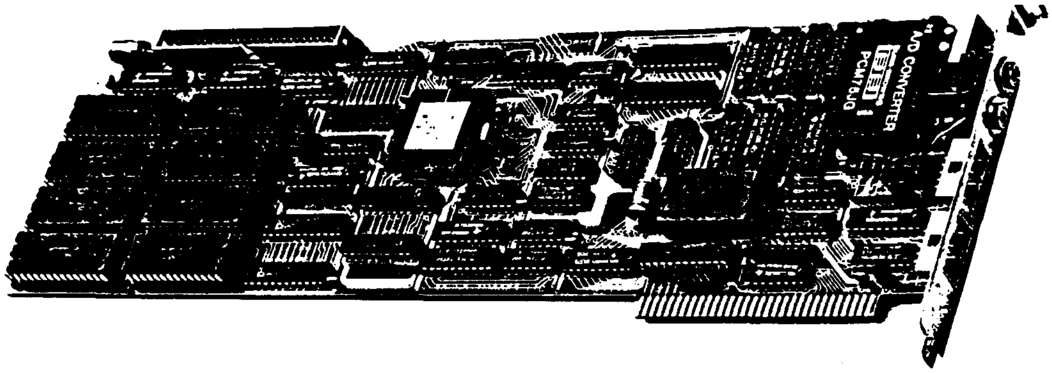
A variety of TMS320C25 development systems that plug into the bus of IBM PC-XT,AT compatible machines presently are available. These boards generally feature the TMS320C25 running at 40 MHz with 100 nsec instruction time, a reasonable amount of onboard memory (64 kbytes, typically) and one or two channels of analog-to-digital and digital-to-analog input/output. The PC and the TMS320C25 communicate via dual-ported memory that allows a user to view and modify data and program memories selectively. A bi-directional interrupt/handshaking facility is available for synchronizing interactions and information transfers between the PC and TMS320C25 microprocessors. Software development for the TMS320C25 utilizes a macro cross-assembler and linker that operate on assembly code written in TMS320 assembler language in the PC's word processing and file handling environment. Once assembled and linked, the executable machine code files are downloaded via the dual-ported memory interface to the TMS320C25 development board for execution there. A full C-language compiler for the TMS320C25 also is available for program development on IBM PC-compatible machines.

The specific TMS320C25 development system selected for implementation of our real-time block compiler is produced by Spectrum Signal Processing, Inc. of Blaine, Washington. A copy of the specification sheet for this board is included in Figs. III.A-2a and III.A-2b. One clear advantage of the Spectrum Signal Processing development system is the availability of a hardware expansion connector that buffers the TMS320C25 data, address, and control buses off the board for interfacing to additional hardware. This feature provides support for multiboard configurations should the added throughput of a multiprocessor system be required. The hardware expansion connector also provides access to the twelve unallocated I/O ports that are not used by the TMS320C25 on the Spectrum development system board.

The Spectrum development system features only one channel of analog-to-digital and digital-to-analog interfacing. This is adequate for the processor designs presently being considered for implementation. (Analog interfacing for this system uses standard Burr-Brown signal conditioning modules so additional channels can be added readily as external hardware if needed at a later time.) Some investigators in the auditory field favor the development board available from Ariel because of its two-channels of analog interfacing. The Aerial board is alleged to have a lower noise analog front end based on manufacturer's specifications. In comparing the two systems, however, we find the Spectrum system better suited for the present design. The Spectrum board's analog front end, designed for 16-bit resolution, uses standard modules that are electrically specified at higher levels than the Ariel system. While the designers at Spectrum do not have their own independent specifications for their front end, there is no reason to suspect that their application significantly degrades the original Burr-Brown module specifications. Considering that both of these systems are

SPECTRUM

TMS320C25
Development System



The TMS320C25 Development System is an IBM PC plug-in board offering full support for digital signal processing applications using the TMS320C25 from Texas Instruments.

Features

- IBM PC, XT, AT plug-in board.
- TMS320C25 processor.
- High speed 16 bit A/D and D/A.
- Sample-and-hold on input.
- 128 Kwords on-board memory capacity.
- Monitor software including single step, breakpoint, and full speed operation.
- Hardware expansion connector.

The TMS320C25 Development Systems offers a general purpose solution to most DSP development needs.

The system runs at full speed (40 MHz) with 35ns on-board RAM and a general purpose on-board timer.

The PC board is configured to handle either analog, serial, or parallel I/O. The hardware expansion connector allows access to the address, control, and data busses of the TMS320C25. The system also supports multi-board configurations.

True dual-ported memory allows users to view and modify program or data memory while the TMS320C25 is running. The host processor and C25 processor can interrupt each other for efficient real time operation.

Development Support

To assist the user in developing applications the system comes with a complete debug monitor which provides single step, breakpoint, and full speed operation. The debug monitor also allows the processor registers and memory to be examined and modified, and includes a disassembler.

Sample programs familiarize the user with program development and give good examples of how a TMS320C25 based system can be used in the PC environment. These sample programs include a 128 point FFT, a FIR filter, and a data logger. Source code for these programs is included as part of the system documentation. Spectrum also supplies TI's Macro Assembler/Linker for the TMS32020/C25 processors.

Data Acquisition and Analysis Software

Spectrum offers SignaLink320 which manages real-time data acquisition and display of signals for the TMS320C25 Development System.

SignaLink320 acquires and stores signals in the on-board memory of the system, where they can be displayed, reprocessed by the hardware, or loaded into a PC file. The software provides high speed pan and zoom, cursor display, peak detection, signal editing, and other functions which allow the user to quickly evaluate large data files.

SignaLink320 also provides an interface to the DADiSP data analysis spreadsheet package from DSP Development Corp. For further information, please refer to the DSP Data Acquisition and Analysis Software data sheet. Demo disks are available.

SPECTRUM SIGNAL PROCESSING INC — AN AFFILIATE OF LOUGHBOROUGH SOUND IMAGES

Fig. III.A-2a. TMS320C25 Development System

SPECIFICATIONS

1. **Processor**
   TMS320C25 running at 40 MHz clock rate.
   16-bit processing including 16 x 16 hardware multiplier, and 32 bit ALU.
   544 words (16 bit) of internal RAM.
   8 auxiliary registers for address pointers and loop counters.
   Internal interval timer.

2. **Memory**
   System comes with 16 Kwords 35ns RAM.
   Supports up to 128K words (16 bit) of on-board memory, link programmable for RAM or EPROM.
   Fast access to memory from IBM PC via I/O ports inserting only one extra wait cycle to TMS320C25 operation for each transfer.
   Selectable wait state (0 or 1) to suit memory speed.

3. **Analog I/O Clocking Options**
   Main sample clock source is a 16 bit on-board interval timer, clocked at 10 MHz to provide precise time reference down to 153 Hz.
   Software generated sampling can be used.
   External clocking that can be easily linked to the internal clock of another board for synchronous sampling.
   Sample clock can be used as processor interrupt.

4. **Analog Input**
   16 bit A/D, conversion time 17 µs, or 12 bit A/D, conversion time <10 µs.
   Voltage range ± 10V.
   Sample-and-hold on input.

5. **Analog Output**
   16 bit D/A, settling time 3µs.
   Voltage range ± 10V.

6. **Interface to PC Host**
   Option 1: Full handshaking16 bit bidirectional register as port to both processors, with status line signalling.
   Option 2: Block transfers through 1 of 8 selectable I/O spaces. (ports)

7. **Hardware Expansion Connector**
   TMS320C25 data, address, and control busses buffered to 50 pin expansion connector to facilitate addition of extra hardware by user.

8. **Serial Interface**
   Two separate 10 pin connectors for serial input and output data, clock and control.
   Cross-connection of cables possible for board linking.

9. **Physical**
   Full length IBM PC plug-in card.
   Dimensions: 13 3/8"l x 4 1/2"h x 5/8"d.

10. **Electrical**
    Power consumption: 5 volts @ 2 Amps from PC supply.

ORDERING INFORMATION:

		Part No.
Description:	TMS320C25 Development System	600-00103
	Documentation Only	601-00120
	* TMS32020/C25 Macro Assembler/Linker from Texas Instruments	100-00090
	* SignaLink320	600-00121
	* DADiSP	100-00054

* These products are not included with the TMS320C25 Development System, and are available separately from Spectrum Signal Processing Inc.

 D/S 601-00139-AB

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1-800-323-1842

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Blaine, WA 98230
U.S. 1-800-663-8986

Litho'd in Canada

Fig. III.A-2b. TMS320C25 Development System designed for 16-bit resolution, any degradation of signal is highly unlikely to present any problem of signal sample quality. Otherwise, the Spectrum development board is clearly the superior choice because of its hardware expansion connector as discussed above.

TMS320C25 Real-Time Processor--Software Considerations

There are three major considerations in the design of software for the TMS320C25 system. These include (1) speed of the processing code to insure real-time operation, (2) range of the processing code to insure breadth of emulation capabilities, and (3) structure of the processing code to enable true block diagram emulation and monitoring. It is clear that these categories are not fully independent and that each has significant bearing upon the design of the others. The following discussion describes a system architecture that has been designed to achieve all of these objectives.

The processing speed necessary to achieve real-time processor operation is not a significant problem for processing strategies of a complexity like that of designs presently in use. The TMS320C25 is a highly optimized device for signal processing problems. For instance, a two-pole recursive filter calculation can be performed in 1.2 usec on the TMS320C25. Assuming that filter operations are one of the more intensive functional block activities, more than eighty such computations could be carried out in one sampling period at a 10 kHz sampling rate. A more reasonable estimate for the number of filter operations required for, say, an eight-channel vocoder band-pass filter block design might be on the order of twenty. As proof in point, the 3M Company's experimental Sprint processor uses a TMS320 family microprocessor that functions at half the TMS320C25's speed, yet demonstrates impressive computation capabilities. The original Sprint design featured a bank of nine resonators (narrowly tuned bandpass filters) each followed by multi-segment compressors (S.D. Soli, personal communication). The Sprint substrate also has been demonstrated to support a continuous analog six-channel design very similar to the Symbion four-channel processing strategy.

A second consideration is the breadth of emulation capability. Previous experience with the present block compiler has demonstrated in principle that block diagram structuring of processing strategies is effective. Vocoder-based frequency analysis strategies are easily implemented on the TSM320C25 substrate. Feature extraction strategies (that used in the Nucleus prosthesis, for instance) also have been simulated on the block diagram compiler (Wilson, et al., 1986b). Morris and Barszczewski (1987) recently have demonstrated very powerful feature extraction algorithms running on the relatively slow TMS320C10 system. Currently these tools are being migrated to the TMS320C25. Dr. Morris is collaborating with us to transfer this capability to our laboratory (see section II.H.).

As outlined above, the block diagram compiler software runs on the PC for maximal flexibility of interaction with the operator. The compiler generates an intermediate TMS320C25 assembly code listing that then is cross-assembled, downloaded to the TMS320C25 system, and executed there. A simple, in-line code structure that sequentially links functional blocks in a fixed computational order will be used to maintain the block diagram architecture of the simulated system. Each functional block is a dedicated in-line code module that has an entry point, a list of nodal input addresses, local computational buffers, local parametric constants, dedicated computation code, a global reset flag facility, a list of nodal output addresses, and a branch point to the next functional block. Processing occurs on a time slice basis, with each new input value processed for each functional block once during each sampling period (100 usec). Before a new output value is computed for a block, all forward path inputs to the block must already have been computed. The order of computation is defined by the branching path of the in-line code structure. This path is determined once by the compiler software prior to generation of the assembly code module. All variable and parameter locations are indirectly addressed to facilitate interaction of the real-time software with monitoring and control software running simultaneously on the PC. Interactions between separate programs running on the PC and the TMS320C25 are essentially transparent to both programs through the use of a dual-ported memory interface. The PC, by establishing an address buffer, may read or modify that address location in the TMS320C25 memory space without significant effect on TMS320C25 operation. (A maximum of one wait state may be imposed on memory access time if both the PC and the TMS320C25 happen to compete for the same address.)

For monitoring purposes the operator can select a node in the simulated system and direct the current value always to be written to the D/A converter for monitoring on an oscilloscope. Similarly, the operator can select a single node or multiple nodes for monitoring during each sample period via screen display or disk storage by the PC. Such operations may be specified even while the processor is running in the TMS320C25, through use of the dual-ported memory.

In a like manner, the operator may manipulate functional block parameters during processor operation. This capability, while suggesting an attractive opportunity for processor optimization, must be viewed with caution on two fronts. First, there is the question of patient safety and comfort in the face of (1) unpredictable transients that might occur as the buffers in each functional block track toward a new operational state and (2) operator error in changing parameters. A variety of techniques are available for protection against this problem, including temporary suppression of outputs pending verification of the new processor state. The second--and greater--concern is the risk that the operator, given the opportunity, may adopt an optimization strategy based on "knob twisting" rather than one based on systematic design and evaluation principles. We are particularly sensitive--and resistant--to this danger. Little new knowledge will come from the former approach, whereas carefully designed parametric studies conducted to test concrete hypotheses will afford the greatest opportunity for learning. Section III.B describes in detail our basic philosophy on this issue and gives examples of the test strategies and analysis tools we plan to employ using the real-time block compiler.

Summary

The proposed Real-Time Block Compiler, then, will be a highly flexible piece of software capable of producing code that can be executed on a highly general bench processor in real time, thus emulating practically any definable speech processing strategy. At least eight channels of stimulation will be supported, as will both analog and pulsatile processing strategies. Interfaces will be provided to a variety of available implanted receivers and electrodes. The processor code resident in the TMS320C25 memory will be a mixture of two types of modules: (1) the unique configuration of processing modules required to realize the compiled strategy of speech processing in real time and (2) an assortment of additional modules required for real-time monitoring, modification and manipulation of the candidate processor during clinical testing. The panoply of available type (1) modules will allow realization of a variety of both frequency filtering and cue extraction approaches.

III.B. Evaluation of Different Speech Processing Techniques in Tests with Implanted Human Subjects

The main purpose of our planned work to evaluate different speech processing techniques is to confirm, refine, and extend our previous comparisons of processing techniques across a much wider range of patients and implant systems. We will continue to emphasize comparisons of the multichannel compressed analog (CA) and interleaved pulses (IP) processors. The results from such comparisons should add substantially to our base of knowledge on how these fundamentally different processing strategies perform with different types of patients and with different types of implant systems. Because many variables are controlled in direct comparisons of processing strategies with individual patients, studies of this kind can be powerful and economical ways to define and improve the performance of auditory prostheses.

A major effort of the proposed project will be to augment and improve the methods we use for the evaluation of speech processing techniques. We plan to use feature transmission analysis of consonant and vowel confusions to identify strengths and weaknesses of various processing strategies (see, e.g., Miller and Nicely, 1955). In addition, we will be using the new laser videodisc materials developed by the cochlear implant team at the University of Iowa. The videodisc contains audiovisual materials for assessing consonant, vowel, and sentence recognition. The primary speech signals are stored on one audio track and a six-talker babble is stored on the second audio track. The recording of speech babble supports studies of processor performance at various signal-to-noise ratios. Random access to all tokens on the videodisc also greatly facilitates computer control of randomized presentations in tests of vowel and consonant confusions. Speech test materials from other laboratories are becoming available on videodisc as well, and will be evaluated for possible use in our studies. Finally, in addition to the tests we have used in the past (see sections II.A and II.B of this proposal), we will be using the Speech Pattern Contrast (SPAC) test developed by Arthur Boothroyd for measurements of the speech perception abilities of patients with cochlear implants (1987) and of subjects with sensorineural hearing loss (1984). Preliminary applications in our laboratory of the SPAC test and feature transmission analysis indicate that both will be highly effective tools for the evaluation of alternative speech processing techniques.

In addition to the work to compare the CA and IP processing strategies, we will be evaluating new processing strategies in studies with patients who can donate a sufficient amount of time for further testing. To minimize the time for evaluation of new strategies, and to maximize the information resulting from the evaluation, we will rely on the SPAC and consonant and vowel confusion tests mentioned above. Results from the SPAC test and from feature transmission analysis of consonant and vowel confusions are excellent indicators of processor performance. The SPAC test typically requires 40 minutes to complete (when two randomizations of the test are used) and the vowel and consonant tests typically require two hours to complete (when ten repetitions of each of 20 consonants and 10 vowels are used). These tests provide a useful picture of processor performance with a minimum investment of precious testing time.

The new processing strategies will include promising variations of the IP strategy. Hypothesis-directed evaluation of these variations will allow us to build on the foundation of knowledge and excellent performance already obtained with IP processors.

We also will evaluate the hybrid CA/IP processor described in section II.A of this proposal (see pp. 22-24). Results from preliminary tests with hybrid processors (in studies with one of the 3M patients) have been encouraging.

Finally, as time with patients permits, we will be evaluating still other types of processors. These will include multichannel CA strategies with cross-coupled output compressors (White, 1986) and strategies for selective enhancement of particular speech features (e.g., see Guelke, 1987 and Revoile et al., 1987). In addition, we will be evaluating various strategies for reducing the deleterious effects of competing noise and speech on the performance of auditory prostheses. Among these strategies will be enhancements of the spectral subtraction algorithm used in our present portable processor (see section II.F). Use of the Iowa videodisc system will greatly facilitate the studies of processor performance under various conditions of competing speech babble.

While first priority will be given to the comparisons of the CA and IP processors (in detailed studies using our entire battery of speech perception tests), we will evaluate new strategies whenever possible. A meaningful evaluation of a new strategy usually can be completed in one morning or afternoon of testing, and the results from such an evaluation are likely to lead to new insights and knowledge if the hypotheses are explicit. The evaluation of new strategies also can lead to important advances in processor design. Indeed, this was the path of initial testing and development for the IP processor.

Another key objective of the proposed project is to relate psychophysical measures to processor performance. The emphasis will be on measures that are likely to be correlated with the extent and pattern of nerve survival in the implanted ear. As outlined in section II.D of this proposal, we already routinely conduct psychophysical studies to measure (a) simultaneous and nonsimultaneous channel interactions; (b) the difference in thresholds to low frequency and high frequency sinusoids; (c) dynamic ranges between threshold and the onset of uncomfortably loud percepts for sinusoids and pulses; and (d) the difference in thresholds for monopolar and radial bipolar simulation with the UCSF electrode array. Pfingst and coworkers have demonstrated significant correlations between survival of spiral ganglion cells in the ears of test monkeys and measures (b) and (c) above (Pfingst et al., 1981; 1985; Pfingst and Sutton, 1983). In addition, the likelihood of such correlations for measure (a) and (d) above is supported by results from animal and human studies conducted by Gardi (1985), Merzenich et al. (1978), Merzenich and White (1977), Van den Honert and Stypulkwoski (1987), Shannon (1983b; 1985a), and White et al. (1984).

In the proposed project we will continue to conduct psychophysical studies to obtain the measures just listed. In addition, we will obtain several other psychophysical measures that may be related to nerve survival and/or the functional integrity of the central auditory pathways:

1. Pfingst and coworkers (1985) have demonstrated a significant correlation between measures of channel discriminations and ganglion cell survival in studies with monkeys. Poor (or absent) channel discrimination in tests with human subjects may also indicate areas of neuronal loss or damage in the implanted ear.

2. Temporal difference limens and measures of gap detection have been correlated with performance on speech perception tests for patients using the 3M/Vienna device (Hochmair-Desoyer et al., 1985). These psychophysical measures may reflect the functional integrity of central auditory structures. It will be important to learn whether significant correlations are also found for these measures and speech perception scores for other types of speech processors and implant systems.

3. Additional measures that may be related to nerve survival include frequency discrimination (Pfingst et al., 1988), loudness growth curves (Merzenich et al., 1978; Shannon, 1985b), and differences in thresholds to single and multiple pulses (White et al., 1987). These measures will be obtained for selected patients.

The results from the psychophysical studies will be valuable for interpreting findings from the speech perception studies and for selecting parameters for different processing strategies. It will be interesting to learn, for example, whether certain of these measures are correlated with indicators of processor performance. Demonstrated correlations may be quite useful for predicting levels of performance for individual patients, for selecting the best type of speech processor for each patient, and for setting the parameters of that processor. Such correlations (or lack of correlations) also would be of great value in helping us attain a better understanding of the bases of patient and processor performance with cochlear implants. We plan to conduct psychophysical studies (a) through (d) above with every tested patient who has the UCSF/MiniMed device so that the possibilities of correlations among psychophysical and speech perception measures can be evaluated. We also will conduct the additional psychophysical studies listed above with patients who can contribute a sufficient amount of time.

It is important to note that the availability of carefully collected psychophysical data will be extremely valuable for post mortem studies of nerve survival in the implanted ear. The direct histological measures of nerve survival can then be correlated with the psychophysical measures. Strong correlations would validate the indirect measures of nerve survival and weak (or absent) correlations would invalidate the use of these measures for the purpose of inferring the pattern of nerve survival. We understand that all patients implanted at UCSF are asked whether they would be willing to donate their temporal bones at death for post mortem studies. We will suggest that the same request be made to patients implanted at our other collaborating institutions. We will be delighted to work with investigators conducting post mortem studies by supplying all relevant psychophysical and speech testing data. We also will assist in the retrospective interpretation of these data in the light of the histological findings.

A final aspect of our planned work is design and evaluation of speech processors for central nervous system auditory prostheses and extracochlear (lateral wall) auditory prostheses. An extracochlear prosthesis may be especially useful for pediatric applications and the CNS auditory prosthesis is required for restoration of some hearing in patients with bilateral loss of the auditory nerve. Work related to the further development of these prostheses is presented below in the subsections titled "Central Nervous System Auditory Prosthesis" and "Lateral Wall Implants."

The remainder of this section will include additional information on the patients who have been identified for participation in the studies of the proposed project, the aforementioned additional information on the CNS and lateral wall auditory prostheses, and some concluding remarks.

Patients

An important contributor to our perspective on the design and evaluation of speech processors for auditory prostheses is our experience with different types of implant patients and prosthesis systems. As indicated in section II.C, this experience has emphasized the likely importance of patient variables on the results obtained with cochlear implants. Moreover, work with a number of different implant devices has provided insights into prosthesis design that would have been totally missed if our studies were limited to patients with a single implant system. Further work with groups of patients using different prostheses will build on this experience and will most likely provide additional insights into the relative importance of different electrode coupling configurations, speech processing strategies, number of stimulation channels, etc.

We plan to broaden the range of studied patients and prosthesis systems in the proposed project. The prosthesis systems will include the new generation of the UCSF device (8 radial bipolar or 16 monopolar stimulus channels, flexible speech processor, highly transparent transcutaneous transmission system), the Symbion device (4 channels, monopolar, percutaneous connector), the Nucleus device (up to 21 pairs of lateral bipolar electrodes, transcutaneous transmission system) and an experimental extracochlear device (see subsection below on "Lateral Wall Implants"). In addition, we will continue our studies with patients implanted with the UCSF/Storz device and with patients implanted with the 3M/Vienna device.

A summary of patients presently identified as candidates for the studies outlined in this proposal is presented in Table III.B-1. Patients implanted with the UCSF/MiniMed device will come to us through our collaboration with the implant centers at UCSF and Duke University Medical Center (DUMC). At this time, we estimate that up to 24 patients implanted with this device may be available for our studies. In addition, we have arranged to study four to five patients implanted with the Symbion device. We will begin studies with these patients in the current contract period, but expect that the studies with Symbion patients will continue into the period of the proposed project. All studies with the Symbion patients will be conducted in collaboration with Dr. D.K. Eddington of the Massachusetts Eye and Ear Infirmary (MEEI). Patients implanted with the Nucleus device will be referred to us from the implant centers at the University of North Carolina Memorial Hospital (UNC Memorial), DUMC and Washington University

TABLE III.B-1. Patients Presently Identified as Candidates for Participation in the Studies Outlined in this Proposal.

Number of Patients	Device	Referring Institution[a]
up to 20	UCSF/MiniMed	UCSF
about 4	"	DUMC
4 or 5	Symbion	MEEI
up to 30	Nucleus	UNC Memorial
about 4	"	DUMC
2 or more	"	WUMC
about 4	3M/Vienna	UNC Memorial
1 or 2	lateral wall implant	KHRI/UM

[a]Abbreviations for the referring institutions are UCSF for University of California at San Francisco; DUMC for Duke University Medical Center; MEEI for Massachusetts Eye and Ear Infirmary; UNC Memorial for University of North Carolina Memorial Hospital; WUMC for Washington University Medical Center; and KHRI/UM for Kresge Hearing Research Institute at the University of Michigan.

Medical Center (WUMC). Up to 36 patients with the Nucleus device are now identified as candidates for our studies. Patients implanted with the 3M/Vienna device also will be made available to us through our collaboration with UNC Memorial. Finally, we expect to study one or two patients with lateral wall implants during the course of the proposed project. Work with these patients will be done in collaboration with the Kresge Hearing Research Institute at the University of Michigan (KHRI/UM).

We anticipate intensive studies with approximately ten patients for each year of the proposed project. As outlined in section VI, this estimate is based on our experience during the past year of our current project. Inasmuch as approximately seventy patients have already been identified as candidates for future studies, we are confident that more than enough patients will be available for the proposed project.

Letters of support from Drs. W.R. Hudson and B.A. Weber of the DUMC, Dr. R.A. Schindler of UCSF, Dr. M.W. Skinner of WUMC, Dr. J.M. Miller of KHRI/UM, and Dr. H.C. Pillsbury of UNC Memorial are presented in section X.B of this proposal. Each of these letters expresses a desire and commitment to provide implant patients for participation in our proposed studies at Duke. Because studies with the Symbion patients from the MEEI will begin in the present contract period, and because Dr. Eddington has already planned these studies with our group, a letter of support was not solicited from him for this proposal.

Finally, we note that not all of the proposed studies can be conducted with each of the prosthesis systems listed in Table III.B-1. For example, the transcutaneous transmission system of the Nucleus device does not allow the use of any type of stimulus except pulses. Therefore, it will not be possible to compare the CA and IP processing strategies in tests with Nucleus patients. We will, however, be able to (a) compare the IP strategy with the feature-extraction strategy used in the Nucleus speech processor (b) obtain many of the psychophysical measures described above. These studies, although limited, will nevertheless provide valuable information.

Central Nervous System Auditory Prosthesis

We have submitted a subcontract proposal to KHRI/UM for the design and evaluation of speech processors for auditory prostheses with stimulating electrodes placed in or on the cochlear nucleus. This subcontract proposal is reproduced here as one of the supporting documents (section X.C). The subcontract proposal accompanied KHRI/UM's primary response to RFP No. NIH-NINCDS-88-03, "Feasibility of a Central Nervous System Auditory Prosthesis."

As outlined in the subcontract proposal, we believe a collaborative study with KHRI/UM will accelerate the introduction of a safe and effective CNS auditory prosthesis into the clinical armamentarium. We are including a copy of the subcontract proposal in this present proposal to provide complete information on our plans for studies related to the development of CNS auditory prostheses. The level of professional effort proposed for the subcontract project is 0.43 person years for each of the three project years. This level of effort would not compromise in any way our ability to dedicate the levels of effort outlined in section VI of this proposal for the present project. Indeed, we would regard the two projects as complementary in that information obtained in one project is likely to be relevant to the work of the other.

Lateral Wall Implants

An electrode system for implants into the lateral wall of the otic capsule has been developed at the KHRI/UM (Miller et al., 1987). The system allows for the placement and anchoring of several extracochlear electrodes without disruption of the ossicular chain. Moreover, results from behavioral studies with monkeys have demonstrated reliable discrimination of the percepts elicited by stimulation at the different electrode sites (Pfingst et al., 1985). These findings suggest that a useful multichannel auditory prosthesis might be based on lateral wall implants. Such extracochlear devices could be used in cases where an intracochlear implant is impossible (e.g., in the cases of an ossified or malformed cochlea) or in pediatric implants. An extracochlear device is desirable for pediatric implants because any sensorineural elements remaining in the cochlea may be better preserved with an extracochlear device than with an intracochlear device (see discussion in Tyler et al., 1987; see Leake et al., 1985 and Sutton, 1984). Because profound deafness cannot be diagnosed with certainty before the age of three (Tyler et al., 1987), an ideal auditory prosthesis for infants and very young children would preserve the ossicular chain and intracochlear structures that may support useful residual hearing in later years.

As indicated in Dr. Miller's letter (see section X.B), all studies proposed for the present project will be with adults who cannot be implanted with intracochlear devices. The purpose of the speech perception studies will be to determine whether certain processing strategies that are highly effective for scala tympani implants can be successfully applied for patients with lateral wall implants. We note that lateral wall implants are likely to have a small number of stimulating channels (e.g., two or three) and high interactions among the available channels (Coninx, 1987).

Effective speech processors will have to function within these constraints. The Breeuwer/Plomp and interleaved pulses (IP) processors described in sections II.A and II.B of this proposal are specifically designed to reduce channel interactions with the use of nonsimultaneous stimuli. In addition, the Breeuwer/Plomp processor supports excellent levels of speech recognition with only two discriminable channels of stimulation. We therefore will begin our studies of speech processors for lateral wall implants with the speech perception abilities of the patients with lateral wall implants will be measured with a variety of tests. These tests will minimally include vowel and consonant identifications and the Speech Pattern Contrast test (Boothroyd, 1987). If time permits, we also will administer all tests of the Minimal Auditory Capabilities (MAC) battery (Owens et al., 1985) and tests of connected discourse tracking with and without the prosthesis (De Filippo and Scott, 1978; Owens and Raggio, 1987).

We expect to test one or two patients with lateral wall implants during the course of the proposed project. Studies with these patients will be conducted in collaboration with the KHRI/UM group.

Concluding Remarks

Our proposed project builds on our past work to compare the CA and IP processing strategies. In the proposed project we will extend such comparisons to a broader range of patients and implant systems. We also will be using more powerful evaluation tools. Notable among these tools are feature transmission analysis of vowel and consonant confusions, the Iowa videodisc system, and the Speech Pattern Contrast test.

In addition to the work to compare the CA and IP processing strategies, we will be evaluating many new processing strategies in studies with selected patients. These strategies will include promising variations of the existing IP strategy; the hybrid CA/IP strategy; CA strategies with cross-coupled output compressors; strategies for enhancement of particular speech features; and strategies for reducing the deleterious effects of background sounds other than the primary speech signal.

Another objective of the proposed project is to relate psychophysical measures to processor performance. The psychophysical measures will include (a) simultaneous and nonsimultaneous channel interactions; (b) the difference in thresholds to low frequency and high frequency sinusoids; (c) dynamic ranges between threshold and the onset of uncomfortably loud percepts for sinusoids and pulses; (d) the difference in thresholds for monopolar and radial bipolar stimulation for patients implanted with the UCSF/MiniMed electrode array; (e) gap detection; (f) frequency difference limens (DLs) at various standard frequencies and levels of presentation; (g) loudness growth curves; (h) thresholds to single and multiple pulses; and (i) channel discriminations. Measure (a) will be obtained for all studied patients with multichannel implants, and measures (b) and (c) will be obtained for all patients. Measure (d) will be obtained for all patients implanted with the UCSF/MiniMed device. The remaining measures will be obtained for patients who can contribute a sufficient amount of time for the tests.

As outlined before, each of these psychophysical measures may reflect in some way the extent, pattern, and/or functional consequences of nerve survival in the implanted ear. Possible correlations of these measures with measures of processor and patient performance will be evaluated. Also, we hope that some patients will agree to donate their temporal bones for post mortem studies. In such cases direct measures of nerve survival can be compared with the indirect psychophysical measures. These comparisons will help to validate (or invalidate) the use of the listed psychophysical measures for the purpose of evaluating nerve survival.

In this section we have very briefly reviewed our plan for the evaluation of different speech processing techniques in implanted human subjects. This plan addresses the specific requirements presented in the work statement with the exception of the requirement to account for differences among subjects based on learning effects. Our approach for meeting this requirement is presented in Section III.D of this proposal, "Evaluation of Learning Effects."

III.C. Design and Fabrication of Wearable Speech Processors

As discussed in section III.A above, when a speech processor is running on the Real-Time Block Compiler the code modules resident in the TMS320C25 memory can be described as a mixture of two types: (1) the sequence of modules that actually accomplish the real-time speech processing, and (2) an assortment of additional modules dedicated to monitoring, modification and manipulation of the candidate processor during laboratory testing. If a TMS320C25 substrate is chosen for a portable processor to evaluate the same strategy under routine use by a patient outside the laboratory, conversion to the code appropriate to that device can be as simple as retaining the type (1) modules from the bench-level device, dispensing with those of type (2), and adding certain additional modules.

Such additional modules will include code to monitor the batteries of the portable unit, implement its squelch, AGC, safety limit, and noise reduction functions, and provide a startup self-test and patient controls--in short, to provide features quite similar to those already developed by us for the more limited real-time processor design presented in section II.F above.

The TMS320C25 itself is a highly attractive candidate microprocessor in allowing use of code modules identical to those of the real-time block compiler. While it is a CMOS device, however, its approximately 1000mW maximum power consumption is quite high in the context of a wearable, battery powered system. The possibility of its use will be thoroughly explored, including possible power-saving measures during squelch intervals and the benefits to be gained from the most recent battery technology.

Package size and weight, frequency of battery changes, and battery life all factor strongly into the final design equation in terms of user acceptance, user convenience, and operating expense. If the power consumption of the TMS320C25 proves an insurmountable hurdle, use of another member of the TMS320 family of devices may minimize the task of code conversion between laboratory and wearable versions of a processing strategy. Figure III.C-1 is a summary chart of the characteristics of TMS320 family members. Several of the devices comprising the first generation of the TMS320 family offer substantially lower power consumption figures and have been used successfully for processing tasks of comparable complexity. (see section III.A above).

In addition, we have become quite familiar with the Motorola 68HC11 and National Semiconductor HPC families of microprocessors through our

TMS320 FAMILY COMPARISON

GENERATION	DEVICE	TECHNOLOGY	CYCLE TIME (ns)	TYPICAL POWER (W)	DATA TYPE	ON-CHIP MEMORY RAM	ON-CHIP MEMORY ROM	ON-CHIP MEMORY EPROM	ON-CHIP MEMORY CACHE	TOTAL MEMORY SPACE	I/O PARALLEL	I/O SERIAL	I/O DMA	TIMERS	HIGH-LEVEL LANGUAGE	MILITARY VERSIONS
1ST	TMS32010	NMOS	200	.9	16-bit integer	144	1.5K	-	-	4K	8	-	-	-	3rd party	Now
	TMS32010-14	NMOS	320	.9	16-bit integer	144	1.5K	-	-	4K	8	-	-	-	3rd party	-
	TMS32010-25	NMOS	160	.9	16-bit integer	144	1.5K	-	-	4K	8	-	-	-	3rd party	-
	TMS32011	NMOS	200	.9	16-bit integer	144	1.5K	-	-	1.5K	6	2	-	1	3rd party	-
	TMS320C10	CMOS	200	.165	16-bit integer	144	1.5K	-	-	4K	8	-	-	-	3rd party	Planned
	TMS320C10-25	CMOS	160	.2	16-bit integer	144	1.5K	-	-	4K	8	-	-	-	3rd party	-
	TMS320E15	CMOS	200	.3	16-bit integer	256	-	4K	-	4K	8	-	-	-	3rd party	Planned
	TMS320C15	CMOS	200	.225	16-bit integer	256	4K	-	-	4K	8	-	-	-	3rd party	Planned
	TMS320C15-25	CMOS	160	.25	16-bit integer	256	4K	-	-	4K	8	-	-	-	3rd party	-
	TMS320E17	CMOS	200	.325	16-bit integer	256	-	4K	-	4K	6	2	-	1	3rd party	-
	TMS320C17	CMOS	200	.25	16-bit integer	256	4K	-	-	4K	6	2	-	1	3rd party	-
	TMS320C17-25	CMOS	160	.275	16-bit integer	256	4K	-	-	4K	6	2	-	1	3rd party	-
2ND	TMS32020	NMOS	200	1.5	16-bit integer	544	-	-	-	128K	16	1	†	1	C compiler	Planned
	TMS320C25	CMOS	100	1.0	16-bit integer	544	4K	-	-	128K	16	1	†	1	C compiler	Planned
3RD	TMS320C30	CMOS	60	1.0	32-bit F/I*	2K	4K	-	64	16M	**	2	‡	2	C compiler	Planned

* Floating-Point/Integer
** Unlimited
† External DMA
‡ Internal/External DMA

Summary Chart of Device Characteristics
of Members of TI TMS320 Family of
Digital Signal Processors

(excerpted from TI publication SPRT 036, "Texas Instruments TMS320C30 Preview Bulletin")

Figure III.C-1.

collaboration with UCSF in the development of a next-generation auditory prosthesis (see section II.G.). This experience, plus the 80C51-based work described in section II.F, leaves us well prepared for the proposed electronic design work.

Our experience in the areas of human engineering and packaging with respect to our portable IP processor, both outlined and pictured in section II.F above, demonstrates a strong creative background for these aspects of the proposed work.

We expect that the first of these wearable devices will be available by the the end of the first year of the project. As required by the contract, two certainly will be in use before the end of the second year. Our expectation is to provide at least one patient per year with such a device. Based on our experience testing patients already fitted with a variety of cochlear implants and our assured access to patients over the next three years, we anticipate no difficulty whatever in identifying and obtaining the cooperation of appropriate subjects for such studies.

III.D. Evaluation of Learning Effects

In the context of the small number of wearable speech processors required to be placed in service for this RFP, assessment of learning effects can at most be anecdotal. While it is hoped that substantial numbers of subjects can be studied eventually, the presently proposed project will not be able to study sufficient numbers of patients to control for differences among processing strategies, extent of nerve survival, order effects, training effects and patient cognitive skills. We can begin to gather a useful body of general data as to how a patient's ability to comprehend speech changes with time after receiving an auditory prosthesis.

We recently have reported an analysis of post implantation evaluations up to one year after surgery for sixteen patients using the compressed analog (CA) coding strategy at UCSF (Wilson et al., 1988c). All subjects were participating in the clinical trials assessment of the UCSF/Storz implant system. In the clinical UCSF/Storz device alternate pairs of the eight available electrode pairs of the UCSF electrode are stimulated simultaneously with the "compressed analog" 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.

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 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. For this discussion we restrict our attention to the most recent results (as of August, 1987) from the MAC battery. Earlier results from the MAC battery and results from the other tests may be found in Schindler and

Kessler (1987) and Schindler et al. (1986).

Results from the speech perception tests of the MAC battery for patients implanted with the UCSF/Storz prosthesis are presented in Table III.D-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).

A pattern of improvements in the scores of speech perception tests after the initial postoperative evaluation is also evident in Table III.D-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. III.D-1 which shows the mean scores of Table III.D-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.

TABLE III.D-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] (N=16)	Postoperative Initial (N=16)	Postoperative 6-8 Weeks (N=14)	Postoperative 6 Months (N=14)	Postoperative 1 Year (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 the closed-set tests.

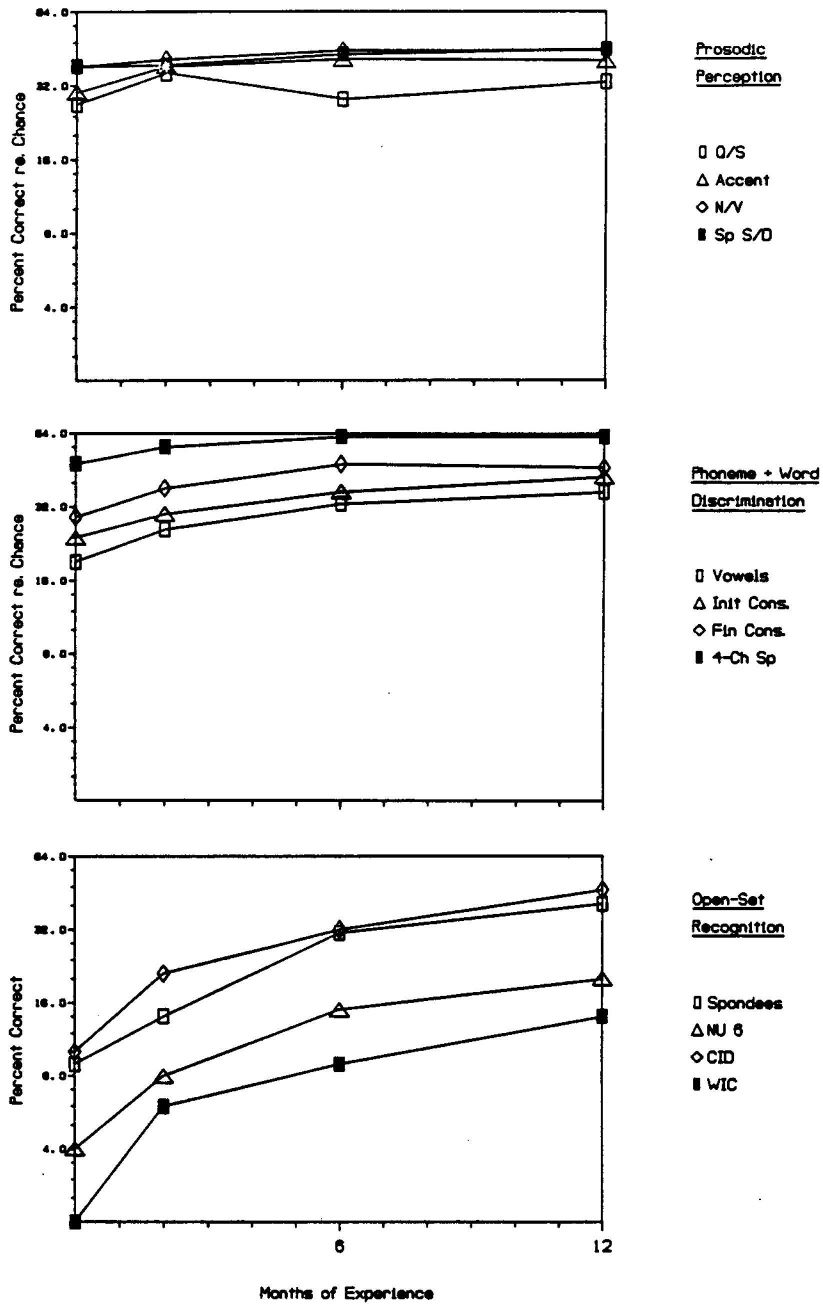

Fig. III.D-1. Plots of the mean scores presented in Table III.D-1 for follow-up evaluations of UCSF/Storz patients. Chance levels are subtracted from the scores of the closed-set tests to indicate actual performance with respect to chance. Abbreviations for the subtests of the Minimal Auditory Capabilities (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.

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. It is clear from Fig. III.D-1 that the rate of improvement is steepest in the 0 to 2 month period. Therefore studies designed to assess improvements should include frequent reassessments early in the post-implantation period. The present schedule of 0, 2, 6 and 12 months appears to be a reasonable temporal spacing. reassessments at even later dates would be appropriate for tests involving open-set recognition.

In addition to the repeated MAC battery speech tests used here, various psychophysical tests may be appropriate. Hochmair-Desoyer and Burian (1985) have reported in two patients who showed improvements over time with NU6 and CID everyday sentence testing that amplitude difference limens decreased, pitch saturation levels increased and frequency difference limens decreased over approximately the same period. We routinely perform psychophysical tests such as thresholds and dynamic ranges on repeated visits at long intervals; however these particular measures have not been included due to limits on time for testing.

Other attractive test options that may be considered for assessing improvement over time are vowel and consonant confusion tests and the Speech Pattern Contrast Test (SPAC) test (Boothroyd, 1987). To complicate matters, test time is quite limited during patient visits and frequent retests of the lengthy MAC battery lead to subject familiarity with the test material. At this time we are not prepared to chose a final battery of tests as optimal for use at reassessment intervals. We plan to evaluate the presently available data using information transfer analysis (Miller and Nicely, 1955) for additional insight into the nature of the speech comprehension improvements that we have seen to date. Based on these results we will be better prepared to design a test battery that is highly sensitive to performance improvements.

IV. Team Capabilities

Almost all of the work outlined in this proposal will be performed by members of the joint Duke/RTI Cochlear Implant Team. This team is highly experienced in (1) the design and evaluation of speech processors for auditory prostheses; (2) the efficient handling and care of referral patients who visit Duke to participate in research studies; and (3) the clinical application of cochlear implants. A record of reporting activity for the Duke/RTI Cochlear Implant Team for the period of February 1985 through February 1988is presented at the end of this section to indicate in greater detail the areas of experience and expertise possessed by the Team. We note that the great majority of the publications and presentations listed in the record of reporting activity describe work conducted under the auspices of our current project from the Neural Prosthesis Program (NIH project N01-NS-5-2396, "Speech Processors for Auditory Prostheses").

In addition to the strong capabilities and integrated approach of the team, the particular investigators identified for this project have experience in areas directly related to the proposed studies. The relevant experience for each investigator is indicated in the following table:

person	areas of expertise and experience
B. Wilson (RTI)	expert in the design and evaluation of speech processors for auditory prostheses; principal investigator for two related contracts for the Neural Prosthesis Program, both titled "Speech Processors for Auditory Prostheses" (N01-NS-3-2356 and N01-NS-5-2396).
C. Finley (RTI)	expert in modeling electric fields produced by various configurations of stimulating electrodes; expert in the design and evaluation of speech processors for auditory prostheses
D. Lawson (RTI)	expert in the design and evaluation of speech processors for auditory prostheses
R. Wolford (Duke)	expert in the evaluation of speech processors for auditory prostheses; expert in the handling and care of implant patients; member of the Audiology staff at Duke

As indicated elsewhere in this proposal (particularly in section V, Project Organization and Budget), the RTI/Duke investigators will be assisted by M.W. White of N.C. State University in Raleigh, S.D. Soli of the 3M Company in St. Paul, and R.V. Shannon of the Boys Town National Institute in Omaha. Dr. White will be helping us with the design of signal processing strategies (particularly for the design of "cross-coupled" compressors at the outputs of multichannel, compressed analog processors, see section III.B) and with the design and conduct of psychophysical studies to infer the extent and pattern of nerve survival in the implanted cochlea. Dr. Soli will be implementing at our laboratory software he has developed for feature transmission analysis of results from tests of vowel and consonant confusions. Dr. Soli also will be instructing us on the proper use of this software and reviewing our studies of speech perception with implant patients, both prospectively and retrospectively. Dr. Shannon will transfer technology he has developed for external control of the implantable receiver system used in the Nucleus auditory prosthesis. He also will transfer software he has developed for psychophysical and speech perception studies, and will provide prospective and retrospective reviews of our psychophysical studies with implant patients. Drs. White, Soli and Shannon are widely acknowledged experts in their respective fields. We are most fortunate to have them working with us.

CVs for B. Wilson, C. Finley, D. Lawson, R. Wolford, M. White, S. Soli and R. Shannon are presented in the section of supporting documents for this proposal (section X.E). Letters of commitment from M. White, S. Soli and R. Shannon are also presented in the section of supporting documents (section X.B).

Finally, we want to mention that the capabilities of our "core team" identified above will be greatly enhanced by our many collaborations. These collaborations are fully described in sections II.G and II.H of this proposal. Briefly, we have ongoing or planned joint projects with investigators at the University of California at San Francisco; the Kresge Hearing Research Institute at the University of Michigan; the Massachusetts Eye and Ear Infirmary in Boston; Washington University Medical Center in St. Louis; the Goethe Universitat in Frankfurt, West Germany; the 3M Company in St. Paul; Carleton University in Ottawa, Canada; and the House Ear Institute in Los Angeles. Among the collaborating investigators are D.K. Eddington (MEEI), R. Hartmann (Goethe Universitat), D.K. Kessler (UCSF), J.M. Miller (KHRI), M.M. Merzenich (UCSF), L.R. Morris (Carleton University), D.W. Nielsen (HEI), B.E. Pfingst (KHRI), R.A. Schindler (UCSF), M.W. Skinner (WUMC), and S.D. Soli (3M). The interest and contributions of these distinguished investigators are of great benefit to our program.

Record of Reporting Activity for the Duke/RTI Cochlear Implant Team

February, 1985 to February, 1988

This compilation of reporting activity for members of the Duke/RTI Cochlear Implant Team includes reports relevant to the cochlear implant field made in the form of publications, abstracts and presentations, major reports, patents, site visits and manuscripts in preparation.

1. Publications

Wilson, B.S.: Comparison of encoding schemes. Invited paper to be published in J.M. Miller and F.A. Spelman (Eds.), Models of the Electrically Stimulated Cochlea (Papers from the 25th Anniversary Symposium of the Kresge Hearing Research Institute, Oct. 3-5, 1988).

Finley, C.C.: 3D finite element analysis. Invited paper to be published in J.M. Miller and F.A. Spelman (Eds.), Models of the Electrically Stimulated Cochlea (Papers from the 25th Anniversary Symposium of the Kresge Hearing Research Institute, Oct. 3-5, 1988).

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.

Wilson, B.S (moderator), L.J. Dent, N. Dillier, D.K. Eddington, I.J. Hochmair-Desoyer, B.E. Pfingst, J. Patrick, W. Sürth and J. Walliker (panelists): Round table discussion on speech coding. In P. Banfai (Ed.), Cochlear Implants 1987, Springer-Verlag, in press.

Wilson, B.S., C.C. Finley, D.T. Lawson and R.D. Wolford: Speech processors for cochlear prostheses. In the special issue of Proc. IEEE on "Emerging Electromedical Systems," September, 1988, in press.

Wilson, B.S., C.C. Finley, J.C. Farmer, Jr., D.T. Lawson, B.A. Weber, R.D. Wolford, P.D. Kenan, M.W. White, M.M. Merzenich and R.A.

Schindler: Comparative studies of speech processing strategies for cochlear implants. Laryngoscope, in press.

Wilson, B.S., C.C. Finley, M.W. White and D.T. Lawson: Comparisons of processing strategies for multichannel auditory prostheses. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press, 1987, pp. 1908-1910.

White, M.W., C.C. Finley and B.S. Wilson: Electrical stimulation model of the auditory nerve: Stochastic response characteristics. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press, 1987, pp. 1906-1907.

Finley, C.C., B.S. Wilson and M.W. White: A finite-element model of bipolar field patterns in the electrically stimulated cochlea -- A two dimensional approximation. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press, 1987, pp. 1901-1903.

Kenan, P.D. and J.C. Farmer, Jr.: Cochlear implantation 1986: An overview, N.C. Med. J., 47: 7-11, 1986.

McElveen, J.T., Jr., W.E. Hitselberger, W.F. House, J.P. Mobley and L.I. Terr: Electrical stimulation of cochlear nucleus in man, Am. J. Otol., 6 (Supplement Part 2): 81-88, 1985.

2. Abstracts and Presentations

Finley, C.C.: Design considerations for auditory prostheses. Invited paper to be presented at the World Cong. on Med. Phys. and Biomed. Eng., San Antonio, TX, Aug. 6-12, 1988.

Finley, C.C.: Co-Chairman, Session on Auditory System Research. World Cong. on Med. Phys. and Biomed. Eng., San Antonio, TX, Aug. 6-12, 1988.

Wilson, B.S.: Various coding schemes used. Invited testimony to be presented at the Cochlear Implant Consensus Development Conf., National Institutes of Health, May 2-4, 1988.

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.: Review of RTI research on coding strategies for cochlear prostheses. Invited lecture presented at the 3M Company in St. Paul, MN, Nov. 12, 1987.

Wilson, B.S.: Speech processors for auditory prostheses. Presented at the Neural Prosthesis Workshop, 1983, 1984, 1985, 1986 and 1987.

Wilson, B.S.: Moderator, Speech Coding Panel, International Cochlear Implant Symposium 1987, Düren, West Germany, Sept. 7-11, 1987.

Schindler, R.A. and B.S. Wilson: Present status and future enhancements of the UCSF/RTI/Duke cochlear implant, Abstr. International Cochlear Implant Symposium 1987, Düren, West Germany, Sept. 7-11, 1987, p. 57.

Finley, C.C.: Status of current spread in auditory prostheses. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, New London, NH, June 29 - July 3, 1987.

Wilson, B.S.: Factors in coding speech for auditory prostheses. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, New London, NH, June 29 - July 3, 1987.

Finley, C.C.: Electrode design and stimulus shaping. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, New London, NH, June 29 - July 3, 1987.

Wilson, B.S., C.C. Finley, M.W. White and D.T. Lawson: Comparisons of processing strategies for multichannel auditory prostheses. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

White, M.W., C.C. Finley and B.S. Wilson: Electrical stimulation model of the auditory nerve: Stochastic response characteristics. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Finley, C.C., B.S. Wilson and M.W. White: A finite-element model of bipolar field patterns in the electrically stimulated cochlea -- A two dimensional approximation. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Finley, C.C., B.S. Wilson and M.W. White: Models of afferent neurons in the electrically stimulated ear. Invited paper presented in the special session on mathematical modeling related to functional electrical stimulation, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Farmer, J.C. Jr. and B.S. Wilson: Cochlear implantation for the profoundly deaf. Invited seminar presentation, Department of Physiology, Duke University Medical Center, June 18, 1987.

Wilson, B.S.: The RTI/Duke cochlear implant program. Presented to the Executive Committee of the Research Triangle Institute (RTI) Board of Governors, June 17, 1987.

Finley, C.C. and R.D. Wolford: Cochlear implants and the Duke Center for the Severely hearing Impaired. Invited lecture, Departments of Otolaryngology and Audiology, UNC School of Medicine, Chapel Hill, NC, May 8, 1987.

Wilson, B.S., C.C. Finley, J.C. Farmer, Jr., B.A. Weber, D.T. Lawson, R.D. Wolford, P.D. Kenan, M.W. White, M.M. Merzenich and R.A. Schindler: Comparative studies of speech processing strategies for cochlear implants. Abstracts of the 90th Annual Meeting of the Triological Society, Denver, CO, April 28-30, 1987.

Lawson, D.T.: Cochlear implants. Invited presentation in the UNC-Greensboro series of Psychology Colloquia, April 10, 1987.

Wolford, R.D.: Audiogram interpretation and the impact of severe hearing loss. Durham Regional Hearing Impaired Parents Organization, Durham, NC, March, 1987.

Wilson, B.S.: Cochlear implants. Invited lecture presented in the session on auditory signal processing, First North Carolina Workshop on Bioelectronics, Quail Roost, NC, Oct. 24-26, 1986.

Lawson, D.T.: Cochlear implants. Invited luncheon address at the Annual Meeting of the NC Regional chapter of the Acoustical Society of America, Tanglewood Park, NC, Oct. 9-10, 1986.

Weber, B.A. and Wolford, R.D.: The role of Audiology in the Otologic practice. Dept. of Otolaryngology, Duke University Medical Center, Durham, NC, Oct. 1986.

Wilson, B.S.: Processing strategies for cochlear implants. Invited faculty lecture for the special course on cochlear implants at the Annual Meeting of the American College of Otolaryngologists, San Antonio, TX, Sept. 18-19, 1986.

Kenan, P.D., J.C. Farmer, Jr., B.A. Weber and B.S. Wilson: Cochlear implants. Invited lecture presented at the Annual Meeting of the Mecklenberg County Otolaryngology, Head and Neck Surgery Soc., Charlotte, NC, Fall, 1986.

Wilson, B.S.: Ensemble models of neural discharge patterns evoked by intracochlear electrical stimulation. Invited speaker presentation at the IUPS Satellite Symposium on Advances in Auditory Neuroscience, San Francisco, CA, July 8-11, 1986.

Finley, C.C. and B.S. Wilson: Field patterns in the electrically-stimulated human cochlea, IUPS Satellite Symposium on Advances in Auditory Neuroscience, San Francisco, CA, July 8-11, 1986.

Wilson, B.S.: Coding strategies for cochlear implants. Invited speaker presentation at the Kresge Hearing Research Institute, University of Michigan, May 22, 1986.

McElveen, J.T., Jr., W.E. Hitselberger and W.F. House: Surgical accessibility of the cochlear nucleus complex in man. Presented at the annual meeting of the American Neurotology Society, Palm Beach, FL, May 2, 1986.

Wilson, B.S.: Comparison of strategies for coding speech with multichannel auditory prostheses. Invited faculty lecture presented at the Conference on Speech Recognition with Cochlear Implants, New York University, April 17-19, 1986.

Finley, C.C. and B.S. Wilson: Sampling of electric fields by myelinated intracochlear neurons. ARO Abstracts, 9th Midwinter Research Conference, p. 170, 1986.

Wilson, B.S. and C.C. Finley: Latency fields in electrically-evoked hearing. ARO Abstracts, 9th Midwinter Research Conference, pp. 170-171, 1986.

Wolford, R.D. and B.A. Weber: Cochlear implants: Clinical issues and future directions. Invited paper presented at the Annual Meeting of the NC Speech, Language and Hearing Association, Charlotte, NC, March, 1986.

Wolford, R.D.: Cochlear implants and the role of the speech pathologist. Invited lecture for continuing education presented at the Murdoch Center, Butner, NC, March, 1986.

Wolford, R.D.: Recent advances in cochlear implants and hearing aids. Project Enlightenment, Raleigh, NC, February, 1986.

Farmer, J.C., Jr., P.D. Kenan and B.S. Wilson: Cochlear implants. Presented at Surgical Grand Rounds, Duke University Medical Center, November, 1985.

Wilson, B.S.: Coding strategies for multichannel auditory prostheses. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, Tilton, NH, Aug. 19-23, 1985.

Finley, C.C.: An integrated field-neuron model of intracochlear stimulation. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, Tilton, NH, Aug. 19-23, 1985.

Wilson, B.S.: Discussion Leader, Gordon Research Conference on Implantable Auditory Prostheses, Tilton, NH, Aug. 19-23, 1985.

Finley, C.C. and B.S. Wilson: Models of neural stimulation for electrically-evoked hearing. Invited paper presented in the special session on neurostimulation, ACEMB Meeting, Sept. 30 - Oct. 2, 1985.

Wilson, B.S. and C.C. Finley: Speech processors for auditory prostheses. Invited paper presented in the special session on signal processing for the hearing impaired, IEEE Bioengineering Conference, Sept. 27-Sept. 30, 1985.

Finley, C.C. and B.S. Wilson: A simple finite-difference model of field patterns produced by bipolar electrodes of the UCSF array. IEEE Bioengineering Conference, Sept. 27-30, 1985.

Finley, C.C.: Co-Chairman for the session on Cochlear Prosthetic Devices, ARO, 8th Midwinter Research Conference, February, 1985.

Wilson, B.S. and C.C. Finley: A computer-based simulator of speech processors for auditory prostheses. ARO Abstracts, 8th Midwinter Research Conference, p. 109, 1985.

Finley, C.C. and B.S. Wilson: An integrated field-neuron model of electrical stimulation by intracochlear scala-tympani electrodes. ARO Abstracts, 8th Midwinter Research Conference, p. 105, 1985.

3. Major Reports

Wilson, B.S., C.C. Finley and D.T. Lawson: Speech processors for auditory prostheses. Quarterly Progress Reports 1, 2, 4, 5, 6, 8 and 9, NIH project NO1-NS-5-2396, September, 1985 to December, 1987.

Wilson, B.S., C.C. Finley and D.T. Lawson: Efficacy of single-channel coding strategies for extracochlear auditory prostheses. Final Report, Storz Instrument Company, June, 1987.

Finley, C.C., B.S. Wilson and D.T. Lawson: Speech processors for auditory prostheses. Quarterly Progress Reports 3 and 7, NIH project NO1-NS-5-2396, March to June, 1986 and March to June, 1987.

Wilson, B.S., C.C. Finley and D.T. Lawson: Speech processors for auditory prostheses. Final Report, NIH project NO1-NS-3-2356, September, 1985.

Wilson, B.S., C.C. Finley and D.T. Lawson: Speech processors for auditory prostheses. Quarterly Progress Reports 6, 7 and 8, NIH project NO1-NS-3-2356, December, 1984 to September, 1985.

Wilson, B.S. and C.C. Finley: Speech processors for auditory prostheses. Quarterly Progress Reports 1 through 5, NIH project NO1-NS-3-2356, September, 1983 to December, 1984.

4. Patents

Wilson, B.S., C.C. Finley and M.W. White: Speech processor apparatus for auditory prostheses. Patent application filed Nov. 13, 1987.

5. Site Visits

Two site visits have been hosted by the Duke/RTI cochlear implant team for NIH representatives. The first site visit was held at RTI in December, 1984, and the second was held at Duke in December, 1986. Representatives from the NIH included F.T. Hambrecht, G.E. Loeb and W. Heetderks.

In addition to visitors from the NIH, many scientists interested in cochlear implants have traveled to Duke or RTI to collaborate in certain studies or to learn more about our program. These individuals include the following:

L.J. Dent, Stanford University, Palo Alto, CA.

D.K. Eddington, Massachusetts Eye and Ear Infirmary, Boston, MA.

A.M. Engebretson, Central Institute for the Deaf, St. Louis, MO.

J.W. Hall, University of North Carolina at Chapel Hill, Chapel Hill, NC.

D.K. Kessler, University of California at San Francisco, San Francisco, CA.

H.J. McDermott, University of Melbourne, Melbourne, Vic., Australia.

M.M. Merzenich, University of California at San Francisco, San Francisco, CA.

J.M. Miller, Kresge Hearing Research Institute, University of Michigan, Ann Arbor, MI.

J.F. Patrick, Nucleus Pty. Ltd., Lane Cove, NSW, Australia.

B.E. Pfingst, Kresge Hearing Research Institute, University of Michigan, Ann Arbor, MI.

S.J. Rebscher, University of California at San Francisco, San Francisco, CA.

D.E. Rose, Mayo Clinic, Jacksonville, FL.

R.A. Schindler, University of California at San Francisco, San Francisco, CA.

M.W. Skinner, Washington University Medical Center, St. Louis, MO.

S.D. Soli, Hearing Research Laboratory, 3M Company, St. Paul, MN.

G. Wakefield, Kresge Hearing Research Institute, University of Michigan, Ann Arbor, MI.

D. Wilkinson, University of California at San Francisco, San Francisco, CA.

6. Manuscripts in Preparation

Wilson, B.S., C.C. Finley and M.W. White: Ensemble models of neural discharge patterns evoked by intracochlear electrical stimulation. I. Simple model of responses to transient stimuli. To be submitted for publication in Hearing Res.

Wilson, B.S., D.T. Lawson, C.C. Finley, R.D. Wolford, D.K. Kessler and R.A. Schindler: Direct comparisons of analog and pulsatile coding strategies with six cochlear implant patients. To be submitted for publication in J. Acoust. Soc. Am.

Wilson, B.S., D.T. Lawson, C.C. Finley, R.D. Wolford and M.W. Skinner: Evaluation of two channel, "Breeuwer/Plomp" processors for cochlear implants. To be submitted for publication in J. Acoust. Soc. Am.

White, M.W., C.C. Finley and B.S. Wilson: A Neurophysiological model of electrical excitation of the auditory nerve. To be submitted for publication in Neuroscience.

Wilson, B.S. and C.C. Finley: Differences in pitch and loudness coding with monopolar and radial bipolar configurations of intracochlear electrodes. To be submitted for publication in Hearing Res.

V. Facilities

Included in this section are brief descriptions of various specific resources available in support of the proposed work. A general description of Research Triangle Institute as a whole may be found in section X.F. below.

Data Processing Facilities

The Neurosicence Program Office's data processing hardware presently includes five personal computers--three with 8086 central processors and two with 80286 CPUs and 80287 coprocessors. A wide range of commercial software is available on these machines for word processing, CAD, mathematical modeling, database management, software development in a variety of languages, and data analysis. One of these personal computers is located in our Duke University Medical Center laboratory, where it is used to configure, load, and monitor the real-time bench processor described in section II.E. above.

Two Data General Eclipse S/140 minicomputers--one at RTI and the other in our DUMC laboratory--are currently available for operation of the block diagram compiler, psychophysical testing, and management and presentation of digitally recorded speech test materials. RTI has committed capital equipment funds to immediate acquisition of two 20 MHz 80386-based computers with both 80387 coprocessors and powerful TMS320C25 coprocessors running at 40 MHz. These devices--again, one in each location--will support development of the second-generation real-time block compiler proposed in section III.A. above and assume the clinical functions of the old Data General hardware. As conversion and development on the new machines allow, all uses of the Eclipse systems will be phased out.

Other Clinical Electronics

RTI will continue to provide our laboratory at Duke University Medical Center with electronic test and monitoring equipment and the necessary source devices for recorded speech testing materials. Among such equipment are a patient electrode impedance meter, oscilloscopes, audio tape and videotape players, video disc player, audio mixer and amplifiers, microphones, and patient interactive terminals.

Clinical Laboratory

As noted in the attached letter from Dr. W. R. Hudson (section X.B. below), Duke University Medical Center will continue to provide laboratory space and facilities for the patient testing we propose. DUMC support was instrumental in the initial setting up of this laboratory and in the maintenance of its aging minicomputer, now being replaced.

Computer-Based Bibliographical and Document Retrieval System

Bibliographic information and photocopy indexing for the Neuroscience Program Office's extensive library of publications on cochlear implants and a variety of related topics are made easily accessible to the professional staff through the use of SCIMATE database management software. This facility is used as well to maintain up-to-date documentation on the many computer programs constantly being generated and revised within NPO. Extensive use of key word labels on the entries to both these databases greatly enhances the accessibility and usefulness of the information they contain.

Facilities for Development of Biomedical Electronics

RTI's Center for Biomedical Engineering has substantial experience in developing advanced electronics systems for biomedical applications, particularly in the area of portable and wearable microcomputer-based systems. A wide range of laboratory electronic instrumentation, in-house parts inventories, and fabrication capabilities are available for rapid evaluation of candidate systems and for thorough shakedown of systems selected for full development.

The Center also has considerable expertise and experience in the area of electrical safety assurance in hospital and clinical research environments.

VI. Project Organization, Budget and Schedule

Project Organization

If approved for funding, the work described in this proposal will be conducted at the Research Triangle Institute (RTI) and the Cochlear Implant Laboratory at the Duke University Medical Center (DUMC). The principal investigator will be Blake S. Wilson, Head of the Neuroscience Program at RTI and adjunct assistant professor of Otolaryngology at DUMC. Working with him will be Charles C. Finley and Dewey T. Lawson of the RTI; Robert D. Wolford of the DUMC; Mark W. White of N.C. State University (NCSU); Sigfrid D. Soli of the 3M Company; Robert V. Shannon of the Boys Town National Institute for Communication Disorders in Children; and Bryan E. Pfingst of the Kresge Hearing Research Institute at the University of Michigan (KHRI/UM). Resumes for these individuals are presented in the "Supporting Documents" part of this proposal (section X.E), as are letters of commitment from Mr. Wolford and Drs. White, Soli, Shannon and Pfingst (section X.B).

The project will be administered at the RTI. A chart of RTI's organization is presented on the next page in Fig. VI-1. The line of managers who would oversee the proposed work is indicated in the chart by arrows.

The relationships among key participants in the proposed project are indicated in Fig. VI.2. The project officer at NIH will oversee the RTI effort. Progress reports will be prepared by the RTI team every quarter to record our principal activities, problems and accomplishments, and to assist the NIH project officer in the reviews of the RTI effort. In the past, we also have asked the project officer and other NIH representatives to visit RTI and Duke for a comprehensive review of completed and planned activities every other year. These site visits have been enormously valuable to us, and we hope that they have been valuable to the project officer and his evaluating team. We recommend continuation of site visits at two-year (or more frequent) intervals.

As outlined in sections II.H ("Collaborations") and III.B (see subsection on "Patients") of this proposal, we have been most fortunate in establishing collaborations for exchange of scientific information and for access to patients. The primary collaborating institutions for this project will be the DUMC, UCSF, Washington University Medical Center (WUMC), KHRI/UM, Massachusetts Eye and Ear Infirmary (MEEI), and the University of North Carolina's Memorial Hospital. Letters of support from Drs. W.R. Hudson and B.A. Weber of the DUMC, Dr. R.A. Schindler of UCSF, Dr. M.W.

RESEARCH TRIANGLE INSTITUTE
Officers and Research Programs

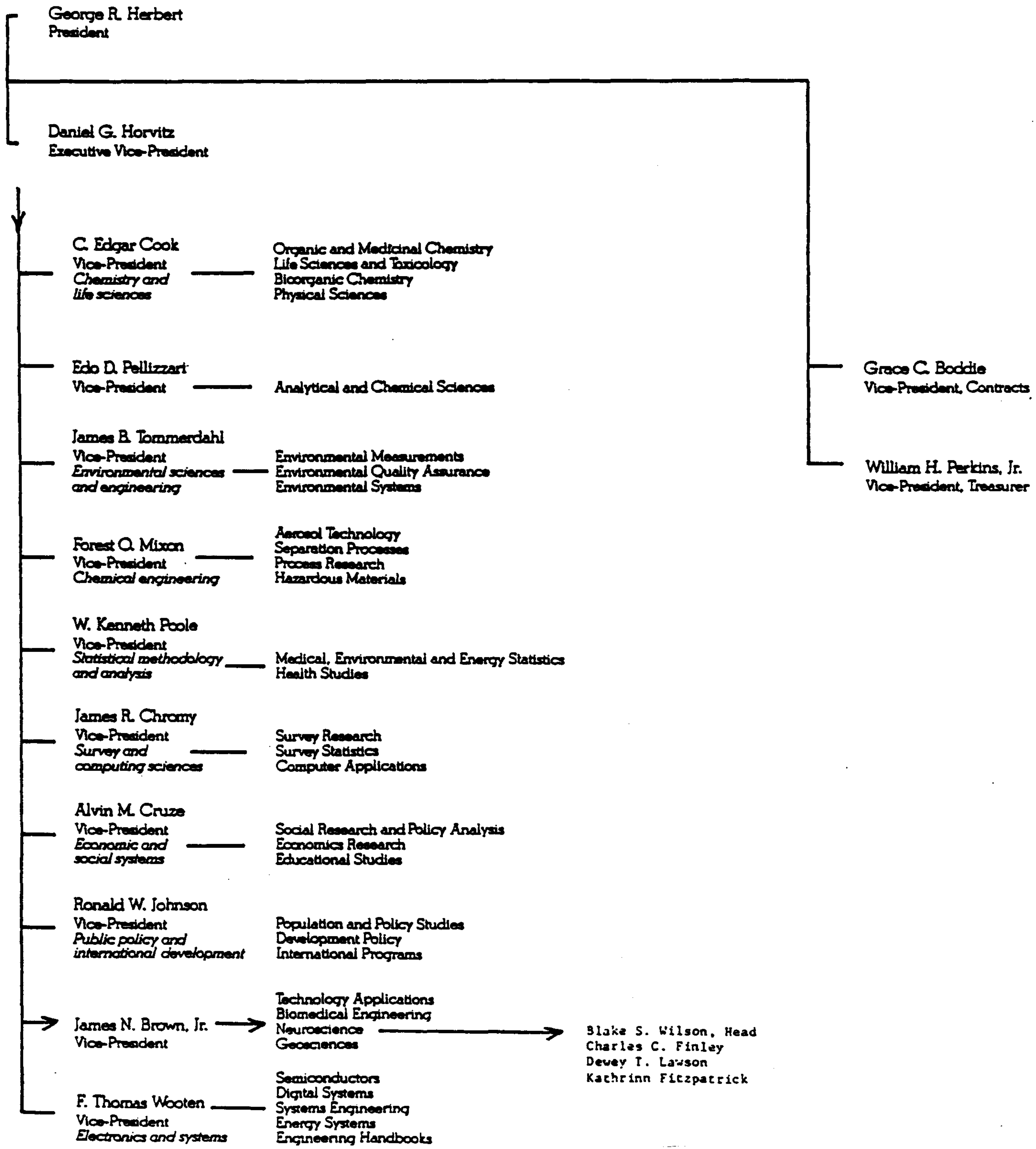

Figure VI-1. Organization chart of the Research Triangle Institute.

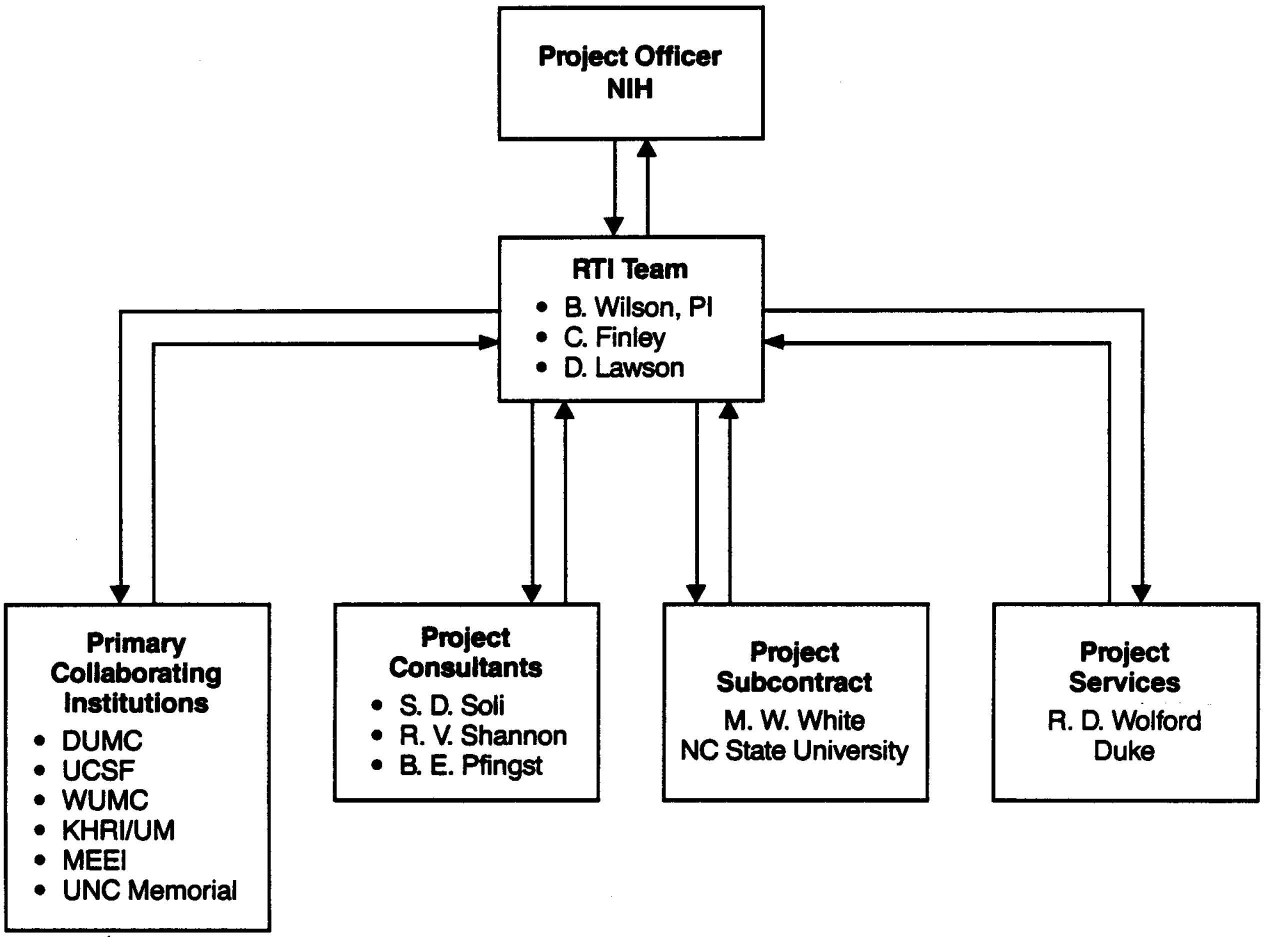

Figure VI-2. Organization of the proposed project.

Skinner of WUMC, Dr. J.M. Miller of KHRI/UM and Dr. H.C. Pillsbury of UNC Memorial are presented in section X.B of this proposal. Each of these letters expresses a desire and commitment to provide implant patients for participation in our proposed studies at Duke. Because studies with the Symbion patients from the MEEI will begin in the current contract period (see sections II.H and III.B), and because Dr. D.K. Eddington has already planned these studies with our group, a letter of support was not solicited from him for this proposal.

In addition to these collaborations with six implant centers, we will also be working with Dr. Rainer Hartmann of the Goethe Universität in Frankfurt and with Dr. Robert Morris at Carleton University in Ottawa. These additional collaborations are described in section II.H of this proposal. As indicated in that section, the collaboration with Dr. Hartmann is completely funded by the Deutsche Forschungsgemeinschaft and a RTI Professional Development Award.

Other than travel and per diem expenses associated with patient testing (primarily at Duke) and visits by RTI team members to collaborating institutions, all collaborations outlined above will come to the project at no cost to the NIH. Investigators at the collaborating institutions have generously offered to donate time in support of our mutual efforts.

An additional relationship indicated in Fig. VI.2 is that of interactions among project consultants and members of the RTI team. The consultants will help us in key areas at very little expense to the project. Dr. S.D. Soli will transfer software he has developed for feature transmission analysis of results from tests of vowel and consonant confusions. He also will provide prospective and retrospective reviews of speech perception studies conducted in our laboratory. In this way we will have the benefit of his expert guidance in designing the studies and we will have his expert interpretation of the results as they become available. Dr. Soli has agreed to work with us here in North Carolina for four days in each year of the proposed project. The total expense for his contribution will be $235/day for consulting plus the costs for travel and per diem associated with three trips between St. Paul and Durham.

Another consultant, Dr. R.V. Shannon, will help us in the work involving the use of psychophysical measurements (see the subsection on "Psychophysical Studies" in section III.B). Like Dr. Soli, Dr. Shannon will provide prospective and retrospective reviews of the psychophysical studies conducted in our laboratory. He also will transfer the technology (hardware and software) he has developed for external control of the receiver chip in the Nucleus device. This transfer will be a necessary prerequisite to our planned investigations with Nucleus patients. Dr. Shannon has agreed to work with us here in North Carolina for four days in each year of the proposed project. The total expense for his contribution will be $235/day for consulting plus the costs of travel and per diem associated with three trips between Omaha and Durham.

The final consultant listed in Fig. VI.2 is Dr. B. E. Pfingst. As indicated in section II.H, Dr. Pfingst will be working with us in studies of frequency and intensity discriminations made by implant patients. He also will help us apply a new technique he has developed for psychophysical measures of these discriminations (Pfingst and Rush, 1987). Because Dr. Pfingst regards our collaboration as making a direct contribution to his own NIH-supported work (through a program project grant to KHRI/UM), he will not require consulting fees for the time he will spend with us. However, he will need funds for one visit in each year of our proposed project. The total expense for Dr. Pfingst's contribution therefore will be for travel and per diem associated with three trips between Ann Arbor and Durham.

The remaining relationships indicated in Fig. VI.2 are those with Dr. Mark White of NCSU and Mr. Robert Wolford of the DUMC. Both of these individuals are full-fledged members of our cochlear implant team and are expected to make major contributions to the project. Dr. White has nearly 20 years of experience in research to develop and evaluate auditory prostheses. He provided essential help and guidance in getting our original experiments underway at UCSF in the early years of our first project with the Neural Prosthesis Program. While at UCSF, he played a leading role in NIH-supported work to develop the multichannel UCSF cochlear implant. Since his move to North Carolina two years ago, Dr. White has collaborated with us in (a) the development of new signal processing strategies for cochlear implants; (b) the investigation of possible mechanisms of intracochlear stimulation using models of the electric field patterns produced by intracochlear electrodes and of the resulting neural responses to the imposed electric fields; and (c) the preparation of several manuscripts for publication. His insight and experience have been invaluable.

In our proposed project we would like to increase the level of Dr. White's participation. He will continue to work with us in the areas indicated above. In addition, he will mount major efforts in the following areas:

1. Design and evaluation of multichannel, "compressed analog" processors with cross-coupled output compressors (see section III.B of this proposal and White, 1986 and 1987);

2. Design and evaluation of noise reduction algorithms for cochlear prostheses (section III.B and White, 1988);

3. Design and conduct of psychophysical studies to (a) evaluate neural models of implant function and (b) infer the extent, pattern and functional consequences of nerve survival in the implanted ear (see subsection of III.B on "Psychophysical Studies" and see White, 1984 and 1985, and White et al, 1987); and

4. Prospective and retrospective reviews of psychophysical and speech perception studies conducted in our laboratory.

Because Dr. White's contribution to the project will be multifaceted and large, we have arranged a subcontract with N.C. State University for 20 percent of his time during the academic year. This commitment will be adequate for completion of the outlined tasks. The cost of the subcontract to NCSU is $17.5k for the first year of the project, $18.4k for the second year, and $19.3k for the third year.

Finally, Mr. Wolford will work with us to evaluate the speech perception abilities of implant patients. In particular, he will administer and help to interpret tests requiring the training and judgment of a skilled audiologist. These tests will include the complete Minimal Auditory Capabilities (MAC) battery (Owens et al., 1985), connected discourse tracking (De Filippo and Scott, 1978; Owens and Raggio, 1987), and additional tests of open-set recognition. Our previous studies with implant patients indicate that these tests can be completed over a 3 to 4 day span. Mr. Wolford can provide his services at a cost of $700 per patient. As outlined in the next subsection on the budget, we expect we will need Mr. Wolford's help in studies with ten patients for each year of the proposed project.

Budget

The budget is based on our experience during the past year of our current contract. We anticipate a similar mix of activities (including patient testing) for future work. During the past year we have (a) conducted intensive studies with ten implant patients; (b) developed new software and hardware for the support of these studies; (c) designed and fabricated a sophisticated, wearable speech processor for one of our percutaneous cable patients; (d) worked with UCSF in the development of a next-generation auditory prosthesis; (e) collaborated with other groups in the conduct of several studies related to the design and evaluation of speech processors for auditory prostheses; (f) continued our work to develop and apply field/neuron models of intracochlear stimulation; (g) prepared seven manuscripts for publication (with three now published and the remaining four in press); (h) prepared four quarterly progress reports; and (i) made twelve major presentations at various national and international meetings.

We have learned from experience that this high level of activity and output cannot be maintained with the budget allocation of our current contract (1.65 professional and 0.40 support years of effort for each year of the project). Therefore, we are requesting an increase in the budget to allow each of the three professionals in our RTI group to spend 70 percent of his time on the project. In addition, we are requesting a small increase in funding for support personnel. This increase (from 0.40 to 0.60 person years of effort/year) is needed for our secretary to keep up with the tasks of manuscript and report preparation; correspondence with collaborators and patients; and administration of certain project activities (such as making travel arrangements, keeping the books, etc.). These new figures are in line with our recent experience. They also are generally consistent with the guideline for professional effort presented in the RFP. This guideline indicates that 2.0 professional plus technical person years of effort for each year of the project is regarded as an appropriate figure by the Government. Our present request is for 2.1 professional years/year plus 0.6 support years/year for each of the three years of the proposed project.

An additional element of cost for the proposed project is that of travel and per diem expenses for patients participating in our studies. During the past year we have worked with three patients from California; one from the state of Washington; one from Alberta, Canada; one from Connecticut; one from Indiana; and one from Minnesota. In addition, we worked with one patient who lives in Durham and we tested a final patient at the 3M facility in St. Paul. Patients visiting Duke from out of town will of course need to be reimbursed for their travel and per diem expenses. In some or all cases a spouse or other companion will accompany the patient. Because we have found that a companion can greatly facilitate the tests by providing support away from the lab and by providing a familiar speaker's voice and lip cues during initial fitting of alternative speech processors, we believe such a person's travel and per diem expenses should also be covered. The total expenses for each patient with an accompanying companion will include airfare, lodging and restaurant costs. Because we usually ask our patients to work with us for six or more days, reduced airfares associated with Saturday-night stayovers can be budgeted. Also, we can use the special rate of $54 per night offered to Duke patients by a local hotel.

This rate is for a double, and the rooms are comfortable. Finally, we allot $40 per day for each couple's restaurant and incidental expenses.

We expect that at least eight patients will travel from out of town to participate in our studies for each year of the proposed project. As indicated in section III.B (see subsection on "Patients"), we expect that many of these patients will be referred to us by the UCSF group. Also, while we will begin seeing patients implanted with the Symbion device (from the Boston area, through our collaboration with the MEEI) during the current contract period, work with these patients will extend into the proposed project. Additional patients will be referred to us by the groups at KHRI/UM and WUMC. For the purpose of planning the budget, we have listed the annual expenses for four patient visits from the San Francisco area, two from the Boston area, one from the Detroit area, and one from the St. Louis area.

Local patients (coming to us from the implant programs at Duke and UNC Memorial) will receive reimbursement for lunch ($10) and parking ($3.20) expenses for each day of participation.

We expect all patients from out of town will undergo our full battery of speech perception tests to evaluate alternative speech processing strategies. In addition, at least two of the local patients will be so evaluated. We therefore have budgeted $7000 for each year of the project to support Mr. Wolford's time for the conduct of these studies (with ten patients per year, at the cost of $700 per patient).

Another expense that will be incurred in the work of the proposed project is the cost of travel for the RTI investigators and visiting consultants. Each of the three consultants will visit RTI and Duke for four days for each year of the project. The consultants will travel to Durham from St. Paul, Omaha, and Ann Arbor. The RTI investigators will be traveling to conferences for presentation of project results and to UCSF to conduct studies with UCSF patients who cannot travel to North Carolina. We plan two trips each year to UCSF. Two RTI investigators will make each of these trips. In addition, we expect to attend several conferences each year. These will include the Annual Neural Prosthesis Workshop (two investigators) and the Annual Midwinter Meeting of the Association for Research in Otolaryngology (two investigators). Attendance at these conferences will involve travel to Bethesda, MD and St. Petersburg, FL. Finally, experience has taught us that attendance at several additional conferences each year is highly productive for the project. During the past year three of us (along with Bob Wolford) attended the Gordon Research Conference on Implantable Auditory Prostheses, in New London, NH; two of us attended the 1987 IEEE/EMBS Meeting, in Boston; one of us attended the International Cochlear Implant Symposium in Düren, West Germany; one of us attended the Mayo Clinic Symposium on Continuing Education in Audiology, in Jacksonville, FL; and one of us attended the 90th Annual Meeting of the Triological Society, in Denver. Major presentations (usually more than one) were made at each of these meetings. Such presentations are an important means of disseminating the most recent results from our studies. Also, interaction with colleagues actively engaged in cochlear implant research is vital to our perspective of the field and helps to ensure that our work will be as effective as possible. We therefore are requesting support for travel to additional conferences. To reflect in part our experience from the past year, our request includes travel to two east coast conferences (the city chosen for budget purposes is Boston) and to two west conferences (the city chosen for budget purposes is San Francisco) for each year of the project. The request also includes an estimate for the aggregate of conference attendance fees and support for per diem expenses for two days at each of the additional conferences.

A final "travel" expense for the RTI investigators is parking at Duke University Medical Center. Each of us spends more than one third of his time working in the laboratory at Duke. Therefore, our request is for parking fees for 100 days for each investigator. The daily parking fee is $3.20.

The remaining costs for the project include those of equipment, electronic parts, computer supplies, graphics services, report duplication, and telephone and shipping charges. Our estimates for all of these items except equipment are based on our experience in the current contract. A special equipment request is made for the first year of the proposed project to allow us to purchase the hardware for the system Dr. R.V. Shannon has developed for external control of the receiver chip in the Nucleus device. He has told us that the system will be fabricated at Boys Town Institute and made available for purchase by outside investigators. The price for this system will be between $1000 and $1500. To be on the safe side, our present request is for $1500. As mentioned before, Dr. Shannon will provide the software for the system at no cost to the project.

A completed summary of labor and direct costs for the three-year duration of the proposed project is presented at the end of this section.

Schedule

The major activities of the proposed project are (a) upgrade of the laboratory and testing facilities, as described in section III.A; (b) psychophysical and speech perception studies with cochlear implant patients, as described in section III.B; and (c) design and fabrication of wearable speech processors, as described in section III.C. We expect to complete most or all of the work associated with point (a) in the first year of the project. Patient testing will continue throughout the three years of the project. Finally, design and fabrication of wearable speech processors will commence as soon as the data from the patient studies indicate that a new type of processor is worthy of an extended trial in the field. We already have such data in hand and therefore expect to begin work on new designs of wearable processors at the outset of the project. We also expect that the additional speech perception data obtained during the course of the proposed project will provide ample incentive and guidance for design and fabrication of wearable processors. We therefore expect to begin right away on the first wearable processor and to start on subsequent wearable processors as the data indicate. Most likely, one or more wearable processors will be built in each year of the project. Two certainly will be built before the end of the second year, as required by the contract.

In addition to these activities, we will continue to prepare manuscripts for publication and to present project results at major conferences and symposia. Also, progress reports of project activity will be submitted to our project officer at NIH on a quarterly basis. We anticipate that presentations at conferences and manuscript preparation will proceed at a fairly uniform rate throughout the course of the project.

Because the exact schedules for patient testing and conferences are difficult to predict except for a few known cases (such as the October or November schedule for the Annual Neural Prosthesis Workshop), any timeline or milestone chart for this project has to be somewhat arbitrary. However, the timeline charts presented below represent our best estimates of known and anticipated events. The major activities presented in these charts are:

1. Upgrade of the laboratory and testing facilities;

2. Psychophysical and speech perception studies with implant patients;

3. Develop software and hardware for the support of these studies;

4. Design and fabricate wearable speech processors;

5. Attend Neural Prosthesis Workshop;

6. Attend ARO Meeting;

7. Attend 25th Anniversary Symposium of the Kresge Hearing Research Institute, on "Models of the Electrically Stimulated Cochlea;"

8. Prepare two invited manuscripts for the book to be published in conjunction with this Symposium;

9. Prepare and submit other manuscripts for publication;

10. Attend the 1989 conference on "Implantable Auditory Prostheses;"

11. Attend other meetings;

12. Submit progress reports of project activity; and

13. Prepare and submit the final report for the project.

CHART VI-1. Timeline of major activities for the first year of the proposed project. (Note: a "+" mark indicates the onset of an activity and a "x" indicates the termination of that activity)

```
 Activity       Oct  Nov  Dec  Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep

    1           +--------------------------------------------------------x
    2           +-------------------------------------------------------->
    3           +-------------------------------------------------------->
    4           +-------------------------------------------------------->
    5                +-x
    6                               +-x
    7           +-x
    8           >-x
    9           +-------------------------------------------------------->
   10                                                   +-x
   11           +-------------------------------------------------------->
   12                     +-x            +-x            +-x            +-x
```

CHART VI-2. Timeline of major activities for the second year of the proposed project. (Note: a "+" mark indicates the onset of an activity and a "x" indicates the termination of that activity)

```
 Activity   Oct  Nov  Dec  Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep

     2      >---------------------------------------------------------->
     3      >---------------------------------------------------------->
     4      >---------------------------------------------------------->
     5           +-x
     6                          +-x
     9      >---------------------------------------------------------->
    11      >---------------------------------------------------------->
    12                +-x            +-x            +-x            +-x
```

CHART VI-3. Timeline of major activities for the third year of the proposed project. (Note: a "+" mark indicates the onset of an activity and a "x" indicates the termination of that activity)

```
 Activity   Oct  Nov  Dec  Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep

     2      >----------------------------------------------------------x
     3      >----------------------------------------------------------x
     4      >----------------------------------------------------------x
     5           +-x
     6                          +-x
     9      >----------------------------------------------------------x
    11      >----------------------------------------------------------x
    12                +-x            +-x            +-x            +-x
    13                                                  +-----------x
```

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SUMMARY OF LABOR AND DIRECT COSTS
(3-Year Total)

COST ELEMENTS	Year 1	Year 2	Year 3	TOTAL
DIRECT LABOR				
Category				
P. I.	70%	70%	70%	70%
Sr. Prof.	70%	70%	70%	70%
Sr. Prof.	70%	70%	70%	70%
Support	60%	60%	60%	60%
Total TH	70%	70%	70%	70%
TOTAL DIRECT LABOR	$167,108	$171,707	$174,831	$513,646
MATERIALS AND SUPPLIES (Exhibit)	3,800	4,000	4,200	12,000
EQUIPMENT	1,500	0	0	1,500
CONSULTANTS/ SUBCONTRACTS (Exhibit)	19,403	20,280	21,200	60,883
TRAVEL (Exhibit)	27,434	27,434	27,434	82,302
OTHER DIRECT COSTS (Exhibit)	8,600	8,730	8,860	26,190
TOTAL DIRECT COSTS	60,737	60,444	61,694	182,875
TOTAL LABOR AND DIRECT COSTS	$227,845	$232,151	$236,525	$696,521

DIRECT COST DETAIL

CATEGORY	YEAR 1	YEAR 2	YEAR 3	TOTAL
MATERIALS & SUPPLIES				
Electronic Parts	3,000	3,100	3,200	$ 9,300
Computer Supplies	800	900	1,000	2,700
Total	$3,800	$4,000	$4,200	$12,000
EQUIPMENT	$1,500	-	-	$ 1,500
CONSULTANTS, SUBCONTRACTORS				
DR. S. D. Soli	940	940	940	2,820
Dr. R. V. Shannon	940	940	940	2,820
NCSU, Dr. Mark White	17,523	18,400	19,320	55,243
Total	$19,403	$20,280	$21,200	$60,883
OTHER DIRECT COSTS				
Evaluation of Speech Perception:				
R. D. Wolford, 10 patients, @ $700	7,000	7,000	7,000	21,000
Conference Fees	800	900	1,000	2,700
Report Reproduction	350	350	350	1,050
Communications & Shipping	450	480	510	1,440
Total	$8,600	$8,730	$8,860	$26,190

TRAVEL PER YEAR
YEARS 1, 2, & 3

RTI INVESTIGATOR TRAVEL EXPENSES/YEAR

1) two trips to UCSF/year

2) two trips to St. Petersburg/Tampa/Year (ARO)

3) two trips to Bethesda/year (Neural Prostheses Workshop)

4) two trips to unknown east coast destination for conferences

5) two trips to unknown west coast destination for conferences

No. Persons	Destination	RT Air Fare	No. of Days	Subsist.	No. of Days	Car	No. of Trips	Total
2	San Francisco	1024	5	95	2	30 1/	2	$ 6,116
2	Tampa/ St. Pete	590	4	77	4	15 1/	1	1,856
2	Bethesda	360	3	117	4	3 2/	1	1,434
1	Boston	610	2	108	3	40 3/	2	1,892
1	San Francisco	1024	2	95	2	20 1/	2	2,508
3	Parking, Duke Medical Center		100	3.20/d				960
	Local Travel			.22/mile, 100 miles				220
Total RTI Investigator Travel/Year								$14,986

1/ Airport Limousine

2/ Washington, DC Metro

3/ Car Rental

TRAVEL PER YEAR
YEARS 1, 2, & 3

Consultant Travel to RTI/Year

1) Dr. Shannon: one trip from Omaha to RTI/year

2) Dr. Soli: one trip from St. Paul to RTI/year

3) Dr. Pfingst: one trip from Ann Arbor to RTI/year

No. Persons	Origination	RT Air Fare	No. of Days	Subsist.	No. of Days	1/ Car	No. of Trips	Total
1	Omaha	674	4	81	2	15	1	$1,028
1	St. Paul	670	4	81	2	15	1	1,024
1	Ann Arbor	610	4	81	2	15	1	964
Total Consultant Travel/Year								$3,016

1/ Airport Limousine

TRAVEL PER YEAR
YEARS 1, 2, & 3

Patient Travel to Duke Medical Center, Durham, NC/Year

No. Persons	Origination	RT Air Fare	No. of Days	Subsist.	No. of Trips	Total
2	San Francisco	308	6	47 1/	4	$4,720
2	Boston	208	6	47	2	1,960
2	Detroit	188	6	47	1	940
2	St. Louis	228	6	47	1	1,020
10	Local		6	10	3.20/day	792
Total Patient Travel/Year						$9,432

1/ Subsistence: $54/night for double room; $40 expenses/day per couple = $94/day for 2

VII. Concluding Remarks

We have worked hard to make the most of the investment NIH has made in our program. We are proud of our progress to date and we look forward to the possibility of continuing our effort.

VIII. Statement of Work

Independently and not as an agent of the Government, Research Triangle Institute (RTI) will exert its best efforts to design, develop and evaluate speech processors for use with implanted auditory prostheses in deaf adults and/or children. The Description of Work as given in RFP No. NIH-NINCDS-88-04 is acceptable to RTI, and is reproduced below for reference.

Specifically, RTI will:

A. Develop or obtain a laboratory-based speech processing system whose configuration can be varied by software. This system should be able to:

   1. Specify stimulus parameters for up to 8 channels.

   2. Control both analog and pulsatile stimulators.

   3. Simulate essentially all of the speech processing schemes which have been published for use with human implants.

   4. Allow the implementation of new speech processing schemes based on both frequency filtering and cue extraction approaches.

B. Evaluate different speech processing techniques in implanted human subjects.

   1. Use psychophysical measures to study the interactions between stimulus parameters and activated electrodes.

   2. Design psychophysical and/or neurophysiological tests to assess functional auditory system survival.

   3. Determine psychophysical factors which best relate to speech comprehension and use this information to design improved speech processing strategies.

4. Compare different speech processing techniques in each subject and determine factors which allow them to utilize or not to utilize specific speech processing features.

   a. Attempt to account for variations among subjects based on nerve survival, cognitive factors, learning, etc.

C. Design wearable speech processors based on results from the above mentioned studies.

   1. They shall be designed for specific implant patients who have either single or multiple electrode auditory prostheses.

   2. They shall be human engineered with respect to weight, durability, and panel component selection and placement.

   3. They shall operate in real time.

   4. They shall have safety features which prevent stimulus levels from reaching harmful levels.

D. Fabricate at least two of these wearable devices for specific individuals who already have auditory implants. These wearable speech processors shall be available before the end of the second year of the contract.

   1. Use these devices to study the effects of learning on the subjects' ability to comprehend speech with their auditory implants.

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X. Supporting Documents

This section contains six appendices in support of this proposal. These appendices in order of inclusion are:

A. Protection of Human Subjects

B. Letters of Collaboration

C. Appendix on "Design and Evaluation of Speech Processors for Auditory Prostheses with Stimulating Electrodes Placed in or on the Cochlear Nucleus"

D. Final Report for NIH Project N01-NS-3-2356, "Speech Processors for Auditory Prostheses"

E. Curriculum Vitae

F. General Qualifications of Research Triangle Institute

X.A. Protection of Human Subjects

This appendix contains a completed copy of form HHS 596 (Rev. 1/82), Protection of Human Subjects--Assurance/Certification/Declaration, as required by the RFP statement.

OMB No. 0925-0637

DEPARTMENT OF HEALTH AND HUMAN SERVICES

PROTECTION OF HUMAN SUBJECTS ASSURANCE/CERTIFICATION/DECLARATION

☐ ORIGINAL ☐ FOLLOWUP ☐ EXEMPTION (previously undesignated)

☐ GRANT ☒ CONTRACT ☐ FELLOW ☐ OTHER

☒ New ☐ Competing continuation ☐ Noncompeting continuation ☐ Supplemental

APPLICATION IDENTIFICATION NO. *(if known)*

POLICY: A research activity involving human subjects that is not exempt from HHS regulations may not be funded unless an Institutional Review Board (IRB) has reviewed and approved the activity in accordance with Section 474 of the Public Health Service Act as implemented by Title 45, Part 46 of the Code of Federal Regulations (45 CFR 46—as revised). The applicant institution must submit certification of IRB approval to HHS unless the applicant institution has designated a specific exemption under Section 46.101(b) which applies to the proposed research activity. Institutions with an assurance of compliance on file with HHS which covers the proposed activity should submit certification of IRB review and approval with each application. (In exceptional cases, certification may be accepted up to 60 days after the receipt date for which the application is submitted.) In the case of institutions which do not have an assurance of compliance on file with HHS covering the proposed activity, certification of IRB review and approval must be submitted within 30 days of the receipt of a written request from HHS for certification.

1. TITLE OF APPLICATION OR ACTIVITY

Speech Processors for Auditory Prostheses

2. PRINCIPAL INVESTIGATOR, PROGRAM DIRECTOR, OR FELLOW

Blake S. Wilson

3. FOOD AND DRUG ADMINISTRATION REQUIRED INFORMATION *(see reverse side)*

4. HHS ASSURANCE STATUS

☐ This institution has an approved assurance of compliance on file with HHS which covers this activity.

________ Assurance identification number ________ IRB identification number

☒ No assurance of compliance which applies to this activity has been established with HHS, but the applicant institution will provide written assurance of compliance and certification of IRB review and approval in accordance with 45 CFR 46 upon request.

5. CERTIFICATION OF IRB REVIEW OR DECLARATION OF EXEMPTION

☐ This activity has been reviewed and approved by an IRB in accordance with the requirements of 45 CFR 46, including its relevant Subparts. This certification fulfills, when applicable, requirements for certifying FDA status for each investigational new drug or device. *(See reverse side of this form.)*

________ Date of IRB review and approval. *(If approval is pending, write "pending." Followup certification is required.)*
(month/day/year)

☐ Full Board Review ☐ Expedited Review

☐ This activity contains multiple projects, some of which have not been reviewed. The IRB has granted approval on condition that all projects covered by 45 CFR 46 will be reviewed and approved before they are initiated and that appropriate further certification *(Form HHS 596)* will be submitted.

☐ Human subjects are involved, but this activity qualifies for exemption under 46.101(b) in accordance with paragraph ______ *(insert paragraph number of exemption in 46.101(b), 1 through 5)*, but the institution did not designate that exemption on the application.

6. Each official signing below certifies that the information provided on this form is correct and that each institution assumes responsibility for assuring required future reviews, approvals, and submissions of certification.

APPLICANT INSTITUTION	COOPERATING INSTITUTION
NAME, ADDRESS, AND TELEPHONE NO. Research Triangle Institute P. O. Box 12194 Research Triangle Park, N.C. 27709 (919) 541-6441	NAME, ADDRESS, AND TELEPHONE NO.
NAME AND TITLE OF OFFICIAL *(print or type)* Dr. D. G. Horvitz Executive Vice President	NAME AND TITLE OF OFFICIAL *(print or type)*
SIGNATURE OF OFFICIAL LISTED ABOVE *(and date)* D. G. Horvitz	SIGNATURE OF OFFICIAL LISTED ABOVE *(and date)*

HHS 596 (Rev. 1/82)

(If additional space is needed, please use reverse side under "Notes.")

X.B. Letters of Collaboration

Following in this section are letters of collaboration from our colleagues. In alphabetical order, these collaborators include:

William R. Hudson, M.D.	Duke University Durham, North Carolina
Josef M. Miller, Ph.D.	Kresge Hearing Research Institute Ann Arbor, Michigan
L. Robert Morris, Prof.	Carleton University Ottawa, Canada
Bryan E. Pfingst, Ph.D.	Kresge Hearing Research Institute Ann Arbor, Michigan
Harold C. Pillsbury, M.D.	University of North Carolina Chapel Hill, North Carolina
Robert A. Schindler, M.D.	University of California, San Francisco San Francisco, California
Robert V. Shannon, Ph.D.	Boys Town National Institute for Communication Disorders in Children Omaha, Nebraska
Margaret W. Skinner, Ph.D.	Washington University St. Louis, Missouri
Sigfrid D. Soli, Ph.D.	3M Company St. Paul, Minnesota
Bruce A. Weber, Ph.D.	Duke University Durham, North Carolina
Mark W. White, Ph.D.	North Carolina State University Raleigh, North Carolina
Robert D. Wolford, M.S.	Duke University Durham, North Carolina

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APPOINTMENTS 684-3834

April 5, 1988

Dr. Blake Wilson
Head, Neurosciences Branch
Research Triangle Institute
Research Triangle Park, North Carolina 27709

Dear Blake:

This letter is to emphasize our intention to continue our very productive relationship with you and the Research Triangle Institute team in the study of cochlear implant patients and the development of improved speech processing strategies and devices to stimulate the residual auditory system in profoundly deaf patients. The Duke facilities for otologic and audiologic testing of such patients, both pre-operatively and post-operatively, will continue to be made available to support our joint efforts. As we have discussed, implantation of the Nucleus device will soon begin in selected patients, particularly those who do not wish to wait for the new Minimed device and/or have no third party coverage to cover the hospital costs of implantation of a device under FDA clinical trials which will be the status of Minimed device once it becomes available later this year. When it does become available, we will certainly participate in the clinical trials of the Minimed device.

At the present time we have a backlog of approximately 8 candidates for cochlear implantation. We expect to begin the implantation of some of these candidates this summer. Once implantation begins, I anticipate a patient volume of 10 to 12 patients per year.

We have been most pleased with our collaboration, especially with the discovery of improved speech processing strategies which can restore speech intelligibility to a greater number of profoundly deaf patients and which have encouraged and molded the design of future generations of cochlear implant devices. We look forward to a continuing long-term and productive association with you and your Research Triangle Institute team.

With best wishes,

Sincerely yours,

William R. Hudson

William R. Hudson, M.D.
Professor and Chief
Division of Otolaryngology
Department of Surgery

WRH:os
cc: Dr. David Sabiston,James B. Duke Professor and Chairman, Dept. Surgery

Kresge Hearing Research Institute

March 29, 1988

Blake Wilson, Ph.D.
Neuroscience Program
P.O. Box 12194
Research Triangle Institute
Research Triangle, NC 27709

Dear Blake:

This letter is to confirm our conversation today. At this time I have been in repeated contact with ITT Cannon and have finally received a price listing on the 9-pin and new 27-pin nanoconnector that they have developed for 3M. The prices are high, but I am sure we will be able to purchase a sufficient quantity among us to develop the percutaneous plugs we need for the human studies. I have also been in contact with the group in Goteborg and have seen a model of a titanium percutaneous pedestal which well fits the nanoconnectors by ITT Cannon. Fortunately, it has worked out that their standard percutaneous plug, that they use with the bone anchored vibrator studies that they are performing, will work ideally for the nanoconnectors. No change in tools, dies or machining will be required to mount these connectors. With their experience now with some 700 implants in humans of these kind and minimal morbidity, I feel quite confident that this will afford a much more reliable base than the carbon glass pedestal.

Nucleus Corp. continues to be supportive of our proposed program to mount a Nucleus electrode on a percutaneous plug for direct assess to the electrodes for a human investigation and our recent animal investigations on the development of the multichannel lateral wall implant continue to look more and more promising. Last month, Anders Tjellstrom and I implanted with ease, four electrodes in the lateral wall of one monkey cochlea and five in another. We will do a dog shortly and then follow this with a human investigation, which will begin in a patient to undergo a labyrinthectomy. I am optimistic with that within the next year we should be well on our way to a first feasibility investigation in one or two human subjects. As you know, I have been far from optimistic about the application of this lateral wall implant to humans in the past. However, on the basis of our studies it now begins to look like a well justified next step. I look forward to working with you and developing an interleave processing system that we might be able to test out with this lateral wall implant system in humans within the next year or two.

We look forward to collaborating with you on the Anderson Neuroprosthesis contract.

My best regards.

Sincerely yours,

Josef M. Miller, Ph.D.
Professor and Director

JMM/yb

Department of Otolaryngology
The University of Michigan
1301 East Ann Street
Ann Arbor, Michigan 48109-0506
(313) 764-8110

Carleton University
Ottawa, Canada K1S 5B6

October 22, 1987

Dr. Charles C. Finley,
Neuroscience Program Office,
Research Triangle Institute,
Research Triangle Park,
North Carolina 27709

Dear Charlie:

This letter is in regard to our recent phone conversation re co-operation in the area of cochlear implant signal processing. It is our intention to supply you in the near future with a TMS32010 based board, essentially the same as the one we demonstrated at the Gordon Conference, together with a load module that you could downline load via a PC RS-232 interface. Initially, you would pick up our output -- pitch, gain and spectral envelope samples -- via an A/D converter synchronized to our system. We might be able to implement a digital interface at some time in the future. We could also alter our algorithms, to some extent, in response to your testing results, if necessary.

We would ask that you send us a letter confirming our collaboration, mainly for attachment to a Grant Application to the Canadian Medical Research Council. We do not intend to apply for any NIH support. In terms of papers or other publications, we would like to be informed of your results so that we could cite them in any paper we write focused on our hardware software. We would keep all results confidential. Conversely, should you write any papers which make use of results obtained using our software, we would expect a citation and, if a major portion of the paper described the algorithms/software/hardware, we would expect that it would be possible for us to be a co-author.

Yours truly,

Bob Morris

L. Robert Morris,
Professor

N.B.: Should the above be agreeable I hope that you can expedite your letter of support/collaboration. Our application to MRC is already in and we have noted that we had spoken to you. The sooner we can follow up with your letter, the greater our chances for grant renewal.

Department of Systems and Computer Engineering
C.J. Mackenzie Building □ (613) 564-3625 B-4

Kresge Hearing Research Institute

April 8, 1988

Blake S. Wilson
Neuroscience Program Office
Research Triangle Institute
Post Office Box 12194
Research Triangle Park, NC 27709

Dear Blake,

This letter is to confirm that I will be most happy to collaborate with you on the studies of discrimination of simultaneous frequency level changes in conjunction with your NIH proposal (NIH RFP No. NIH-NINCDS-88-04). As we have discussed, I believe these proposed studies in your human subjects are a logical and important extension of the studies we have been conducting in monkeys, and I cannot think of a research group with which I would rather be involved in this work. Your research environment, your subjects with percutaneous access to the electrode arrays, and the extensive excellent work which you have done on speech discrimination and basic psychophysics in these subjects all combine to strengthen this aspect of the proposal and provide a high probability of a successful and significant outcome. I am anxious to get this project underway.

Sincerely,

Bryan

Bryan E. Pfingst
Associate Professor

Department of Otolaryngology
The University of Michigan
1301 East Ann Street
Ann Arbor, Michigan 48109-0506
(313) 764-8110

THE UNIVERSITY OF NORTH CAROLINA
AT
CHAPEL HILL

School of Medicine
Department of Surgery
Division of Otolaryngology
Head and Neck Surgery
(919) 966-3341

CB# 7070, Burnett-Womack Clinical Sciences Bldg.
The University of North Carolina at Chapel Hill
Chapel Hill, N.C. 27599-7070

April 13, 1988

Charles C. Finley, Ph.D.
Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

Dear Charlie:

This letter is to confirm our willingness at the University of North Carolina to collaborate with you and your colleagues on your research to develop speech processors for cochlear prostheses. In particular, I wish to endorse the proposed research plan that you are submitting to the Neural Prosthesis Program at NIH in response to a request for proposals to develop speech processors for cochlear implants. As part of this plan you are proposing to study the basic psychophysics of, and evaluate alternative speech processing strategies for, patients using the Nucleus cochlear prosthesis.

Here at UNC in the Division of Otolaryngology of the Department of Surgery we have been very active in the clinical application of implant devices. Our experience has included use of the House, 3M/Vienna and Nucleus systems. At present we have twenty-two patients using the Nucleus device and expect that number to exceed thirty by the end of the year. Most of these patients are located within a fifty mile radius of the Research Triangle and should provide a convenient population of candidates for our collaborative study. Our center also is actively participating in the Nucleus pediatric implant study and those patients would be available as well.

Participation of our patients will of course be contingent upon each individual's informed consent. As you indicated in our discussions, equipment used to stimulate these patients will be fully compatible with the present Nucleus receiver systems and will in no way jeopardize the safety of testing and/or the continued proper operation of the patient's implanted device. Appropriate testing and evaluation to document this performance of the test equipment will be conducted before patients are recruited.

I have been following the research progress of the RTI group for several years and have been impressed with your findings that in patients with relatively poor performance speech processor designs tailored specifically to the medical *needs of the individual patient can significantly boost performance. I'm enthusiastic about our collaboration and look forward to the resources of UNC and RTI being jointly applied to aid the profoundly hearing impaired.*

Sincerely yours,

Harold C. Pillsbury, M.D.
Professor and Chief
Otolaryngology/Head & Neck Surgery

HCP/st

UNIVERSITY OF CALIFORNIA, SAN FRANCISCO

BERKELEY • DAVIS • IRVINE • LOS ANGELES • RIVERSIDE • SAN DIEGO • SAN FRANCISCO | SANTA BARBARA • SANTA CRUZ

DEPARTMENT OF OTOLARYNGOLOGY
ROOM A-730
SAN FRANCISCO, CALIFORNIA 94143
(415) 476-4952

John C. and Edward Coleman Memorial Laboratory (1921)
Saul and Ida Epstein Otoneurological Laboratory (1976)

April 12, 1988

Blake Wilson
Research Triangle Institute
P.O. Box 12194
Research Traingle Park
North Carolina 27709

Dear Blake;

I'm writing to you on behalf of the entire UCSF Cochlear Implant Team to tell you how much we've enjoyed your collaboration on the cochlear implant project and look forward to continuing collaboration between RTI and UCSF. As you know the UCSF-RTI-Mini Med device will soon be placed in clinical trials. We are very anxious to participate with you on the development of newer and more sophisticated speech processors for the multi-channel cochlear implant. It is our intention at UCSF to provide you with complete access to all our patients implanted with the new device so that you will have an opportunity to try out new speech processing strategies and help us implement the most effective way for clinical fitting of these devices.

I'm delighted that we will be able to continue our collaborative work together and I look forward to great success in the development of our new multi-channel auditory prostesis.

Warm personal regards,

Robert A. Schindler, M.D.
Professor & Vice-Chairman
Dept. of Otolaryngology-
Head and Neck Surgery, UCSF
Clinical Director of the UCSF
Cochlear Implant Project.

BOYS TOWN

Boys Town National Institute for Communication Disorders in Children

Patrick E. Brookhouser, M.D., Director

April 6, 1988

Blake Wilson
Research Triangle Institute
P.O. Box 12194
Research Triangle Park, North Carolina 27709

Dear Blake:

I would be happy to serve as a consultant and collaborator on your project "Speech Processors for Auditory Prostheses", NIH-NINCDS-88-04. Speech processors should take advantage of the known perceptual consequences of electrical stimulation. My recent model (see enclosed prepprint) should allow the conversion of any arbitrary acoustic waveform into an electrical stimulus that would preserve all loudness and timing relationships of the original acoustic stimulus. My current research is focusing on the psychophysics of speech features. I am measuring implanted patients basic perceptual capabilities and discrimination ability with nonspeech stimuli that mimic acoustic properties than are known to be important in speech categorization.

I look forward to working with you on your excellent work in designing speech processor strategies for cochlear implants.

Sincerely,

Bob Shannon

Robert V. Shannon, Ph.D.
Coordinator, Sensory Aids Laboratory

555 North 30th Street, Omaha, Nebraska 68131, (402) 449-6511

WASHINGTON UNIVERSITY SCHOOL OF MEDICINE
AT WASHINGTON UNIVERSITY MEDICAL CENTER

DEPARTMENT OF OTOLARYNGOLOGY—HEAD AND NECK SURGERY

April 7, 1988

Blake S. Wilson, Ph.D., Director
Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

Dear Blake:

We would like very much to collaborate with you, Charles Finley and Dewey Lawson on your research "Speech Processors for Cochlear Implants" for which you are submitting a contract proposal renewal to NIH through the Neural Prosthesis Program.

In our program we have implanted six postlinguistically deaf adults with the Nucleus 22-Electrode Intracochlear Implant; all of them can recognize some words by sound alone, and they can communicate fluently when they use their implant in conjunction with lipreading. Two patients have said they would be happy to participate in research projects which require extended testing; both are excellent observers and would be willing to be evaluated in St. Louis or Durham. The others would be happy to participate in more restricted projects. We anticipate implanting our first prelinguistically deaf adult in July, and I believe he would be interested in some research as well.

Although we are committed to using the Nucleus implant at the present time, we will consider using other devices as they may become available. Our own research program will be centered around maximizing benefit that these devices provide to the individual patient by studying the effects of various coding parameters on speech preception. For this reason we are most eager to work with your group.

With my best regards,

Marg Skinner

Margaret W. Skinner, Ph.D.
Director of Audiology

Box 8115
517 South Euclid Avenue
St. Louis, Missouri 63110
(314) 362-7552

Biosciences Laboratory
Health Care Products and
Services Group Laboratory/3M

3M Center
St. Paul, Minnesota 55144-1000
612/733 1110

3M

11 April 1988

Dr. Charles Finley
Neurosciences Program Office
Building 7, Room 207
Research Triangle Institute
Research Triangle Park, North Carolina 27709

Dear Charlie:

This letter confirms in writing my part of our agreement to serve as a consultant for your cochlear implant research project over the next three years.

In accordance with our discussions, I agree to provide software for processing and analysis of perceptual tests to include matrix processing, information transmission analysis, sequential information transmission analysis, and multidimensional scaling analysis. I will also assist in the transfer of this software to a laboratory PC and in the validation of the software on the PC. In addition, I will work with you to perform these analyses, to interpret their results, and to design experiments that use these methods of analysis.

I am eager to extend the interaction and collaboration we have already begun, and I am confident that out interactions will continue to be synergistic.

Please find that I have enclosed a current copy of my resume, as you requested.

Sincerely,

Sigfrid D. Soli, Ph.D.
Senior Speech Scientist
270-4S-11
(612/733-3312)

Enclosure

Duke University Medical Center
DURHAM, NORTH CAROLINA
27710

DEPARTMENT OF SURGERY
CENTER FOR SPEECH AND
HEARING DISORDERS

TELEPHONE (919) 684-3859
P. O. BOX 3887

April 6, 1988

Mr. Blake S. Wilson
Head, Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

Dear Blake:

Approximately three years ago I wrote a letter stating the support of the Speech Pathology and Audiology Programs for your research efforts in the development of speech processors for cochlear prostheses. I was most enthusiastic about your program because I could envison collaborative efforts between Duke Medical Center and RTI which would be of major benefit to the profoundly hearing-impaired, as well as adding to the strengths of each of our programs.

It is indeed with pleasure that I write today to express how pleased I have been with the interactions that have occurred over the past three years. The RTI involvement in the multi-disciplinary Center for the Severely Hearing Impaired, is a major reason for its wide acceptance as one of the premier programs in the world. Our close and harmonious working arrangement has been to the benefit of all. We in the Center for Speech and Hearing Disorders wish to express our sincere thanks for the contributions the RTI staff has made on behalf of the hearing-impaired patients here at Duke Medical Center.

We are all very excited about the progress you and your team have made in your development of speech processors for cochlear implant patients. We feel fortunate to have your research laboratory in close proximity to our clinic. We will certainly do everything we can to continue this arrangement. You can be assured that you, Charlie and Dewey have our unqualified support and you need only contact us if we can be of any assistance in your research efforts.

Sincerely,

Bruce

Bruce A. Weber, Ph.D.
Associate Professor

BAW/bjb

North Carolina State University
School of Engineering

Department of
Electrical and Computer Engineering

Box 7911
Raleigh, NC 27695-7911
919-737-2336

April 15, 1988

Research Triangle Institute
P.O. Box 12194
Research Triangle Park, N.C. 27709

Dear Sirs:

I am writing this letter to express my strong interest and willingness to work with the RTI Cochlear Implant Group. Attached to this letter is a "Statement of Work" which describes my participation. As indicated in the attached subcontract budget, my level of participation is at 20% of full time. In regard to invention rights, the RTI Cochlear Implant Group and I have shared the rights related to our joint efforts and will continue to do so.

Sincerely,

Mark W. White

Mark W. White

Statement of Work

Dr. White will continue his collaboration with the RTI/Duke cochlear implant group in: (a) the development of new signal processing strategies for cochlear implants; (b) the investigation of possible mechanisms of intracochlear stimulation, using models of the electric field patterns produced by intracochlear stimulation and using models of the resulting neural responses to the imposed electric fields; and (c) the preparation of manuscripts for publication. In addition to these activities, Dr. White will conduct research in the following areas:

1. Design and evaluation of multichannel "compressed-analog" processors with cross-coupled output compressors.
2. Design and evaluation of noise reduction algorithms for cochlear prostheses.
3. Design and conduct of psychophysical studies to (a) evaluate neural models of implant function and (b) infer the extent, pattern and function of nerves surviving in the implanted ear.
4. Prospective and retrospective reviews of psychophysical and speech perception studies conducted in the RTI/Duke Cochlear Implant Laboratory.

Duke University Medical Center
DURHAM, NORTH CAROLINA
27710

DEPARTMENT OF SURGERY
CENTER FOR SPEECH AND
HEARING DISORDERS

TELEPHONE (919) 684-3859
P. O. BOX 3887

April 11, 1988

Mr. Blake S. Wilson
Neuroscience Program Office
Research Triangle Institute
RTP, NC 27709

Dear Blake:

I would be happy to work with you and other members of the RTI/Duke team in the design and evaluation of speech processors for auditory prostheses. I understand that RTI is proposing this project in response to NIH RSP #NIH-NINCDS-88-04, "Speech Processors for Auditory Prostheses."

As my contribution to this project, I will continue to work with you and other members of the RTI team in evaluating various speech processing designs as they are applied to the patients. Specifically, I will take responsibility for the administration and scoring of a full battery of speech perception tests, including the administration of the complete Minimal Auditory Capabilities Battery, Speech Tracking Studies, and Open Set Speech Discrimination Test. It has been our previous experience that this testing has been completed over a 3-4 day span. I will be able to provide this service at a cost of $700 per patient. I look forward to working with you on this project.

Sincerely,

Robert D. Wolford

Robert D. Wolford, M.S.
Audiologist

RDW/bh

X.C. Appendix on "Design and Evaluation of Speech Processors for Auditory Prostheses with Stimulating Electrodes Placed in or on the Cochlear Nucleus"

Design and Evaluation of Speech Processors for Auditory Prostheses with Stimulating Electrodes Placed in or on the Cochlear Nucleus

Subcontract Proposal to the University of Michigan

from the

Neuroscience Program Office

Research Triangle Institute

Research Triangle Park, NC 27709

Note: Supporting documents e, f and g of this appendix are not included for brevity. This material may be found elsewhere in the present proposal as follows:

- e. summary of reporting activity of the Duke/RTI Cochlear Implant Team — see Section X.C.
- f. appendix on the "Design and Evaluation of a Two Channel 'Breeuwer/Plomp' Processor for Auditory Prostheses" — see Section II.B.
- g. CVs for B. Wilson, C. Finley, D. Lawson and R. Wolford — see Section X.G.

CONTENTS

* see note on previous page C-1

Introduction

The Research Triangle Institute (RTI) is pleased to submit this proposal to the Kresge Hearing Research Institute at the University of Michigan (KHRI/UM). The purpose of the proposed work is to design and evaluate speech processors for auditory prostheses with stimulating electrodes placed in or on the cochlear nucleus. Initial studies will be conducted with four or more patients implanted with surface electrodes at the House Ear Institute (HEI) in Los Angeles. These patients will be fitted with percutaneous connectors for direct electrical access to the two or three stimulating plates in their electrode arrays. The studies with these patients will include (a) an extensive series of psychophysical tests, to determine the limits within which attributes of sound can be coded for electrical stimulation of the cochlear nucleus, and (b) evaluation of several alternative speech processing strategies, to determine whether certain strategies that are highly effective for cochlear prostheses can be successfully applied for patients with central nervous system auditory prostheses. All patient studies will be performed in the Cochlear Implant Laboratory at the Duke University Medical Center (DUMC). Each patient will visit the Laboratory for approximately ten days of testing, and special problems the patients may have (e.g., with their percutaneous connectors) will be attended to by members of the ENT and audiology departments at Duke.

An additional element of the work outlined in this proposal is the design of next-generation speech processors for central nervous system auditory prostheses. This effort will have two major components. The first will be to interpret the results from the studies with the HEI patients in terms of processor design. Specifically, we will attempt to identify and exploit opportunities for mapping stimuli along the full dimensions of auditory perceptions for these patients (as demonstrated by the results from the psychophysical studies) and for modifying the speech processing strategies in light of the results from the initial evaluation studies. The procedures used for processor refinement will be similar or identical to those developed in our laboratory for the refinement of processing strategies for scala tympani implants (see, e.g., Wilson et al., 1988).

The second component of work to specify possibilities for improved speech processors for central auditory system prostheses will be to examine in detail the special problems of stimulus coding for effective use of electrodes in or on the cochlear nucleus. This component of proposed work is based on the recognition that the best processing strategies for the cochlear nucleus prosthesis may be quite different from those used for scala tympani implants. In particular, the complex cytoarchitecture and cell functions among the divisions of the cochlear nucleus suggest that the percepts elicited by cochlear nucleus stimulation may be much more difficult to control than the percepts elicited by intracochlear stimulation. Our examination of the coding problems for cochlear nucleus stimulation will include considerations of electrode placement, number of stimulating electrodes, and the structure, location, orientation, and functions of the different cell types and divisions within the nucleus. The product of this part of the project will be a list of suggestions and testable hypotheses related to the further development of electrodes and speech processors for cochlear nucleus prostheses.

This proposal is submitted for possible inclusion as a supplement to the KHRI/UM response to RFP No. NIH-NINCDS-88-03, "Feasibility of a Central Nervous System Auditory Prosthesis." The major tasks presented in the Statement of Work for this RFP are the following:

A. Using non-human mammals, identify and evaluate surgical approaches to the cochlear nucleus, means of electrode implantation, and the effects of microstimulation;

B. Using human cadaver material, identify potential sites within the cochlear nucleus for future electrode implantation;

C. Prepare for future human microstimulation studies of the cochlear nucleus based on the aforementioned studies.

We understand that the KHRI/UM response to the RFP will contain detailed plans for addressing each of these major tasks. The work outlined in our present proposal is intended to complement the work presented in the primary proposal from KHRI/UM. In particular, results from the psychophysical and speech processing studies of the present proposal will provide additional information for the design of future human microstimulation studies of the cochlear nucleus. Also, the described work on development of next-generation processing strategies will provide important inputs to the task of identifying potential sites within the cochlear nucleus for future electrode implantation. We believe the combined efforts of our teams at KHRI/UM, HEI, Duke and RTI will bring us rapidly to our shared goal of safe and effective electrical stimulation of the human cochlear nucleus.

<u>Patients</u>

The psychophysical and speech perception studies outlined in this proposal will be conducted with four or more patients implanted with surface electrodes at the HEI. Elements of the HEI device are shown in Fig. 1. The active electrodes are placed on the surface of the ventral cochlear nucleus (VCN) and consist of two platinum plates mounted on a woven pad of Dacron mesh. Cables from the backs of the plates connect the electrodes to contacts in a percutaneous pedestal. Also attached to the pedestal is a platinum wire with a flamed-ball termination. A portion of this wire and its termination are implanted in the temporalis muscle to provide a remote reference for monopolar stimulation of the electrodes on the surface of the VCN.

Among the seven patients implanted to date with this device, five have had difficulties with the percutaneous pedestal (Eisenberg <u>et al</u>., 1987). A discontinuity in the connections between the electrodes and the pedestal necessitated removal of the device in one of these five patients, and

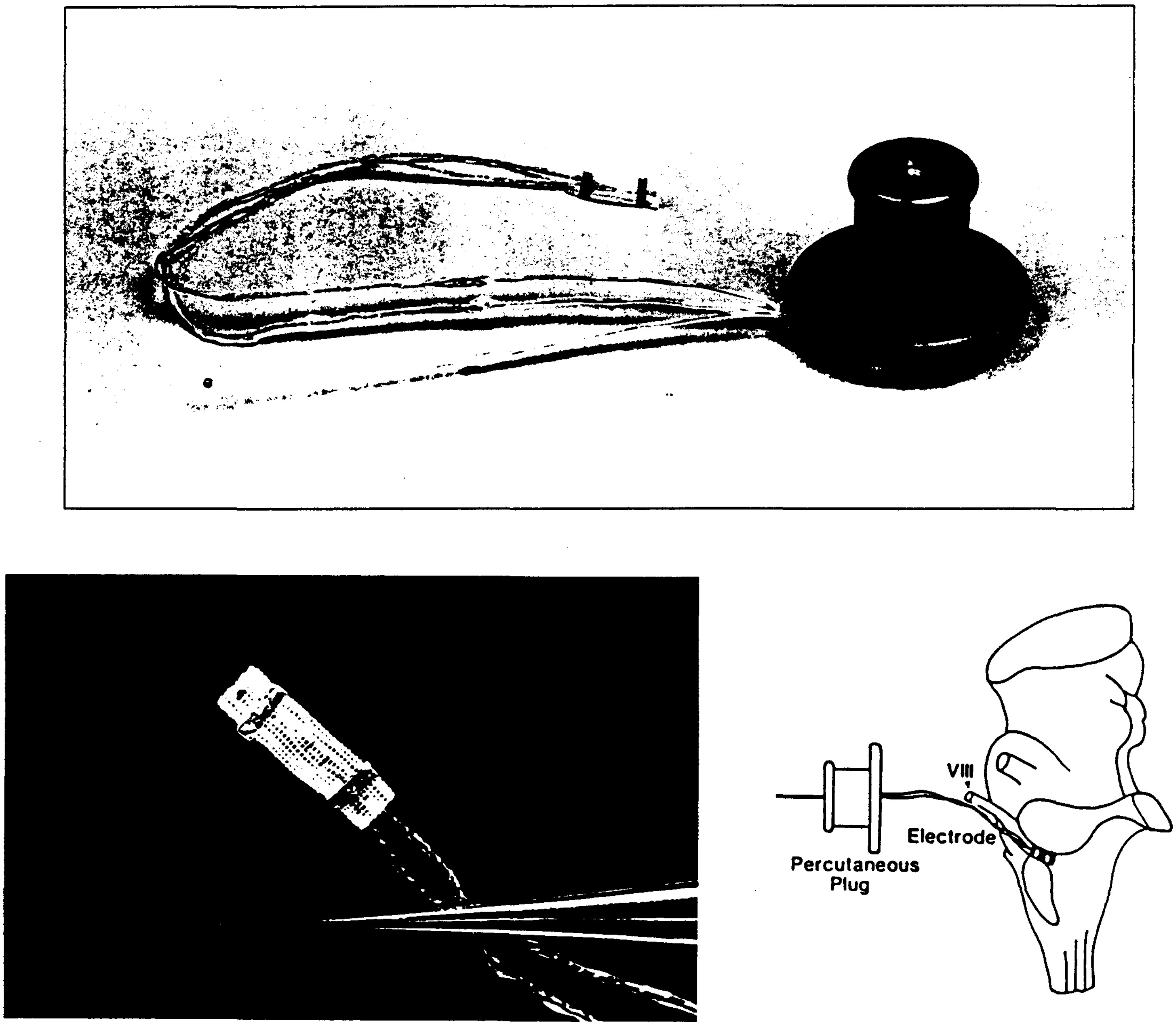

Fig. 1. Elements of the "central electroauditory prosthesis" developed at the House Ear Institute (HEI). The top panel shows the active and remote electrodes attached to the percutaneous pedestal; the lower left panel shows an enlargement of the active electrodes in their dacron mesh carrier; and the lower right panel indicates the placement of the active electrodes on the surface of the cochlear nucleus. Illustrations are from Eisenberg et al., 1987.

infection at the exit site caused rejection of the pedestal in the remaining four patients. The percutaneous pedestal was removed in the last four patients and replaced with the transcutaneous transmission system used in the HEI (and 3M/House) cochlear prosthesis.

The HEI plans to implant three or four additional patients within the next year (D. Nielsen, personal communication, February, 1988). A modified strategy will be used to seat the percutaneous pedestal with the aim of reducing the risk of infection. Also, the electrode array applied to the surface of the VCN will be modified to increase the number of stimulating plates from two to three.

All of the patients to be implanted with this new system in the coming year will be asked to participate in the studies of this proposal. In addition, two or three of the presently-implanted patients will be asked to participate. Each participating patient will travel to North Carolina for 10 days of testing in our Cochlear Implant Laboratory at the Duke University Medical Center. All travel and per diem expenses will be reimbursed from project funds. In some or all cases a spouse or other companion will accompany the patient. Because we have found (in our previous studies with UCSF and other referral patients) that a companion can greatly facilitate the tests by providing support away from the lab and by providing a familiar speaker's voice and lip cues during initial fitting of alternative speech processors, we recommend that such a person's travel and per diem expenses should also be reimbursed from project funds. We will ask the patients to arrive the Sunday immediately before the first week of testing and to stay for twelve days thereafter. This will allow us to test each patient for a total of ten days (taking the weekend off) and to budget reduced airfares associated with Saturday-night stayovers. No funds other than travel and per diem costs are requested for the support of patient participation.

When the patients arrive for the first day of testing, Dr. John McElveen will examine their percutaneous pedestals and conduct several tests of neurologic and otologic function. In addition, Dr. McElveen and members of the Audiology staff at Duke will attend to special problems the patients may have (e.g., with the pedestal or with the psychological stress that may arise from testing).

For planning and budgetary purposes we estimate that a total of four HEI patients will be studied in the course of this proposed project. A letter from Dr. Donald Nielsen of the HEI in support of these studies is presented in this proposal as one of the supporting documents.

Psychophysics

The purpose of the psychophysical studies outlined in this proposal is to determine the limits within which attributes of sound can be coded for electrical stimulation of the cochlear nucleus. Previous studies conducted at the HEI indicate that patients with electrodes on the surface of the VCN have relatively narrow dynamic ranges between the current levels required for threshold stimulation and uncomfortably-loud stimulation (Eisenberg et al., 1987). Representative results are presented in Fig. 2. The dynamic range for bipolar stimulation of the two electrode plates is approximately 6 dB at 150 Hz and approximately 4 dB at 16 kHz. The dynamic ranges for monopolar stimulation are between 7 and 5 dB across the tested frequencies for electrode plate A and between 5 and 3 dB for electrode plate B.

In addition to the measurements of dynamic range, the HEI group has conducted studies of frequency and channel discrimination with three patients using the monopolar coupling configuration (Eisenberg et al, 1987). The channel discrimination tests were performed with stimuli that were "balanced for frequency and intensity for the two electrode plates" (it is unclear whether or not the stimuli were balanced for equal loudness of evoked auditory percepts). Under these conditions patient HR was able to discriminate the two sites of stimulation for 100% of the trials. One of the remaining two patients also demonstrated an ability to discriminate between the sites of stimulation (percent correct score not reported) and the other patient did not exhibit any ability to make this discrimination.

In the tests of frequency discrimination patient HR was able to discriminate 250, 500 and 1000 Hz sinusoids with stimulation of plate B (see Fig. 2), but could not discriminate these frequencies with stimulation of plate A. Results for the other two patients were not reported.

Finally, frequency and intensity difference limens (DLs) were measured in tests with the first implanted patient using the bipolar coupling configuration (Edgerton et al., 1982). The standard frequencies for the frequency DL tests were 250 and 500 Hz. On ascending trials the DLs for these frequencies were 30 and 263 Hz, respectively, and on descending trials the DLs were 170 and 348 Hz, respectively. The intensity DLs for 90, 500, 1000 and 2000 Hz sinusoids presented at the most comfortable loudness (MCL) levels ranged from 17% of the standard intensity for the 90 Hz stimulus to 2 % of the standard intensity for the 500 and 2000 Hz stimuli. An intermediate value (5%) was obtained for the 1000 Hz stimulus.

The picture that emerges from these findings is one of large differences in dynamic range and frequency discrimination for cochlear nucleus implants versus scala tympani implants. The dynamic ranges reported for cochlear nucleus implants are much lower than the dynamic ranges typically found for scala tympani implants, especially at low frequencies of sinusoidal stimulation (Eddington et al., 1978; Pfingst, 1984; Shannon, 1983a). At 150 Hz, for example, the dynamic ranges reported for cochlear nucleus implants approximate 6 dB while typical dynamic ranges for scala tympani implants usually exceed 20 dB. Such a large difference has important implications for speech coding. One implication is that much higher compression ratios will be required to map sinusoidal stimuli into the narrow dynamic range of cochlear nucleus implants compared to the ratios used for scala tympani implants.

The second difference mentioned above is that of frequency discrimination. For patients with scala tympani implants perceived pitch increases with increases in the frequencies of loudness-balanced stimuli up

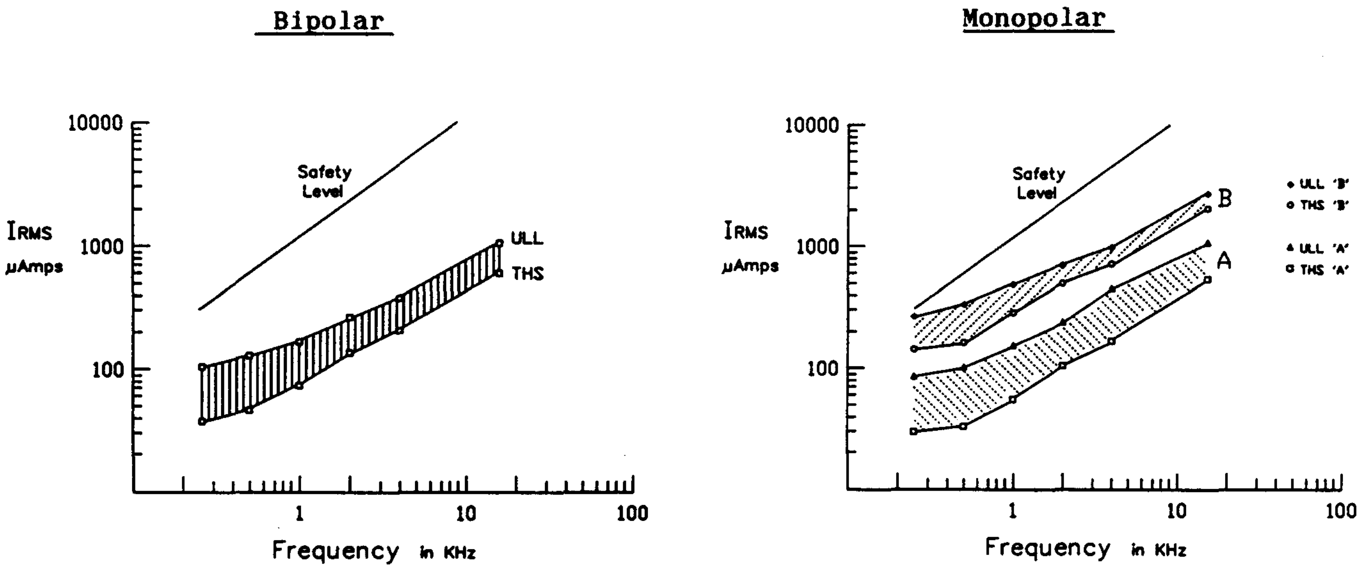

Fig. 2. Current levels of sinusoidal stimulation for threshold (THS) and uncomfortably loud (ULL) auditory sensations for patient HR. The left panel shows these levels for bipolar stimulation of the two plates in the HEI electrode array, and the right panel shows these levels for monopolar stimulation of the two plates. The line marked "safety level" in the two panels indicates a charge density limit of 17 $\mu C/cm^2$/phase across frequencies. Illustrations are from Eisenberg et al., 1987.

to a "pitch saturation" limit of about 300 Hz (Pfingst, 1985). Although a few exceptional patients can discriminate different frequencies up to 1000-2000 Hz (Hochmair-Desoyer and Burian, 1985), the great majority of patients with scala tympani implants cannot discriminate frequencies above the 300 Hz limit. It is thus somewhat surprising to learn that patients with cochlear nucleus implants demonstrate an ability to discriminate 500 and 1000 Hz sinusoids in one case and to discriminate 500 and 763 Hz sinusoids in another case. In addition, the frequency DLs for ascending trials in the tests with cochlear nucleus implants are lower than the DLs for descending trials. The opposite is found for scala tympani implants. One implication of these findings is that the encoding of frequency information at the cochlear nucleus may be quite different from the encoding of this information at the auditory nerve.

In order to determine the limits within which attributes of sound can be coded for cochlear nucleus stimulation, it is clear that many more psychophysical studies need to be conducted with a larger population of patients. The apparent differences in dynamic range and frequency discrimination between cochlear nucleus implants and scala tympani implants need to be verified and explored in detail. In addition, psychophysical studies related to the potential application of various types of speech processing strategies need to be conducted. Tests of channel discriminations and channel interactions, for example, are obviously required for an informed decision as to whether multichannel processing strategies might be useful for patients implanted with surface electrodes overlying the VCN.

Our plan for the psychophysical evaluation of the HEI patients is to conduct a wide range of tests that we routinely conduct with our cochlear implant patients. The results should provide clear comparisons between the possibilities for coding attributes of sound with scala tympani implants versus the possibilities for coding such attributes with cochlear nucleus implants. The results will also provide guidance on the selection of speech processing strategies for patients with cochlear nucleus implants, as noted above. The tests we have in mind are the following:

1. Measurements of thresholds and most comfortable loudness levels (MCLs) for a variety of stimuli including sinusoids, single pulses, and pulse trains. The frequencies of the sinusoids and pulse trains will be varied between 100 Hz and 4 kHz, and the durations of single pulses and pulses within the pulse trains will be varied between 0.1 and 1.0 msec/phase. Balanced biphasic pulses will be used, and all stimuli will be current controlled and delivered through our stimulus isolation unit (see section on "Tools"). Procedures similar to those described by Shannon (1983a) will be used for these measurements (also see Wilson et al., 1986).

2. Measurements of simultaneous channel interactions, using the loudness summation paradigm described by Shannon (1983b and 1985). Measurements of nonsimultaneous channel interactions will also be made by comparing reported loudnesses for different temporal offsets between sequential pulses delivered to two different channels (see White et al., 1984). The range of temporal offsets will be from 0.1 to 10.0 msec, along an exponential scale.

3. Measurements of channel discriminations using loudness-balanced stimuli. As with the measurements of point 1 above, the stimuli will include sinusoids, single pulses, and pulse trains. A procedure similar to that described by Eddington et al. (1978) will be used.

4. Measurements of loudness growth curves for pulse trains and sinusoids. The procedure will be similar to the one described by Shannon (1985b).

5. Measurements of frequency DLs and pitch saturation limits using loudness-balanced stimuli. The stimuli will include pulse trains and sinusoids, presented at the MCLs. If time permits, additional measurements may be made at a number of levels approximating the MCLs of test stimuli, to provide further controls for pitch differences that can result from small differences in loudness between the standard and comparison stimuli (Pfingst and Rush, 1987).

6. Measurements of intensity DLs for pulse trains and sinusoids at 100 and 300 Hz. The loudness of the standard stimuli will be at the MCL. The procedure will be similar to the one described by Pfingst (1984).

7. Measurements of the DLs for gap detection. The procedure will be similar to the one described by Hochmair-Desoyer _et al_. (1985).

All tests of channel interactions and channel discriminations will be performed with the monopolar coupling configuration, and the remaining tests will be performed with both the monopolar and bipolar coupling configurations. We expect that the outlined psychophysical studies will require five days to complete with cooperative and attentive subjects. For other subjects (see section on "Potential Problems"), we may have to make selected measurements to conserve time for the speech studies. Our strategy in such cases will be to reduce the number of different stimuli used for each test, as opposed to eliminating one or more of the basic measurements.

Speech Studies

The purpose of the speech studies is to determine whether certain processing strategies that are highly effective for scala tympani implants can be successfully applied for patients with central nervous system auditory prostheses. As outlined in the previous section on psychophysics, patients with the HEI cochlear nucleus implant have relatively narrow dynamic ranges for both monopolar and bipolar stimulation. In addition, two of three tested patients with the two-electrode system could discriminate between the two sites of stimulation when the electrode plates were excited in the monopolar coupling configuration. These findings indicate that two-channel speech processing strategies might be productively applied for at least some of the HEI patients with a percutaneous pedestal, and that speech processors used with the HEI patients must map their stimulus outputs into a narrow dynamic range. Finally, some or all of the patients to be implanted with the three-electrode system may receive benefit from a three-channel speech processor.

In previous and ongoing studies supported by the Neural Prosthesis Program (projects N01-NS-3-3256 and N01-NS-5-2396), we have identified two highly effective processing strategies for cochlear implants with two channels of stimulation (Wilson _et al_., 1987; Wilson _et al_., in preparation) and for cochlear implants with three or more channels of stimulation (Wilson et al., in press; Wilson et al., 1988). The first processing strategy is described in an appendix to this proposal titled "Design and Evaluation of a Two Channel, 'Breeuwer/Plomp' Processor for Auditory Prostheses". As outlined in the appendix, results obtained from our evaluation of Breeuwer/Plomp processors for cochlear implants demonstrate that (1) the Breeuwer/Plomp processor can act as a powerful adjunct to lipreading, as evidenced by large improvements in consonant identification (all five tested subjects) and connected discourse tracking (the one subject tested) when the processor is used in conjunction with lipreading; (2) this aid in consonant identification is likely to apply to most implant patients, as indicated by the improvements obtained for every tested subject in our series of five; (3) in addition to its utility as an adjunct to lipreading, the Breeuwer/Plomp processor supports a high degree of vowel and consonant identification with hearing alone; and (4) the high scores of the one subject tested with the full Minimal Auditory Capabilities (MAC) battery further indicate that the Breeuwer/Plomp processor can provide useful information even when visual cues from lipreading are not available. These promising results suggest the possibility that patients with two-electrode arrays on the surface of the VCN may also benefit from the application of a Breeuwer/Plomp processor.

For patients with three or more channels of stimulation, we have found that an "interleaved pulses" (IP) processor can produce results that are even better than those obtained with the two channel Breeuwer/Plomp processor (Wilson et al., 1988). Therefore, future HEI patients implanted with arrays of three electrodes on the surface of the VCN may also receive further benefit from the application of an IP processor.

We note that both the Breeuwer/Plomp and IP processors use nonsimultaneous pulses as stimuli. That is, the electrode channels are stimulated in sequence with no overlap between pulses for each channel. This nonsimultaneity of stimulus presentations can greatly reduce channel interactions that result from electric field summation with simultaneous stimuli (White et al., 1984; Shannon, 1985a; Wilson et al., in press). Such a reduction might be particularly important for patients with cochlear nucleus implants inasmuch as the small size of the nucleus demands a close spacing of electrodes for multichannel stimulation. A close spacing of electrodes usually exacerbates channel interactions, as does the coupling of stimuli to the electrodes in a monopolar configuration.

Finally, we note that the Breeuwer/Plomp and IP processing strategies can provide high levels of performance even for patients with extremely narrow dynamic ranges of stimulation. One of our studied patients, for example, had dynamic ranges of 4 dB or lower for pulsatile stimulation for each of his eight pairs of intracochlear electrodes (Wilson et al., in press). Application of an IP processor for this patient tremendously improved his speech perception scores compared to the scores obtained with other types of processor. Patients with the HEI implant, who also exhibit narrow dynamic ranges, may therefore receive special benefit from Breeuwer/Plomp or IP processors.

Our plan for the evaluation of alternative speech processors for the HEI patients is to test the Breeuwer/Plomp processor for all patients who have two or more discriminable channels of stimulation. For patients who cannot discriminate between channels, we will test a reduced version of the Breeuwer/Plomp processor that presents a single channel of output reflecting the fundamental frequency of voiced speech sounds; whether a given speech input is voiced (periodic) or unvoiced (aperiodic); and the overall amplitude of the speech signal. Results of studies conducted in our laboratory and elsewhere (Moore et al., 1985) indicate that a single-channel processor of this class can provide a valuable supplement to lipreading information. Finally, the IP processor will be tested for all patients with three or more discriminable channels of stimulation.

As in our studies with cochlear implant patients, the speech perception abilities of the HEI patients will be measured with a variety of tests. These tests will include vowel and consonant confusion tests (Wilson et al., 1988); all subtests of the MAC battery (Owens et al., 1985); the Diagnostic Discrimination Test (DDT) of consonant perception (Grether, 1970); connected discourse tracking with and without the use of the prosthesis (De Filippo and Scott, 1978; Owens and Raggio, 1987); the Iowa test of medial consonant identification with lipreading cues (Tyler et al., 1983); and the Speech Pattern Contrast (SPAC) test (Boothroyd, 1987). We typically complete all these tests in a three-day period with cochlear implant patients, and we would expect to complete the same tests in a comparable amount of time for cooperative and attentive subjects in the HEI series.

Processor Development

As noted in the Introduction, the proposed work to develop next-generation speech processors for central nervous system auditory prostheses has two major components. The first is to interpret the results from the studies with the HEI patients in terms of processor design. Specifically, we will attempt to identify opportunities for mapping stimuli along the full dimensions of auditory perceptions for these patients (as demonstrated by the results from the psychophysical studies) and for modifying the speech processing strategies in light of the results from the initial evaluation studies.

The second component of work to specify possibilities for improved speech processors for central auditory system prostheses will be to examine in detail the special problems of stimulus coding for effective use of electrodes in or on the cochlear nucleus. This component of proposed work is based on the recognition that the best processing strategies for the cochlear nucleus prosthesis may be quite different from those used for scala tympani implants. In particular, the complex cytoarchitecture and cell functions among the divisions of the cochlear nucleus suggest that the percepts elicited by cochlear nucleus stimulation may be much more difficult to control than the percepts elicited by intracochlear stimulation. Our examination of the coding problems for cochlear nucleus stimulation will include considerations of electrode placement, number of stimulating electrodes, and the structure, location, orientation, and functions of the different cell types and divisions within the nucleus. The product of this part of the project will be a list of suggestions and testable hypotheses related to the further development of electrodes and speech processors for cochlear nucleus prostheses.

Our plan for the work just outlined includes close collaboration among experts in speech coding (B. Wilson), the structure and functions of the different cell types and divisions with the cochlear nucleus (J. Casseday), and the modeling of electric field patterns produced by different geometries and placements of stimulating electrodes (C. Finley). These individuals will meet at the beginning of the project to review all proposed studies with the HEI patients before the actual conduct of these studies. Certain tests may be modified or added at this stage to obtain additional information on coding considerations for cochlear nucleus stimulation. A review of the results obtained in the studies with each of the HEI patients will also be made by this group as the data become available. Revisions or refinements in the procedures used for studies with subsequent HEI patients may be recommended in the course of these reviews.

An additional aspect of the work will be to model the electric field patterns produced by the HEI surface electrodes and by the electrode pads of the University of Michigan's penetrating electrode array (Wise et al., 1987). For the modeling of these field patterns Dr. Finley will adapt a three-dimensional, finite-element model he has already developed for the study of field patterns produced by scala tympani electrodes. The results of the modeling work for the cochlear nucleus implants should provide insights into (1) the likely degree of channel interactions that could be expected for the surface and probe electrodes and (2) possibilities of improved geometries and placements of electrodes for cochlear nucleus stimulation.

Our plan also includes a visit to KHRI/UM by Wilson, Casseday and Finley. This visit will allow these RTI/Duke investigators to discuss and use the three-dimensional anatomical models of the human cochlear nucleus that have been developed by Dave Anderson. Work with these models should help us to appreciate the possibilities and anatomical constraints for electrode placement within or on the cochlear nucleus.

Potential Problems

Information provided to us by Donna Eskwitt and Don Nielsen of the HEI indicates that we may have problems in the testing of at least some of the HEI patients. The etiology of these patients is von Recklinghausen's syndrome with bilateral acoustic tumors. Because the disease process of this syndrome can affect virtually every part of the central nervous system, most of these HEI patients are afflicted with severe CNS disorders and related psychological disturbances. Ms. Eskwitt told us that two of the presently-implanted patients are not reliable subjects for psychophysical testing and therefore would not be suitable for our proposed studies. Among the remaining five patients, two might be able to come to North Carolina and participate in a productive way. The productive participation of the other three patients is regarded as questionable by Ms. Eskwitt. Both patients with the best prospects for participation are fitted with the HEI transcutaneous transmission system (TTS).

In addition to the seven presently-implanted patients, two new patients are scheduled for surgery this April. One of these patients will be fitted with a pedestal and the other with a TTS. The patient to be fitted with the pedestal is young and highly motivated. Ms. Eskwitt thinks he would be a good candidate for our studies.

Finally, as mentioned before, the HEI plans to implant two or three more patients this year after the two surgeries in April. The plan for these future implants is to fit percutaneous pedestals in all cases.

The potential problems we face in the proposed studies involving the HEI patients include (1) the inability of many of these patients to provide reliable responses in psychophysical tests; (2) the inability of some of the remaining patients to travel to North Carolina, for personal or psychological reasons; and (3) the likelihood of slow progress in the tests with patients who can make the trip. We hope (and expect) that at least four HEI patients will be able to participate in our proposed studies at Duke. With the help of the HEI team we have identified three candidates who would be able to participate in a productive way and who would most likely be willing to travel to North Carolina. These candidates include two presently-implanted patients with a TTS and one patient to be implanted in April and fit with a percutaneous pedestal. In addition, some or all of the patients to be implanted after April may be good candidates for our studies.

In the event that fewer than four patients are willing or able to travel to North Carolina for participation in the proposed studies, our "backup" plan is to conduct selected experiments at the HEI in Los Angeles. Ms. Eskwitt suggested that more patients would be able to participate if the tests were to be conducted at the HEI because many of the patients live in the Los Angeles area. Also, the HEI staff is familiar with the particulars of each case and can help to make the tests productive with difficult patients. Despite these advantages though, our strong preference would be to conduct the tests at our Cochlear Implant Laboratory at the DUMC, where we have a complete set of equipment for the described studies and the full resources of our Duke/RTI team.

If we need to conduct studies at HEI to attain our objective of at least four tested patients, then we will use a portable test system now under development at RTI. This portable test system will use an 80386-based portable computer with appropriate interfaces to a real-time speech processor board (Finley et al., 1986) and stimulus isolation equipment. Ultimately, the portable system will replace our present laboratory system based on a large Eclipse S-140 computer. We expect the transition to occur sometime in the fall of 1988, which would be in time for possible studies with HEI patients in Los Angeles.

Tools

As indicated in the previous section, our plan is to test all four HEI patients in the Cochlear Implant Laboratory at Duke. This laboratory is fully equipped for the investigations described in the "Psychophysics" and "Speech Studies" sections of this proposal. Indeed, similar or identical investigations have been conducted with cochlear implant patients over the last several years using Laboratory equipment and software. Key tools available in the Laboratory for the present studies include the following:

- an eight-channel isolation unit for safe, current-controlled stimulation through percutaneous connectors

- an Eclipse S-140 computer system for (1) controlling the delivery of stimuli for psychophysical and speech perception tests; (2) obtaining responses from the subject; (3) analyzing the responses; and (4) simulating various types of speech processors for auditory prostheses

- all software for the psychophysical and speech perception tests outlined in this proposal

- a "Block-Diagram Compiler" for the specification and computer simulation of a wide variety of speech processing strategies (Wilson and Finley, 1985)

- a real-time bench processor for the implementation of two channel, "Breeuwer/Plomp" processors and multichannel interleaved-pulses processors (Finley et al., 1986).

We are pleased to note that the development of all custom hardware and software for the Laboratory was supported by our two "Speech Processors" contracts from the Neural Prosthesis Program (NIH projects N01-NS-3-2356 and N01-NS-5-2396). Construction of the Laboratory, along with the purchase of components for the computer system, was supported by RTI and by the Department of Surgery at the DUMC. The availability of the Laboratory and its tools will allow us to begin the studies with the HEI patients at the outset of the proposed project and to conduct these studies at a much lower cost than would otherwise be possible.

Finally, if some patient tests need to be conducted at the HEI, the portable system described in the previous section will be used. This system will have all of the safeguards and most of the capabilities of the Laboratory system, and is expected to be operational in the fall of 1988.

Reporting

If approved for funding, the principal investigator of this subcontract project (B. Wilson) will report to the PI of the prime project at KHRI/UM (D. Anderson). Results of the subcontract project will be presented in the quarterly progress reports of the prime project, as instructed by Dr. Anderson. These results may be presented as an entire progress report for the prime project, or as separate sections or appendices in selected reports for the prime project.

In addition to the contributions to the quarterly progress reports for the prime project, frequent (at least once every quarter) telephone communications and visits (once every year) will help to maintain an active and productive collaboration between the KHRI/UM and RTI/Duke teams.

Finally, we expect to present the results of the subcontract project at national meetings and in published papers. One possibility for the former would be to make a presentation at one or more of the annual Neural Prosthesis Workshops. The PI of the subcontract project would be pleased to do this if desired by the KHRI/UM group and by Dr. Hambrecht.

Team Capabilities

Almost all of the work outlined in this proposal will be performed by members of the joint Duke/RTI Cochlear Implant Team. This team is highly experienced in (1) design and evaluation of speech processors for auditory prostheses; (2) the efficient handling and care of referral patients who visit Duke to participate in research studies; and (3) the clinical application of cochlear implants. A summary of reporting activity for the Duke/RTI Cochlear Implant Team for the period of 2/85 to 2/88 is presented in this proposal as one of the supporting documents.

In addition to the strong capabilities and integrated approach of the team, the particular investigators identified for this project have experience in areas directly related to the proposed studies. The relevant experience for each investigator is indicated in the following table:

person	areas of expertise and experience
B. Wilson (RTI)	expert in the design and evaluation of speech processors for auditory prostheses; principal investigator for two related contracts for the Neural Prosthesis Program, both titled "Speech Processors for Auditory Prostheses" (N01-NS-3-2356 and N01-NS-5-2396).
C. Finley (RTI)	expert in modeling electric fields produced by various configurations of stimulating electrodes; expert in the design and evaluation of speech processors for auditory prostheses
D. Lawson (RTI)	expert in the design and evaluation of speech processors for auditory prostheses
R. Wolford (Duke)	expert in the evaluation of speech processors for auditory prostheses; expert in the handling and care of implant patients; member of the Audiology staff at Duke
J. Casseday (Duke)	expert on the anatomy and physiology of the cochlear nucleus and central auditory pathways; principal investigator of many projects supported by the NIH and NSF
J. McElveen (Duke)	expert in the surgical aspects of cochlear nucleus implants (see, e.g., McElveen et al., 1985); expert in the medical and surgical care of patients with brainstem implants; while at the House Ear Institute, Dr. McElveen was one of the primary surgeons for the implantation of the HEI central nervous system auditory prosthesis.

Project Organization and Budget

If approved for funding, the work described in this proposal will be conducted at the Research Triangle Institute (RTI) and the Cochlear Implant Laboratory at the Duke University Medical Center (DUMC). The principal investigator will be Blake S. Wilson, Head of the Neuroscience Program at RTI and adjunct assistant professor of Otolaryngology at DUMC. Working with him will be Charles C. Finley and Dewey T. Lawson of the RTI, and Robert D. Wolford, John T. McElveen, Jr. and John H. Casseday of the DUMC. Resumes for these individuals are presented in the "Supporting Documents" part of this proposal, as are letters of commitment from Mr. Wolford, Dr. McElveen and Dr. Casseday.

The project will be administered at the RTI. A chart of RTI's organization is presented on the next page, and the line of managers who would oversee the proposed work is indicated in the chart by arrows.

RESEARCH TRIANGLE INSTITUTE
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- George R. Herbert
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- Daniel G. Horvitz
  Executive Vice-President
  - C. Edgar Cook
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      - Dewey T. Lawson
      - Kathrinn Fitzpatrick
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  - F. Thomas Wooten
    Vice-President
    Electronics and systems
    - Semiconductors
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    - Energy Systems
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- William H. Perkins, Jr.
  Vice-President, Treasurer

As outlined in previous sections of this proposal, the work of the described project is divided into four major activities. These activities are (1) psychophysical and speech perception studies with four HEI patients; (2) development of next-generation speech processors; (3) reporting; and (4) maintenance of active and productive collaborations among the KHRI/UM, RTI/Duke and HEI teams. The budget elements for each of these activities are presented below. A detailed breakdown of total costs (including indirect costs) for the aggregate of these budget elements is presented in a separate business proposal for this project.

1. Psychophysical and speech perception studies.

Our previous experience from studies with cochlear implant patients (see, e.g., Wilson et al., 1988) is that six days of testing are usually adequate for evaluation of two speech processing strategies and for completion of rudimentary psychophysical studies for the specification of processor parameters. In addition, several days of effort by all members of the RTI team are needed to prepare for upcoming studies with each patient, and ten or more days of effort by Wilson and Lawson are needed to analyze the data from these studies once completed. In all, approximately three full weeks of effort are spent by Wilson and Lawson and two full weeks of effort by Finley in the conduct of tests with cochlear implant patients referred to us by other centers. Also, Bob Wolford typically spends three days in the studies with each patient to administer and score the tests of the Minimal Auditory Capabilities (MAC) battery and of connected discourse tracking.

The proposed studies with the HEI patients will have much greater emphasis on psychophysical testing than the aforementioned studies with cochlear implant patients. In addition, the studies with the HEI patients are likely to be more difficult than our previous studies with cochlear implant patients (see section of this proposal on "Potential Problems"). To accommodate these differences we have extended the six-day period of studies with cochlear implant patients to a ten-day period for the HEI patients. Also, we have budgeted a little more time for the preparation for a patient visit and for data analysis. We expect that studies with each of the HEI patients will require four weeks of Wilson's time, four weeks of Lawson's time, three weeks of Finley's time, and three days of Wolford's time. The hardware and software for the described studies has already been implemented under the support of our ongoing project with the Neural Prosthesis Program, "Speech Processors for Auditory Prostheses" (NIH project N01-NS-5-2396).

In addition to costs for professional time, as outlined above, each participating patient will be reimbursed for travel and per diem expenses. In some or all cases a spouse or other companion will accompany the patient. Because we have found that a companion can greatly facilitate the tests by providing support away from the lab and by providing a familiar speaker's voice and lip cues during initial fitting of alternative speech processors, we believe such a person's travel and lodging expenses should also be covered. The total estimated expenses for each patient with an accompanying companion will include airfare ($816 for two round-trip tickets between Los

Angeles and Raleigh/Durham with a Saturday stayover), lodging ($648, for twelve nights at $54 per night for a double, using the special rate for Duke patients at a local hotel) and restaurant ($420, for a $35 rate per day for each couple) expenses.

Finally, Dr. McElveen will examine each patient prior to testing at DUMC (see section on "Patients"). Dr. McElveen has offered to perform this service for $500 per year, for the three years of the proposed project (see his letter of commitment in the section of "Supporting Documents").

A summary of budget elements for the psychophysical and speech perception studies with four HEI patients is presented below:

a. Professional time:

person	role	time
Wilson	patient testing and data analysis	16 weeks
Lawson	"	16 weeks
Finley	"	12 weeks
Wolford	"	2.4 weeks (12 days)

b. Medical examination and support: $1500

c. Patient costs:

item	cost
airfare	816
lodging	648
restaurant	420

$1884 x four patients = $7536

2. Development of next-generation speech processors.

As outlined before, the work to develop next-generation speech processors for central nervous system auditory prostheses includes (1) interpretation of results from the studies with the HEI patients in terms of processor design and (2) detailed examination of the special problems of stimulus coding for effective use of electrodes in or on the cochlear nucleus. Our examination of the coding problems for cochlear nucleus stimulation will include considerations of electrode placement, number and spacing of stimulating electrodes, and the structure and functions of the different cell types and divisions within the nucleus.

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Supporting Documents

The following supporting documents are presented in the remainder of this proposal:

1. letter from D. Nielsen, PhD, House Ear Institute;

2. letter from J. Casseday, PhD, Duke University Medical Center;

3. letter from J. McElveen, MD, Duke University Medical Center;

4. letter from R. Wolford, MS, Duke University Medical Center;

5. summary of reporting activity for the Duke/RTI Cochlear Implant Team for the period February, 1985 to February, 1988;

6. appendix on the "Design and Evaluation of a Two Channel, 'Breeuwer/Plomp' Processor for Auditory Prostheses";

7. CVs for B. Wilson, C. Finley, D. Lawson, J. Casseday, J. McElveen and R. Wolford

(Note: pages 28-30 are intentionally not included in this proposal)

HOUSE EAR INSTITUTE

. . . so all may hear

March 7, 1988

Mr. Blake Wilson
Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

Dear Blake:

I read with interest your subcontract proposal to accompany the University of Michigan's response to RFP No. NIH-NINCDS-88-03, "Feasibility of a Central Nervous System Auditory Prosthesis" and I enthusiastically support your study.

The House Ear Institute will encourage all of its new patients to be subjects for your psychophysical and speech processing testing. It is our understanding that you would like to test four or more patients implanted with surface electrodes on the cochlear nucleus and with percutaneous plugs attached. It is understood that you will require that the patient travel to Duke for ten days of testing during a twelve-day period and that you will pay travel and per diem cost for the patient and an accompanying person. Your proposal will be approved for human rights by your Institutional Review Board and during their stay at Duke you will provide medical care as needed for the patients.

Your speech processing strategies are innovative and fit nicely with our plans to increase the number of surface electrodes from the current two to a maximum of four before attempting the multichannel penetrating electrodes.

While we cannot promise that every patient will participate in your project, we look forward to a combined effort of Duke/Research Triangle Institute, Kresge Hearing Research Institute, University of Michigan and the House Ear Institute to bring us rapidly to our shared goal of safe and effective electrical stimulation of the human cochlear nucleus so all can hear.

Sincerely,

Don Niel

Donald W. Nielsen, Ph.D.
Executive Vice President,
Research

DWN:cla
cc: Dr. John House
Mr. Brad Volkmer
Dr. Bill House
Ms. Donna Eskwitt
Mr. Phil Mobley

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A Non-Profit Institute affiliated with the University of Southern California

A summary of budget elements for the development of next-generation speech processors for cochlear nucleus implants is presented below:

a. Professional time:

person	role	time
Wilson	integrate and report on inputs provided by Casseday, Finley and members of the KHRI/UM team; provide inputs on considerations related to speech coding	4 weeks
Casseday	provide inputs on considerations related to the structure and functions of the different cell types and divisions within the cochlear nucleus; review studies with the HEI patients; assist in manuscript preparation	3 weeks
Finley	model the field patterns of the HEI surface electrode and the University of Michigan's probe electrode; provide recommendations for the further development of electrodes and speech processors based on the results of the modeling studies	4 weeks

3. Reporting.

A summary of tasks and budget elements for reporting is presented below:

a. Professional time:

person	role	time
Wilson	primary author for supplements to KHRI/UM progress reports; primary author for manuscripts to be submitted for publication; presenter at the Neural Prosthesis Workshop, if desired by the KHRI/UM group and by Dr. Hambrecht	6 weeks
Lawson	coauthor	2 weeks
Finley	coauthor	2 weeks
Fitzpatrick	secretarial support	2 weeks

4. Maintenance of active and productive collaborations among the KHRI/UM, RTI/Duke and HEI teams.

An active and productive collaboration between the KHRI/UM and RTI/Duke teams will be maintained through reports, frequent telephone communications, and visits. We request support for Wilson or Finley to travel to KHRI/UM for a two-day visit for each year of the project. The purpose of these trips will be to (1) present results of studies conducted at RTI and Duke; (2) obtain advice and inputs from members of the KHRI/UM team on work to develop next-generation speech processors for cochlear nucleus implants; and (3) support the work at KHRI/UM to identify potential sites within the cochlear nucleus for future electrode implantation and to prepare for future human microstimulation studies.

In addition to these trips, we request support for Casseday and Finley to accompany Wilson for one of the above visits to KHRI/UM. This will allow these three RTI/Duke investigators to discuss and use the three-dimensional anatomical models of the human cochlear nucleus that have been developed by Dave Anderson. A full appreciation of the possibilities and anatomical constraints for electrode placement will be invaluable for our proposed studies related to the development of next-generation electrodes and speech processors for the cochlear nucleus prosthesis.

Finally, we want to mention that members of the HEI team have expressed a strong interest in participating in the proposed studies with the four HEI patients. The HEI investigators who may participate include Dr. Donald W.

Nielsen, Executive Vice President for Research at HEI; Mr. J. Phil Mobley, Director of Engineering at HEI; and Dr. Steve Otto, Psychoacoustician at HEI. Travel support for these individuals would be provided by the HEI.

A summary of budget elements for maintenance of active and productive collaborations is presented below:

a. Travel expenses for five visits to KHRI/UM by RTI/Duke investigators:

item	cost
airfare	590
limo	30
lodging	122
restaurant	50

$792 x five trips = $3960

Concluding Remarks

We at Duke and RTI are committed to the development and clinical application of central nervous system auditory prostheses. In this proposal we have outlined a plan for the evaluation of promising alternative speech processors for patients already (or soon to be) implanted with surface electrodes overlying the ventral cochlear nucleus, and we have described a way in which new processors and electrode systems can be designed and evaluated. We believe the work presented in this proposal will greatly accelerate the clinical application of advanced prostheses with stimulating electrodes in or on the cochlear nucleus. In particular, results from the proposed psychophysical and speech perception studies will provide detailed information for the design of future human microstimulation studies of the cochlear nucleus. Also, the described work on development of next-generation processing strategies will provide important inputs to the task of identifying potential sites within the nucleus for future electrode implantation. These contributions of the subcontract project directly address main tasks B and C of the Work Statement for the prime contract (see Introduction, p. 4).

In addition to studies directly related to the work specified in the RFP, the practical experience gained in the tests with the four HEI patients should be invaluable for the smooth and effective conduct of future human studies. Furthermore, if the alternative processing strategies improve the abilities of these patients to recognize and understand speech, then our level of confidence for continued work on the development of central nervous system auditory prostheses will be greatly increased. That is, we will be in a position of improving designs that have already been shown to be effective. Such a demonstration would facilitate the introduction of central nervous system auditory prostheses into the clinical armamentarium and accelerate the design and testing of modified devices. Finally, the conduct of this project would be an opportunity to help present patients with brainstem implants. If substantial gains in performance are demonstrated in our tests of alternative processing strategies with the HEI patients, then we will make all reasonable efforts to provide them with portable processors for their personal use. Possible arrangements for the funding to support the design, construction and maintenance of such processors will be discussed with the HEI group and with Dr. Hambrecht of the Neural Prosthesis Program.

Finally, we would like to note that the request for support made in this subcontract proposal is modest. Over the three years of the project the average level of professional and technical effort is 0.43 person years/year. This is a relatively small fraction of the level of 3.00 person years/year that the Government considers to be appropriate for the conduct of the prime contract (RFP, p. L2-2). We can offer to do the work outlined in this subcontract proposal at a low cost because all of the work to prepare for the proposed studies has already been done under the auspices of two other contracts from the Neural Prosthesis Program.

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Duke University Medical Center
DURHAM NORTH CAROLINA 27710

DEPARTMENT OF SURGERY
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AUDITORY RESEARCH LABORATORY

P.O. BOX 3943
TELEPHONE (919) 684-6636

9 March, 1988

Blake Wilson
Neuroscience Program Office
Research Triangle Institute
Research Triangle Park NC 27709

Dear Blake:

I will be happy to work with you and other members of the RTI/Duke team on your project "Design and Evaluation of Speech Processors for Auditory Prostheses with Stimulating Electrodes Placed in or on the Cochlear Nucleus. I understand that your proposal for this project is as a subcontract to the University of Michigan" response to NIH RFP No. NIH-NINCDS-88-03, "Feasibility of a Central Nervous Sy stem Auditory Prosthesis."

My contribution to the proposed project will be to consult with you and your staff on the structure and function of the cochlear nucleus, to review studies of patients with the House Ear Institute implant, and to assist in preparation of manuscripts. I understand that the amount of consulting time is expected to be 15 days at a rate of $235 per day.

I want to add that I found your proposed studies timely and important. As you pointed out in your proposal, the morphological differences within the cochlear nucleus mean that the processing strategies that should be used with cochlear nucleus implants may be very different than those used with scala tympani implants. Indeed, it is quite possible that different divisions of the cochlear nucleus will require different coding strategies. The fact that the cochlear nucleus consists of a number of different functional parts, may be viewed as a present difficulty for cochlear nucleus implants; however, with additional studies such as those you propose this fact can also be viewed as an opportunity. That is, it might ultimately be possible to provide a patient with a greater variety of usable stimulus codes at the cochlear nucleus than is now possible at the cochlea.

Sincerely,

JH Casseday

John H. Casseday

JHC/pc

Duke University Medical Center
DURHAM, NORTH CAROLINA 27710

JOHN T. MCELVEEN, JR., M.D.
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DIVISION OF OTOLARYNGOLOGY
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March 3, 1988

Mr. Dewey Lawson
Research Triangle Institute
Post Office Box 12194
Research Triangle Park, North Carolina 27709-2194

Dear Dewey:

I would be pleased to work with you and the other members of the RTI/Duke team in the design and evaluation of speech processors for central nervous system auditory prostheses. I understand that RTI is proposing this project as a subcontract to the University of Michigan's response to NIH RFP No. NIH-NINCDS-88-03, "Feasibility of a Central Nervous System Auditory Prosthesis." One aspect of this project that needs to be addressed is the testing of the individuals already implanted with the surface electrode array. By altering speech processing strategies, we may improve their auditory perception. Prior to testing, each of these patients should have an otologic evaluation. In addition, a physician should be available should any complications arise during the testing procedure. I will be able to provide this service at a cost of $500.00 per year. I look forward to working with you in this project.

Respectfully,

John T. McElveen, Jr., M.D.

JTM/jd
Enclosure

Duke University Medical Center
DURHAM, NORTH CAROLINA
27710

DEPARTMENT OF SURGERY
CENTER FOR SPEECH AND
HEARING DISORDERS

TELEPHONE (919) 684-3859
P. O. BOX 3887

March 3, 1988

Mr. Blake S. Wilson
Neuro Science Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

Dear Blake:

I would be pleased to work with you and the other members of the RTI/Duke team in the design and evaluation of speech processors for central nervous system auditory prostheses. I understand that RTI is proposing this project as a subcontract to the University of Michigan's response to NIH RFP No. NIH-NINCDS-88-03, "Feasibility of a Central Nervous System Auditory Prosthesis."

As my contribution to the proposed project I will, at a consulting rate of $300 per day, take responsibility for the administration and scoring of a full battery of speech perception tests, including but not limited to the Minimal Auditory Capabilities Battery, Speech Tracking Studies, and Open Set Speech Discrimination Tests.

Again, I look forward to working with you on this project.

Sincerely,

Robert D. Wolford

Robert D. Wolford, M. S., Audiologist

Coordinator of the Center for the
Hearing Impaired
Duke University Medical Center

RDW/bjb

X.D. Final Report for NIH Project N01-NS-3-2356, "Speech Processors for Auditory Prostheses"

Final Report

September 26, 1983 through September 26, 1985

NIH Contract N01-NS-2356

Speech Processors for Auditory Prostheses

Prepared by

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

Neuroscience Program Office
Research Triangle Institute
Research Triangle Park, NC 27709

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. In this final report we will briefly review our efforts to meet these objectives and offer several suggestions for future work.

II. Brief Descriptions of Project Activities

Major activities of our first, two-year project with the Neural Prosthesis Program included the following:

1. Design, build and test a hardware interface to provide a high-bandwidth communications link between an Eclipse computer and implanted electrodes;

2. Develop and apply an integrated field-neuron model of electrical stimulation by intracochlear electrodes;

3. Identify and contrast promising approaches to the design of speech processors for auditory prostheses;

4. Build a computer-based simulator that is capable of rapid and practical emulation of these approaches in software;

5. Develop software for support of basic psychophysical studies and speech testing;

6. Conduct tests with two patients at the University of California at San Francisco (UCSF) to (a) confirm proper operation of the equipment and software indicated in points 1, 4 and 5 above; (b) obtain basic measures of psychophysical performance in one patient fitted with the UCSF transcutaneous transmission system and one patient fitted with the UCSF percutaneous transmission system; and (c) compare the performance of different, multichannel speech processing strategies with the second patient;

7. Design, build and test a portable, real-time speech processor appropriate for use with single-channel auditory prostheses;

8. Develop and apply ensemble models of the spatial and temporal patterns of neural discharge produced by intracochlear electrical stimulation;

9. Help to establish strong collaborations between UCSF, Duke University Medical Center, Washington University Medical Center and RTI, so that parallel series of tests with implant patients can be conducted in San Francisco, Durham and St. Louis;

10. Build laboratory facilities at UCSF and Duke for testing cochlear-implant patients; and

11. Report the results of this project at major conferences and in manuscripts in preparation.

In the following subsections of this section on project activities we will briefly describe the activities indicated in points 1, 2, 4, 6c, 7, 8 and 10 above. Additional information on all project activities can be found in our quarterly progress reports. To facilitate access to this information, Appendix 1 presents a listing of key contents of the quarterly reports.

A. Hardware interface

The hardware interface is designed to provide a safe means of delivering high-bandwidth stimuli to all eight channels of the UCSF electrode array via a percutaneous cable. Outputs on each of the eight channels can be updated under computer control every 50 usec, and the resolution of these outputs is 12 bits. The clock rate of updates can be increased to 60 kHz if the number of simultaneous outputs is reduced to two. The bandpass of each channel is 5 Hz to 60 kHz. In all, then, the "stimulation side" of the hardware interface supports a very high bandwidth of transmission to the electrode array.

In addition to the stimulation circuitry just described, the hardware interface provides a communications link <u>from</u> the implanted electrode array. Specifically, two channels of artifact rejection and analog-to-digital conversion allow measurement of potentials on both stimulated and unstimulated electrodes at each clock pulse. The assignment of the monitored channels is under computer control. The ability to measure potentials at unstimulated electrodes permits studies of electric field patterns produced by intracochlear electrodes and of the shapes and growths of evoked neural potentials in the cochlea. These "intracochlear evoked potentials" may provide objective measures that complement measures we routinely obtain in psychophysical tests with implant patients. Finally, measurement of potentials on stimulated electrodes permits automated determinations of impedances for all electrodes in the array.

B. Computer-based simulator of speech processors

One of the most-important tools developed in this project is our computer-based simulator of speech processors for auditory prostheses. Use of this simulator allows for rapid and flexible emulation of promising coding strategies in software, which in turn allows us to make valid comparisons between many different approaches to processor design in tests with single subjects. In this way, controls are provided for (a) inter-subject differences in pathology (i.e., differences in the densities, stimulus-response properties and loci of surviving neural elements in the cochlea, and possible differences in the integrity of central auditory structures); (b) the type of electrode array used; and (c) apposition of individual monopolar or bipolar-pair electrodes to excitable tissue. These differences among subjects, along with differences in testing procedures among laboratories, have greatly complicated the interpretation of results obtained in previous studies of processing strategies.

The software for the computer-based simulator of speech processors for auditory prostheses includes the following main programs:

CPEXEC -- executive program for managing communications between, and execution of, other programs in the set;

DESIGN -- program for the design of a signal-processing system, in which the user specifies the function and position of each block within a network of blocks;

MODIFY -- program to modify signal-processing systems previously defined by program DESIGN;

PREPARE -- program that transforms files generated by program DESIGN into files that are used by program EXECUTE;

EXECUTE -- program that executes the simulation of signal-processing systems;

SHOWNTELL -- program for display of outputs generated by EXECUTE, either as graphs on the computer console or as acoustic signals produced over the D/A converter;

SAMPLE -- program to sample speech and other data with the A/D converter, and to store these data on disk in contiguous files with identifying headers;

ASNELEC -- program to assign electrode channels to receive data from the outputs of EXECUTE, and to translate these data into the code required for control of and communication with the RTI Patient Stimulator;

TEST -- program to send data out to the electrodes from the files generated by program ASNELEC, and to monitor and log patient responses to processed speech stimuli.

These programs have been in use for over one year and allow for simulation of a wide range of processing strategies. For example, the DESIGN and EXECUTE programs are fully capable of specification and subsequent simulation of every speech processor for auditory prostheses described in the published literature.

C. Integrated field-neuron model

An important element in the design of speech processors for auditory prostheses is knowledge of the "electrical-to-neural transformer" that characterizes the properties of neural responses to stimuli delivered by intracochlear electrodes. These response characteristics are dependent on a variety of factors including (a) the physical locations, dimensions and electrical parameters of the implanted electrodes and (b) the survival patterns and physiological integrity of neural structures in the cochlea. In an effort to understand the complexities of intracochlear electrical stimulation, we have developed an integrated field-neuron model that couples a description of the electric fields produced by intracochlear electrodes with a description of neural responses resulting from the application of such fields. In particular, the field model is used to compute potential gradients (or the profile of voltages) along the path of a neuron and the neural model is used to predict the patterns of responses that are produced with the imposed voltage profiles.

The potential gradients are calculated by an iterative, two-dimensional, finite-difference model of a cochlear cross section, which includes a pair of electrodes in the scala tympani in transverse-plane sections and many pairs of electrodes in spiral-plane sections. Grid points in the model are 20 um apart and resistivities linking the grid points are defined according to published values for resistivities of tissues and fluids appearing in the cross section. The bipolar electrodes are defined as equipotential conductors mounted in an insulating carrier medium. Fixed voltages are assigned to each electrode and the resultant field patterns are computed by iteration for the entire cross section. Finally, the potential levels at points along the loci of cochlear neurons are extracted from the last iteration of the field calculations.

To predict patterns of neural responses to the imposed voltage profiles, a lumped-element model of a myelinated fiber is used. This model is a modification of McNeal's axon model (McNeal, 1976) of resistively-linked, Frankenhauser-Huxley nodes. The modified model includes myelinated axon cable properties and uses mammalian node of Ranvier characteristics instead of the characteristics for Frankenhauser-Huxley frog nodes. Eighteen active nodes are included, each separated by ten myelinated segments. One section includes characteristics of a cell body, resembling the bipolar cells of the cochlea. A system of simultaneous, nonlinear differential equations is solved iteratively to calculate the model's response to any arbitrary stimulus waveform, applied as a voltage profile along the entire length of the axon. The neuron model, in conjunction with the field potential models, constitutes an integrated model of single fiber behavior in the electrically-stimulated cochlea.

Initial applications of the integrated field-neuron model have included (a) simulation of electric field patterns produced in the transverse and spiral planes by the bipolar electrodes of the UCSF array; (b) examination of the sensitivity of placement of such electrodes in the scala tympani in terms of neural thresholds and spread of excitation; (c) examination of the interaction and crosstalk at a single neural element for stimulation of two or more bipolar pairs in the UCSF array; (d) evaluation of likely effects of bone and other impedance boundaries on field patterns produced by the UCSF electrodes; (e) preliminary examination of field patterns produced by other configurations of intracochlear electrodes; and (f) demonstration of basic properties of neural excitation with voltage profiles approximating those produced by intracochlear electrodes. In general, the results of studies a and b above show excellent agreement with the results of _in vivo_ measurements. Also, the results of the remaining studies provide insight into likely properties of stimulation with cochlear implants that have not yet been determined in animal experiments. Detailed presentations of all of these results can be found in our quarterly reports (see Appendix 1).

D. Ensemble models of neural responses evoked by intracochlear electrical stimulation

In addition to the integrated field-neuron model, described in the previous subsection, we have developed a series of ensemble models of the spatial and temporal patterns of neural discharge produced by intracochlear electrical stimulation. Like the field-neuron model, the ensemble models actually consist of two models: one to describe the field patterns generated by intracochlear electrodes and the other to describe the neural responses evoked by the imposed electric fields. The simplest ensemble model couples an exponential-falloff model of field patterns with a mathematical description of strength-duration curves for intracochlear electrical stimulation. This combined model (emsemble model 1) provides a powerful tool for demonstrating basic patterns of neural responses evoked by a wide range of electrodes and stimuli. In addition, it stands on a firm foundation of previous work in which the exponential-falloff model was used (see, e.g., Black and Clark, 1980; Merzenich and White, 1977; O'Leary _et_ *al*., 1985) and in which measurements of strength-duration relationships were made for various configurations of intracochlear electrodes (Loeb *et al*., 1983; van den Honert and Stypulkowski, 1984).

As reviewed in detail in our 8th Quarterly Progress Report, results obtained from this simple ensemble model are consistent with the following observations:

1. A parabolic-like profile of latencies is found in the fields of neural responses evoked by stimulation with intracochlear electrodes;

2. The extent of the excitation field, and the shape of the latency profile, are not necessarily constant for stimulation with constant-charge pulses;

3. Fundamental attributes of the auditory stimulus, such as intensity and frequency, might be coded by appropriate manipulations in the latency profiles of evoked neural responses;

4. Severe interactions between channels can be produced by simultaneous stimulation of different electrodes (or electrode pairs) in a multichannel array;

5. Response fields found in a heterogeneous population of neurons are similar to the fields found for a uniform population for spatially-selective electrodes, but dissimilar in important ways for electrodes with large space constants;

6. Surprisingly, the "equivalent space constants" of the neural density profile found for monopolar stimulation can be much less than the space constants of the imposed electric field;

7. This may explain how patients implanted with monopolar arrays can rank their electrodes;

8. For patients with good nerve survival monopolar electrodes may preferentially excite dendritic nodes over the dynamic range of stimulation, while bipolar electrodes may excite dendritic nodes near threshold and axonal nodes thereafter;

9. It is likely that a higher bandwidth of temporal information can be represented to the central auditory system with dendritic activation than with axonal activation; and

10. Therefore a tradeoff between spatial selectivity and temporal bandwidth may exist for auditory prostheses.

In summary, initial application of the simplest of our ensemble models has been useful for demonstrating basic patterns of neural responses evoked by intracochlear electrical stimulation and for generating testable hypotheses of improved stimulus coding for cochlear implants. We will be evaluating the hypotheses implicit in points 3, 7 and 10 above in tests with future implant patients. In addition, we plan to develop and apply more-sophisticated ensemble models to elucidate details in the response fields not evident in the predictions of ensemble model 1. Results of these future studies will be reported as they become available.

E. <u>Design of a portable speech processor</u>

We have developed a portable, real-time speech processor appropriate for use with single-channel auditory prostheses. The main objectives of this effort were to (a) demonstrate that the fundamental frequency (F_0) of voiced speech sounds could be reliably extracted with a low-power processor for both noisy and quiet acoustic environments; (b) demonstrate that this processor could reliably mark and code the boundaries between voiced, unvoiced and silent intervals in running speech, in the same acoustic environments; (c) provide a "building block" for multichannel speech processors in which signals representing excitation of the vocal tract are coded separately from signals representing the "short-time" configuration of the vocal tract; (d) provide a working hardware system for implementing other promising strategies in a portable unit; and (e) make a prototype processor to provide speech input that is largely complementary to the input provided by information available in lipreading, primarily for application in extracochlear prostheses for infants and young children (after full evaluation of this and competing coding strategies with adults).

To meet these objectives we designed a portable processor based on the CMOS ("Complementary Metal Oxide Semiconductor," a low-power technology for integrated circuits) version of the INTEL 8031 microcontroller. This microprocessor has a 1 microsecond instruction cycle and on-chip peripherals that facilitate its use in a low-cost, battery-powered processor for real-time analysis of speech.

A block diagram of the current configuration of the hardware is shown in Fig. 1. The hardware consists of four main sections: the analog section for bringing speech from the environment to the input of an analog-to-digital converter (ADC); the ADC itself; the microcontroller section with memory; and a digital-to-analog converter (DAC) for output to the electrode driver(s). Under construction are two variations of this basic configuration, both to increase "processing throughout" with either the addition of another 8031 or a CMOS 12x12 bit multiplier (one of the ADSP-1000 series of multipliers made by Analog Devices, Inc.). These additional devices are not required for the present processing strategy, but may be required for more complex strategies such as those that might be used for multichannel prostheses. The power consumption of the present processor is about 70 mW for quiet environments, where not much current is drawn by the analog section, and about 74 mW when intense noise and speech are present at the microphone. At these power levels the processor will run continuously for several days on a 5-volt NiCad battery without recharging.

Also compatible with the objective of a portable unit is the small size of the instrument. Even with low-density construction, the entire processor easily fits on a 12x9 cm board. Improved packaging could easily reduce the size of the processor to that of a pack of cigarettes.

In addition to portability, another important objective of our effort was to extract a reliable and accurate representation of F_0 for voiced speech sounds. We selected the "Average Magnitude Difference Function" (AMDF) algorithm (Ross et al., 1974; Sung and Un, 1980; Un and Yang, 1977) because its computational complexity is relatively modest and its performance is robust in noisy acoustic environments (Paliwal, 1983). In

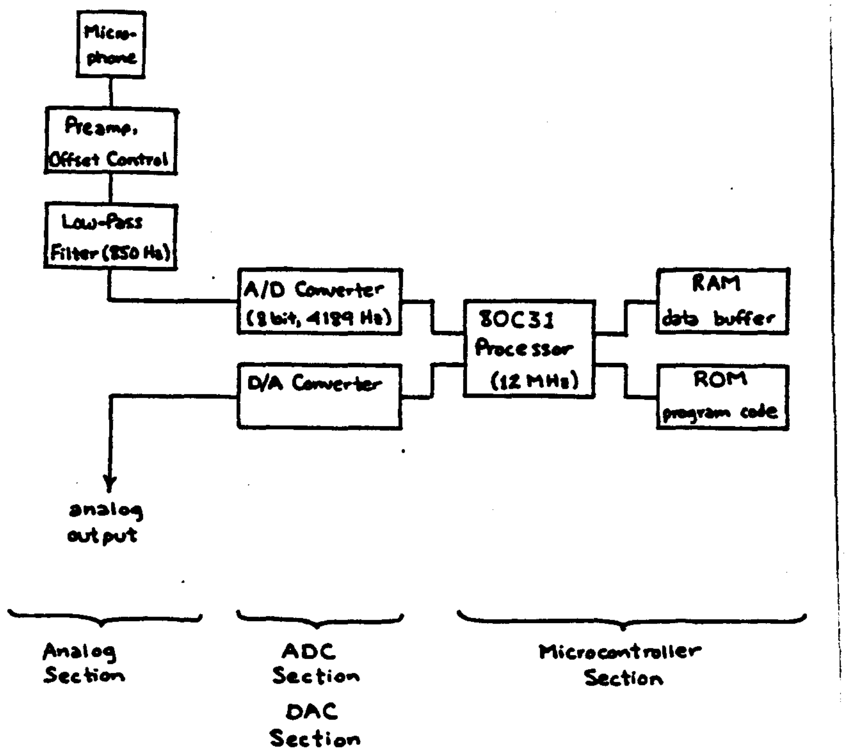

Fig. 1. Block diagram of the 80C31-based processor

our implementation of this algorithm the AMDF output is further processed for median smoothing, detection of erronous indications of F_0, and detection and signalling of intervals that contain unvoiced speech sounds. Tests with inputs of sinusoids, noise and speech material indicate that the processor functions according to its design. We therefore have available a portable processor for accurate extraction and representation of voice fundamental frequency.

F. Evaluation of processing strategies in tests with patient LP

In June and July of 1985 we conducted psychophysical and speech-testing studies with one of the percutaneous-cable patients at UCSF. Briefly, this patient (LP) presented a tremendous challenge to the UCSF and RTI teams in that his psychophysical performance along almost every measured dimension was worse than any previous patient in the UCSF experimental series. Moreover, only one of his scores on speech tests (voice/unvoice) was above chance for the "compressed analog outputs" strategy used in the present UCSF processor.

With these discouraging results in mind, our approach was first to reproduce one version of the analog-type UCSF processor in the software of our block-diagram compiler (see section II.B); then determine if the simulated processor produced results essentially identical to those obtained with the UCSF "tabletop" analog processor; and finally to evaluate other processing strategies in an attempt to improve LP's understanding of speech. The basic plan of these other processors was to reduce in steps the temporal and spatial overlap between channels and introduce (in the last two processors tested) a representation of the linear-prediction residual signal. In all, the block-diagram compiler was used to simulate 5 distinctly different processing strategies. As described in detail in our 7th Quarterly Progress Report, some of these processors produced percepts that were clearly in the "speech mode," that were spontaneously recognized as the speech test tokens delivered to the processor, and that produced test scores well above chance on confusion-matrix material. More specifically, the results of the tests with patient LP were consistent with the following:

1. Although some patients have good or excellent performance with multichannel processors that present "compressed analog" signals at their outputs (e.g., EHT, the previous experimental patient at UCSF), other patients have miserable performance with these processors;

2. The patients who have little or no recognition with the "compressed analog outputs" processor are likely to exhibit various manifestations of poor nerve survival and severe channel interactions;

3. In tests with patient LP, reduction of the spatial bandwidth of transmission of compressed analog outputs to the electrode array (by reducing the number of simultaneous output channels from 6 to 2) did not improve performance over the "6-channel, all outputs on" strategy (zero performance for both);

4. An immediate and compelling increase in speech recognition can be obtained (at least in LP and probably in patients with similar patterns of nerve survival) with a 6-channel strategy in which interleaved pulses are delivered to the two channels that have the highest RMS energy in each time frame (strategy 3);

5. Use of one representation of the linear-prediction residual signal (the "multipulse excitation sequence," as applied in strategies 4 and 5) can improve the "naturalness" of speech percepts and apparently also can convey much information over a single channel of stimulation;

6. However, performance on speech tests is in general lower with the "multichannel, multipulse excitation" strategies than with the "multichannel, interleaved pulses" strategy, possibly because the RMS energy levels in the selected channels are not represented in the former; and

7. It is likely, in view of points 1 and 4 above, that different processing strategies will be required for patients with different classes of neural pathology.

G. Reporting

A major effort of this project was in dissemination of research findings. In addition to our quarterly progress reports, we have prepared drafts of three manuscripts for publication, hosted a site visit for this project at RTI in December, 1984, and presented many papers at major conferences. The manuscripts in preparation are the following:

Wilson, BS and Finley, CC: Ensemble Models of Neural Discharge Patterns Evoked by Intracochlear Electrical Stimulation. I. Simple Model of Responses to Transient Stimuli. To be submitted for publication in Hearing Res.

Wilson, BS: Control of Temporal Channel Interactions in Multichannel Auditory Prostheses. To be submitted for publication in Hearing Res.

Weber, BA, Wilson, BS, Farmer, JC and Kenan, PD: The Duke University Cochlear Implant Program. To be submitted for publication in Am. J. Otol.

Finally, a list of major conference presentations is presented below:

Wilson, BS: Speech processors for auditory prostheses. Presented at the Neural Prosthesis Workshop, 1983, 1984 and 1985.

Wilson, BS: Coding strategies for multichannel auditory prostheses. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, Aug. 19-23, 1985.

Finley, CC: An integrated field-neuron model of intracochlear stimulation. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, Aug. 19-23, 1985.

Wilson, BS: Discussion Leader, Gordon Research Conference on Implantable Auditory Prostheses, Aug. 19-23, 1985.

Wilson, BS: Comparison of strategies for coding speech with multichannel auditory prostheses. Invited paper to be presented at the Conference on Speech Recognition with Cochlear Implants, New York University, April 17-19, 1986.

Finley, CC and BS Wilson: Models of neural stimulation for electrically evoked hearing. Invited paper presented in the special session on neurostimulation, ACEMB Meeting, Sept. 30-Oct. 2, 1985.

Wilson, BS and CC Finley: Speech processors for auditory prostheses. Invited paper presented in the special session on signal processing for the hearing impaired, IEEE Bioengineering Conf., Sept. 27-30, 1985.

Wilson, BS and CC Finley: A computer-based simulator of speech processors for auditory prostheses. ARO Abstracts, 8th Midwinter Research Conference, p. 109, 1985.

Finley, CC and BS Wilson: An integrated field-neuron model of electrical stimulation by intracochlear scala-tympani electrodes. ARO Abstracts, 8th Midwinter Research Conference, p. 105, 1985.

Finley, CC: Co-chairman for session on Cochlear Prosthetic Devices, ARO, 8th Midwinter Research Conference, February, 1985.

Farmer, JC, Jr., Kenan, PD and Wilson, BS: Cochlear implants. Presented at Surgical Grand Rounds, Duke University Medical Center, November, 1985.

Wilson, BS and Finley, CC: Latency fields in electrically-evoked hearing. To be presented at the 9th ARO Meeting, February, 1986.

Finley, CC and Wilson, BS: A simple finite-difference model of field patterns produced by bipolar electrodes of the UCSF array. Presented at the 8th IEEE-EMBS Meeting, September, 1985.

III. Concluding Remarks and Recommendations

This has been a highly-productive project. In addition to meeting fully all requirements of the contract work statement with the completion of the activities described in sections II.A, II.B and II.E of this report, we have been able to (a) build powerful tools for understanding and defining the "electrical-to-neural transformer" that links the outputs of the speech processor to the inputs of the central nervous system (sections II.C and II.D); (b) compare the performance of competing processing strategies in tests with a single implant patient (section II.F); and (c) help establish new collaborative programs for testing implant patients at Duke University Medical Center and at Washington University Medical Center. Work in this first project with the Neural Prosthesis Program was primarily directed at development of tools for future work. These tools include the hardware interface (section II.A), the computer-based simulator of speech processors (section II.B), and the field-neuron and ensemble models mentioned above. Our goal for the next project is to apply the tools we have developed in the first project. We expect that patients in San Francisco, Durham and St. Louis will be included in an extensive series of tests, and that application of the above-named tools will allow us to improve significantly the performance of multichannel auditory prostheses.

IV. Acknowledgement

We are pleased to acknowledge the many contributions to this project made by our coworkers on the cochlear-implant team at UCSF. From the beginning they have offered assistance, encouragement and insights without hesitation. Moreover, we have been inspired by the quality and scope of their work on the development of auditory prostheses and by their determination to improve present devices. In retrospect, our progress on this project would have been far, far less without the enthusiastic support of the UCSF team.

V. References

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Loeb, G.E., White, M.W. and Jenkins, W.M., Biophysical considerations in electrical stimulation of the auditory nervous system, Ann. N. Y. Acad. Sci., 405 (1983) 123-136.

McNeal, D.R., Analysis of a model for excitation of myelinated nerve, IEEE Trans. BME, 23 (1976) 329-337.

Merzenich, M.M. and White, M., Cochlear implants: The interface problem. In F.T. Hambrecht and J.B. Reswick (Eds.), Functional Electrical Stimulation: Applications in Neural Prostheses, New York, Marcel Dekker (1977), pp. 321-340.

O'Leary, S.J., Black, R.C., and Clark, G.M., Current distributions in the cat cochlea: A modelling and electrophysiological study, Hearing Res., 18 (1985) 273-281.

Paliwal, K.K., Comparative performance evaluation of different pitch estimation algorithms for noisy speech, Acoustics Lett., 6 (1983) 164-166.

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Un, C.K. and Yang, S.-C., A pitch extraction algorithm based on LPC inverse filtering and AMDF, IEEE Trans. on Acoust., Speech & Signal Processing, ASSP-25 (1977) 565-572.

van den Honert, C. and Stypulkowski, P.H., Physiological properties of the electrically stimulated auditory nerve. II. Single fiber recordings, Hearing Res., 14 (1984) 225-243.

Appendix 1: Key Contents of Quarterly Progress Reports for NIH Project N01-NS-2356, "Speech Processors for Auditory Prostheses"

<u>Quarterly</u>	<u>Contents</u>
1	Description of initial, set-up trip to UCSF; Initial plans of a collaboration at Duke University Medical Center.
2	Model of field patterns produced by intracochlear electrodes; Collaboration between UCSF, Storz and Duke; First descriptions of (a) the hardware interface for communication between the Eclipse computer and patient electrodes, (b) the software for the block-diagram compiler, and (c) the rationale of intracochlear EP measurements.
3	Brief descriptions of hardware interface, computer-based simulator, DCU control software; Initial description of the Frankenhauser-Huxley model component of the Integrated field-neuron model.
4	Overview of first-year effort; Complete descriptions on (a) the development of the Frankenhauser-Huxley Axon component of an integrated field-neuron model of intracochlear electrical stimulation and (b) the use and application of a computer-based simulator of speech processors for multichannel auditory prostheses.
5	Description of spiral-plane calculations with the finite-difference field model; Initial examination of the effects of bone-fluid interfaces on current densities in the scala tympani and excitable tissue.

6 Development of portable, real-time hardware; Description of software for support of the RTI Patient Stimulator; Description of software for support of basic psychophysical studies and speech testing; Outline of Proposed tests with the present implant patient at UCSF, for the months of June and July, 1985.

7 Speech-testing studies with patient LP; Appendix on present status and functional description of the block-diagram compiler.

8 Development and application of ensemble models of the spatial and temporal patterns of neural discharge produced by intracochlear electrical stimulation.

X.E. Curriculum Vitae

This appendix contains curriculum vitae for key participants in this proposal. Vitae are included in order of percentage contribution of effort to the plan outlined in the proposal.

Blake S. Wilson	Head, Neuroscience Program Office Research Triangle Institute
Charles C. Finley, Ph.D.	Senior Research Scientist/Engineer Neuroscience Program Office Research Triangle Institute
Dewey T. Lawson, Ph.D.	Senior Research Scientist Neuroscience Program Office Research Triangle Institute
Mark W. White, Ph.D.	Associate Professor Department of Electrical Engineering N.C. State University
Robert D. Wolford, M.S.	Clinical Audiologist Center for Speech & Hearing Disorders Duke University
Sigfrid D. Soli, Ph.D.	Senior Speech Scientist Hearing Research Laboratory 3M Company
Robert V. Shannon, Ph.D.	Laboratory Coordinator, Sensory Aids Boys Town National Institute for Communication Disorders in Children
Bryan E. Pfingst, Ph.D.	Associate Professor Kresge Hearing Research Institute University of Michigan

BLAKE S. WILSON

Positions and Experience

1984 to date: Adjunct Assistant Professor of Experimental Otolaryngology, Duke University Medical Center (DUMC). The primary responsibility for this position is to direct research aimed at the development of auditory prostheses. Additional responsibilities are to (1) coordinate research efforts at DUMC with those at the University of California at San Francisco (UCSF); (2) assist in the development of procedures used in the clinic for evaluation and treatment of cochlear-implant patients; and (3) participate in the development and clinical application of advanced, signal-processing hearing aids.

1974 to date: Several positions at the Research Triangle Institute (RTI), including Research Engineer ('74-'78); Senior Research Engineer ('78-date); Senior Research Scientist ('79-date); and Head, Neuroscience Program Office ('83-date). Experience in these positions is indicated below.

Principal Investigator of a project to develop speech processors for multichannel auditory prostheses. Major activities in this project include the following: (1) design and evaluate new strategies for presentation of speech information through cochlear implants; (2) measure psychophysical performance of implant patients; (3) model neural discharge patterns evoked by intracochlear electrical stimulation; (4) build a computer-based simulator that is capable of rapid and practical emulation of a wide range of processing strategies in software; and (5) design and fabricate portable, real-time processors for use in field trials. (Funded by the NINCDS, 1983-88)

Principal Investigator of a feasibility study to design and evaluate single-channel coding strategies for extra-cochlear auditory prostheses. Many of the tools and activities listed above also apply to this project; the primary objective was to develop auditory prostheses that could be safely and effectively applied for use by infants and young children. (Funded by Storz Instrument Company, 1984-87)

Principal Investigator of a study to identify the sites at which nonionizing radiation acts in eliciting auditory responses. Methods that were used include: (1) recording and analysis of single-unit responses in the auditory nerve and cochlear nucleus to pulses of microwave irradiation and (2) mapping of radiation-induced alterations in brain metabolism using the [^{14}C]-2-deoxy-D-glucose method. (Funded by the NIEHS, 1979-81)

Principal Investigator of a study to evaluate possible effects of nonionizing radiation on brain structures outside of the auditory system. Structures studied included nuclei of the vestibular system, hypothalamus, and cerebral cortex. Patterns of brain activity were again measured using the [^{14}C]-2-deoxy-D-glucose method. (Funded by the EPA, 1979-83)

Project Leader at RTI of a collaborative study to improve the mechanical design of vascular prostheses. To explore the relationships between design parameters and velocities of flow, stresses at the sutures, and coefficients of reflected energy at the lines of anastomosis, we developed a computer simulation model of blood flow dynamics in the healthy leg and in legs in which a femoro-popliteal bypass graft had been inserted. This model was based on finite-difference solutions of the one-dimensional, Navier-Stokes equations of fluid flow in compliant tubes. (Funded by the VA, 1978-79)

Principal Investigator of a study to evaluate the [^{14}C]-2-deoxy-D-glucose method for use in research on the biological effects of microwave radiation. (Funded by the NIEHS, 1976-77)

Project Leader for software development of microprocessor-based, six station audiometer. (Funded by Monitor, Inc., 1976-77)

Principal Investigator of a pilot study to record and compare responses in the auditory nerve to acoustic clicks and to pulses of microwave irradiation. (Funded by the EPA, 1975)

Engineer in a project to develop a speech-analyzing lipreading aid for the profoundly deaf based on the cued-speech system of visual speech communication. Speech analysis work included the design of a voice pitch extractor, development of advanced algorithms for speech segmentation, and computer recognition of speech phonemes in real time. (Funded by the NINCDS and Gallaudet College, 1974-76, and by NASA and the VA thereafter; B. Wilson's participation was in the years 1974-76)

Member of a biomedical applications team to define unsolved problems in biomedical technology through consultation with research physicians and then to identify solutions for these problems with the aid of NASA technology. (Funded by NASA; B. Wilson's primary participation was in the years 1974-75)

1971 to 1973: Electronics technician at the Duke University Medical Center, Department of Surgery.

Responsibilities for this position were design and fabrication of instruments for biomedical research; design and fabrication of equipment to monitor and ensure patient safety; repair of critical electronic equipment in the operating rooms.

Education

B.S., Electrical Engineering, Duke University, 1974.

Professional Honors and Activities

Recipient of Professional Development Awards from the Research Triangle Institute to (1) develop speech processors for auditory prostheses (1977); (2) participate in an expedition sponsored by the National Geographic Society to elucidate the acoustic basis of prey recognition by mustache bats (1983); and (3) work with investigators at the Goethe Universität to elucidate the mechanisms of neural encoding with cochlear implants (1988).

Appointment to the subcommittee on microwave and laser exposure of the N.C. Radiation Protection Commission, 1981-1986.

Member of the oversight committee for the cochlear implant program at the Kresge Hearing Research Institute, University of Michigan (1987-date).

Member of several site visit teams to evaluate program project grant applications in the areas of auditory prostheses (for the NIH) and biological effects of nonionizing radiation (for the VA).

Reviewer of grant applications for the NIH, VA, NSF, and Medical Research Council of Canada

Invited participant and discussion leader for two Gordon Research Conferences on Implantable Auditory Prostheses (1985 and 1987).

Moderator of the Speech Coding Panel, International Cochlear Implant Symposium, Düren, West Germany, Sept. 7-11, 1987.

Invited speaker for the Cochlear Implant Consensus Development Conference, National Institutes of Health, May 2-4, 1988.

Faculty member for several continuing-education courses on cochlear implants.

Chairman of the session on Cardiovascular Fluid Dynamics, 2nd Mid-Atlantic Conference on Bio-Fluid Mechanics, April, 1980.

Member of the IEEE (special section on Engineering in Medicine and Biology), Society for Neuroscience (N.C. Chapter), and the Bioelectromagnetics Society.

Papers and Book Chapters

Wilson, BS: Comparison of encoding schemes. Invited paper to be published in J.M. Miller and F.A. Spelman (Eds.), Models of the Electrically Stimulated Cochlea (Papers from the 25th Anniversary Symposium of the Kresge Hearing Research Institute, Oct. 3-5, 1988).

Wilson, BS, RA Schindler et al.: Present status and future enhancements of the UCSF/RTI/Duke cochlear implant. To be published in P. Banfai (Ed.), Cochlear Implants 1987, Springer-Verlag.

Wilson, BS (moderator), LJ Dent, N Dillier, DK Eddington, IJ Hochmair-Desoyer, BE Pfingst, W Sürth and J Walliker (panelists): Round table discussion on speech coding. To be published in P. Banfai (Ed.), Cochlear Implants 1987, Springer-Verlag.

Wilson, BS, CC Finley, DT Lawson and RD Wolford: Speech processors for cochlear prostheses. Invited paper accepted for publication in the special issue of Proc. IEEE on "Emerging Electromedical Systems," September, 1988.

Wilson, BS, CC Finley, JC Farmer, Jr., DT Lawson, BA Weber, RD Wolford, PD Kenan, MW White, MM Merzenich and RA Schindler: Comparative studies of speech processing strategies for cochlear implants. Laryngoscope, in press.

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White, MW, CC Finley and BS Wilson: Electrical stimulation model of the auditory nerve: Stochastic response characteristics. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press (CH2513-0/87/0000), 1987, pp. 1906-1907.

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Scott, SM and BS Wilson: The mechanical design of vascular prostheses. In P Puel, H Boccalon and A Enjalbert (Eds.), Hemodynamics of the Limbs, Institut National de la Sante et de la Recherche Medicale, Paris, 1979, pp. 251-259.

Wilson, BS and SM Scott: Hemodynamic design considerations for an improved artery shunt prosthesis. In DJ Schneck (Ed.), Bio-Fluid Mechanics, VPI Press, Blacksburg, Va., 1978, pp. 93-98.

Cornett, RO, RL Beadles and BS Wilson: Automatic cued speech. In JM Pickett (Ed.), Papers from the Research Conference on Speech-Processing Aids for the Deaf, May 24-26, 1977, published by Gallaudet Research Institute, Gallaudet College, Washington, D.C., 1981, pp. 224-239.

Joines, WT, BS Wilson and S Sharp: Temperature-controlled heating of tumors by microwaves. Proc. of the IEEE Southeastern Conference, 1977, pp. 124-128.

Wright, D, J Hebrank and B Wilson: Pinna reflections as cues for localization. J. Acoust. Soc. Am., 56: 957-962, 1974.

Abstracts and Major Presentations

Wilson, BS: Various coding schemes used. Invited testimony to be presented at the Cochlear Implant Consensus Development Conf., National Institutes of Health, May 2-4, 1988.

Wilson, BS: Review of RTI research on coding strategies for cochlear prostheses. Invited lecture presented at the 3M Company in St. Paul, MN, Nov. 12, 1987.

Wilson, BS: Speech processors for auditory prostheses. Presented at the Neural Prosthesis Workshop, 1983, 1984, 1985, 1986 and 1987.

Wilson, BS: Moderator, Speech Coding Panel, International Cochlear Implant Symposium 1987, Düren, West Germany, Sept. 7-11, 1987.

Schindler, RA and BS Wilson: Present status and future enhancements of the UCSF/RTI/Duke cochlear implant, Abstr. International Cochlear Implant Symposium 1987, Düren, West Germany, Sept. 7-11, 1987, p. 57.

Wilson, BS: Factors in coding speech for auditory prostheses. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, New London, NH, June 29 - July 3, 1987.

Wilson, BS, CC Finley, MW White and DT Lawson: Comparisons of processing strategies for multichannel auditory prostheses. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

White, MW, CC Finley and BS Wilson: Electrical stimulation model of the auditory nerve: Stochastic response characteristics. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Finley, CC, BS Wilson and MW White: A finite-element model of bipolar field patterns in the electrically stimulated cochlea -- A two dimensional approximation. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Finley, CC, BS Wilson and MW White: Models of afferent neurons in the electrically stimulated ear. Invited paper presented in the special session on mathematical modeling related to functional electrical stimulation, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Farmer, JC Jr. and BS Wilson: Cochlear implantation for the profoundly deaf. Invited seminar presentation, Department of Physiology, Duke University Medical Center, June 18, 1987.

Wilson, BS: The RTI/Duke cochlear implant program. Presented to the Executive Committee of the Research Triangle Institute (RTI) Board of Governors, June 17, 1987.

Wilson, BS, CC Finley, JC Farmer, Jr., BA Weber, DT Lawson, R Wolford, PD Kenan, MW White, MM Merzenich and RA Schindler: Comparative studies of speech processing strategies for cochlear implants. Abstracts of the 90th Annual Meeting of the Triological Society, Denver, CO, April 28-30, 1987.

Wilson, BS: Cochlear implants. Invited lecture presented in the session on auditory signal processing, First North Carolina Workshop on Bioelectronics, Quail Roost, NC, Oct. 24-26, 1986.

Wilson, BS: Processing strategies for cochlear implants. Invited faculty lecture for the special course on cochlear implants at the Annual Meeting of the American College of Otolaryngologists, San Antonio, TX, Sept. 18-19, 1986.

Farmer, JC, Jr., PD Kenan, BA Weber and BS Wilson: Cochlear implants. Invited lecture presented at the Annual Meeting of the Mecklenberg County Otolaryngology, Head and Neck Surgery Soc., Charlotte, NC, Fall, 1986.

Wilson, BS: Ensemble models of neural discharge patterns evoked by intracochlear electrical stimulation. Invited speaker presentation at the IUPS Satellite Symposium on Advances in Auditory Neuroscience, San Francisco, CA, July 8-11, 1986.

Finley, CC and BS Wilson: Field patterns in the electrically-stimulated human cochlea, IUPS Satellite Symposium on Advances in Auditory Neuroscience, San Francisco, CA, July 8-11, 1986.

Wilson, BS: Coding strategies for cochlear implants. Invited speaker presentation at the Kresge Hearing Research Institute, University of Michigan, May 22, 1986.

Wilson, BS: Comparison of strategies for coding speech with multichannel auditory prostheses. Invited faculty lecture presented at the Conference on Speech Recognition with Cochlear Implants, New York University, April 17-19, 1986.

Finley, CC and BS Wilson: Sampling of electric fields by myelinated intracochlear neurons. ARO Abstracts, 9th Midwinter Research Conference, p. 170, 1986.

Wilson, BS and CC Finley: Latency fields in electrically-evoked hearing. ARO Abstracts, 9th Midwinter Research Conference, pp. 170-171, 1986.

Farmer, JC, Jr., PD Kenan and BS Wilson: Cochlear implants. Presented at Surgical Grand Rounds. Duke University Medical Center, November, 1985.

Wilson, BS: Coding strategies for multichannel auditory prostheses. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, Tilton, NH, Aug. 19-23, 1985.

Wilson, BS: Discussion Leader, Gordon Research Conference on Implantable Auditory Prostheses, Tilton, NH, Aug. 19-23, 1985.

Finley, CC and BS Wilson: Models of neural stimulation for electrically-evoked hearing. Invited paper presented in the special session on neurostimulation, Alliance Conf. for Engineering in Medicine and Biology, Sept. 30 - Oct. 2, 1985.

Wilson, BS and CC Finley: Speech processors for auditory prostheses. Invited paper presented in the special session on signal processing for the hearing impaired, IEEE Bioengineering Conf., Sept. 27-30, 1985.

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Henson, OW, Jr., BS Wilson, JB Kobler, AL Bishop, MM Henson and R. Hansen: Radiotelemetry and computer analysis of biosonar signals emitted by the free-flying bat. ARO Abstracts, 8th Midwinter Research Conference, p. 70, 1985.

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Wilson, BS, JB Kobler, JH Casseday and WT Joines: Spectral content of microwave-induced auditory stimuli as demonstrated by [^{14}C]-2-deoxy-D-glucose uptake at the inferior colliculus. Bioelectromagnetics Abstracts, 5th Annual Meeting, p. 46, 1983.

Blackman, CF and BS Wilson: Distribution of label in studies on the effects of nonionizing radiation on the association of calcium ions with brain tissue. Bioelectromagnetics Abstracts, 5th Annual Meeting, p. 73, 1983.

Wilson, BS, WT Joines, JH Casseday and JB Kobler: Responses in the auditory nerve to pulsed, CW, and sinusoidally-modulated microwave radiation. Bioelectromagnetics, 1: 237, 1980.

Wilson, BS, WT Joines, JH Casseday and JB Kobler: Identification of sites in brain tissue affected by nonionizing radiation. Bioelectromagnetics, 1: 208, 1980.

Wilson, BS: Problems and opportunities in the design of speech processors for cochlear implant prostheses. Proc. AAMI Annual Meeting, 13: 295, 1978.

Major Reports

Wilson, BS: Quarterly reports for NIH projects N01-ES-9-008, N01-NS-3-2356 and N01-NS-5-2396; and for EPA projects 68-02-2231 and 68-02-3276.

Wilson, BS, CC Finley and DT Lawson: Efficacy of single-channel coding strategies for extracochlear auditory prostheses. Final Report, Storz Instrument Company, June, 1987.

Wilson, BS, CC Finley and DT Lawson: Speech processors for auditory prostheses. Final Report, NIH project N01-NS-3-2356, September, 1985.

Wilson, BS: Identification of sites in brain tissue affected by nonionizing electromagnetic radiation. Final report, EPA project 68-02-3276, November, 1983.

Wilson, BS: Critical review of methods used for diagnosing depth of injury in burn victims. May, 1982. (supported by a NASA contract for a "Biomedical Applications Team")

Wilson, BS, JH Casseday and JB Kobler: Laboratory computer facility for auditory research. August, 1981. (supported by NIH contract N01-ES-9-008)

Wilson, BS and JB Kobler: Cochlear nerve simulator. Final Report, NIH project PR-048281, February, 1981.

Wilson, BS: Investigations to determine the peripheral and central receptors mediating effects of microwave radiation on brain activity. Final Report, NIH project N01-ES-9-008, August, 1981.

Wilson, BS and RL Beadles: Real-time speech analysis and display software for the automatic cuer. Final report for Gallaudet College contract 37301, November, 1976.

Wilson, BS and RL Beadles: A pitch extractor for real-time applications of speech analysis. 1975. (supported by an NIH contract to "Develop a Speech Autocuer")

Manuscripts in Preparation

Wilson, BS, DT Lawson, CC Finley, RD Wolford, DK Kessler and RA Schindler: Direct comparisons of analog and pulsatile coding strategies with six cochlear implant patients. To be submitted for publication in J. Acoust. Soc. Am.

Wilson, BS, CC Finley and MW White: Ensemble models of neural discharge patterns evoked by intracochlear electrical stimulation. I. Simple model of responses to transient stimuli. To be submitted for publication in Hearing Res.

Wilson, BS, DT Lawson, CC Finley, RD Wolford and MW Skinner: Evaluation of two channel, "Breeuwer/Plomp" processors for cochlear implants. To be submitted for publication in J. Acoust. Soc. Am.

White, MW, CC Finley and BS Wilson: A Neurophysiological model of electrical excitation of the auditory nerve. To be submitted for publication in Neuroscience.

Wilson, BS and CC Finley: Differences in pitch and loudness coding with monopolar and radial bipolar configurations of intracochlear electrodes. To be submitted for publication in Hearing Res.

Inventions

Wilson, BS, CC Finley and MW White: Speech processor apparatus for auditory prostheses. Patent application filed Nov. 13, 1987.

Several additional patent applications in the general area of cochlear implants are in preparation.

FEBRUARY, 1988

CURRICULUM VITAE

Charles Finley, Ph.D.

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DATE OF BIRTH: January 10, 1949 SS No: 420-66-4216

PLACE OF BIRTH: Florence, Alabama, USA

MARITAL STATUS: Married, one child

MAJOR RESEARCH INTERESTS:

Neurophysiology of Sensory Mechanisms
Coding Mechanisms for Cochlear Prostheses
Field Analysis for Electrical Neural Stimulation

EDUCATION:

Georgia Institute of Technology, Atlanta, Georgia
B.S. in Electrical Engineering/Co-operative Program 67-72

Swiss Federal Technical Institute (ETH), Zurich, Switzerland
Electrical Engineering Exchange Student 72-73

University of North Carolina at Chapel Hill
PH.D. in Neurobiology 73-83

EXPERIENCE:

Project Director of Ga. Tech Electric Vehicle Design Program 70-72

Co-op Student - Electronic Design Laboratory, Central Intelligence Agency, Washington, D.C. 68-71

Research Assistant - Department of Neurology, Kanton Hospital, Zurich, Switzerland 72-73

Electronic Technician - Medical School Electronics Laboratory, University of N.C. at Chapel Hill 81-83

Private Consultant in development of multiple-subject, computer-based audiometric testing system 76-83

Neuroscientist/Engineer - Neuroscience Program Office, Research Triangle Institute 84-87

Senior Neuroscientist/Engineer - Neuroscience Program Office, Research Triangle Institute 87-Present

HONORS:

Tau Beta Pi   Phi Kappa Phi   Eta Kappa Nu

Selected Outstanding Student Engineer 1972 by the Professional Engineers of Greater Atlanta

Recipient of the World Student Fund Scholarship of Ga. Tech 1972

Professional Development Award - Research Triangle Institute 1985

PUBLICATIONS:

Henn V, Young LR and Finley C (1974): Vestibular nucleus units in alert monkeys are also influenced by moving visual fields. Brain Research 71: 144-149.

Kaufmann P, Finley C, Bennett P and Farmer J (1979): Spinal cord seizures elicited by high pressures of helium. Electroenceph. clin. Neurophysiology 47: 31-40.

Finley C (1983): Monitoring primary vestibular afferents during active, free-ranging behavior of the gerbil: Access to centrifugal control functions of efferent fibers. Dissertation, University of North Carolina at Chapel Hill.

Finley C, Frye G and Breese G (1985): Brainstem evoked potential correlates of neural supersensitivity in rats following propylthiouracil treatment. (in preparation)

Dawson G, Finley C, Phillips S and Galpert L (1986): Hemispheric specialization and the language abilities of autistic children. Child Development 57: 1440-1453.

Dawson G, Finley C, Phillips S and Galpert L (1985): Cognitive processing of verbal and musical stimuli in autistic children as indexed by P300 of the event-related potential. Journal of Experimental and Clinical Neuropsychology 7:626.

Dawson G, Finley C, Phillips S and Galpert L (1988): P300 of the event-related brain potential: Its relationship to language abilities in autism. Journal of Autism and Developmental Disorders. (in press).

Wilson BS, Finley CC, Lawson DT and Wolford RD (1988): Speech processors for cochlear prostheses. Invited paper accepted for publication in the special issue on "Emerging Electromedical Systems," Proc. IEEE, September.

Wilson BS, Finley CC, White MW and Lawson DT (1987): Comparisons of processing strategies for multichannel auditory proshteses. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press (CH2513-0/87/0000), pp. 1908-1910.

White MW, Finley CC and Wilson BS (1987): Electrical stimulation model of the auditory nerve: Stochastic response characteristics. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press (CH2513-0/87/0000), pp. 1906-1907.

Finley CC, Wilson BS and White MW (1987): A finite-element model of bipolar field patterns in the electrically stimulated cochlea--A two dimensional approximation. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press (CH2513-0/87/0000), pp. 1901-1903.

Dawson G, Finley C, Phillips S and Levy A (1988): A comparison of patterns of cerebral lateralization for speech in autistic and dysphasic children. (under review).

Wilson BS, Finley CC, Farmer JC Jr, Lawson DT, Weber BA, Wolford RD, Kenan PD, White MW, Merzenich MM and Schindler RA (1988): Comparative studies of speech processing strategies for cochlear implants. (in press).

Finley CC (1988): Models of neural stimulation in the electrically stimulated cochlea. Invited paper to be published in J.M. Miller and F. A. Spelman (Eds.) Models of the Electrically Stimulated Cochlea. Papers from the 25th Anniversary Symposium of the Kresge Hearing Research Institute, Oct. 3-5).

Wilson BS, Schindler RA, Finley CC, Lawson DT, Kessler DK and Wolford RD (1988): Present status and future enhancements of the UCSF/RTI/Duke cochlear implant. To be published as an invited chapter in P. Banfai (Ed.), Cochlear Implants 1987, Springer-Verlag.

PATENTS

Wilson BS, Finley CC and White MW (1987): Speech processor apparatus for auditory prostheses. Patent application filed Nov. 13, 1987.

ABSTRACTS, POSTERS AND PRESENTATIONS:

Henn V, Young L and Finley C (1973): Vestibular nucleus units in alert monkeys are also influenced by moving visual fields. Abstr. in Fortschritte der Zoologie 23(1): 247.

Henn V, Young L and Finley C (1974): Unit recording from the vestibular nucleus in the alert monkey. Abstr. for Workshop Meeting of the European Brain and Behavior Society - Vestibular Functions and Behavior, April 25, Pavia (Italy).

Finley C, Bennett P, Farmer and Kaufmann (1978): High pressure nervous syndrome at the spinal level in rats. Presentation and abstr. for the Undersea Biomedical Society, Undersea Biomedical Research 5: 44.

Finley C (1983): Expanded capabilities of audiometric testing using microprocessors. Presentation for N.C. Acoustical Society of America, April 28, Spring Meeting.

Martinkosky SJ, Howard JF, Finley CC and Quint SR (1983): Pre- and postplasmaphresis treatment measures obtained from myasthenia patients. Poster for American Speech and Hearing Association Meeting, Cinn., Ohio.

Dawson G, Finley C and Frei T (1984): Hemisphere processing in echolalic and nonecholalic autistic children. Presented at the 1984 Meeting of the Body for Advancement of Brain, Behavior, and Language Enterprises (BABBLE), Niagra Falls, Ontario.

Finley CC and Wilson BS (1985): An integrated field-neuron model of electrical stimulation by intracochlear scala-tympani electrodes. ARO Abstracts, 8th Midwinter Research Conference, p. 105.

Wilson BS and Finley CC (1985): A computer-based simulator of speech processors for auditory prostheses. ARO Abstracts, 8th Midwinter Research Conference, p. 109, 1985.

Finley CC (1985): Co-chairman for session on Cochlear Prosthetic Devices, ARO Abstracts, 8th Midwinter Research Conference, February, 1985.

Dawson G, Finley C, Phillips S and Galpert L (1985): Hemispheric specialization and language development of autistic children. Accepted for presentation at the 1985 Meeting of the Society for Research in Child Development, Toronto, Canada.

Finley CC (1985): An integrated field-neuron model of intracochlear stimulation. Invited presentation, Gordon Research Conference on Implantable Auditory Prostheses, Aug. 19-23, 1985.

Finley CC and Wilson BS (1985): Models of neural stimulation for electrically evoked hearing. Invited presentation for the special session on neurostimulation, ACEMB Meeting, Sept. 30 - Oct. 2, 1985.

Wilson BS and Finley CC (1985): Speech processors for auditory prostheses. Invited presentation for the special session on signal processing for the hearing impaired, IEEE Bioengineering Conference, Sept. 27-30, 1985 (full-length paper to be published in the proceedings).

Finley CC and Wilson BS (1985): A simple finite-difference model of field patterns produced by bipolar electrodes of the UCSF array. IEEE Bioengineering Conference, Sept. 27-30, 1985.

Wilson BS and Finley CC (1986): Latency fields in electrically-evoked hearing. ARO Abstracts, 9th Midwinter Research Conference, pp. 170-171.

Finley CC and Wilson BS (1986): Sampling of electric fields by myelinated intracochlear neurons. ARO Abstracts, 9th Midwinter Research Conference, p. 170.

Finley CC and Wilson BS (1986): Field patterns in the electrically-stimulated human cochlea, IUPS Satellite Symposium on Advances in Auditory Neuroscience, San Francisco, CA, July 8-11, 1986.

Dawson G, Finley C, Phillips S and Galpert L (1986): Cognitive processing of verbal and nonverbal stimuli in autistic children as indexed by P300 of the event-related potential. Presented at the 1986 Meeting of the International Neuropsychological Society, Denver, CO.

Wilson BS, Finley CC, Farmer JC Jr, Weber BA, Lawson DT, Wolford RD, Kenan PD, White MW, Merzenich MM and Schindler RA (1987): Comparative studies of speech processing strategies for cochlear implants. Abstracts of the 90th Annual Meeting of the Triological Society, Denver, CO, April 28-30, 1987.

Finley CC and Wolford RD (1987): Cochlear implants and the Duke Center for the Severely Hearing Impaired. Invited lecture, Departments of Otolaryngology and Audiology, UNC School of Medicine, Chapel Hill, NC, May 8, 1987.

Finley CC (1987): Electrode design and stimulus shaping. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, New London, NH, June 29-July 3, 1987.

Finley CC (1987): Status of current spread in auditory prostheses. Invited paper presented at the Gordon Research Conference on Implantable Auditory Prostheses, New London, NH, June 29-July 3, 1987.

Finley CC, Wilson BS and White MW (1987): Models of afferent neurons in the electrically stimulated ear. Invited paper presented in the special session on mathematical modeling related to functional electrical stimulation, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Finley CC, Wilson BS and White MW (1987): A finite-element model of bipolar field patterns in the electrically stimulated cochlea--A two dimensional approximation. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

White MW, Finley CC and Wilson BS (1987): Electrical stimulation model of the auditory nerve: Stochastic response characteristics. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Wilson BS, Finley CC, White MW and Lawson DT (1987): Comparisons of processing strategies for multichannel auditory prostheses. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Dawson G, Finley C, Phillips S and Levy A (1987): A comparison of cerebral lateralization for speech in autistic and dysphasic children. Presented at the 1987 Meeting of the International Neuropsychological Society, Washington, DC.

Dewey Tull Lawson

Birth date:	February 6, 1944
Birthplace:	Kinston, North Carolina, U.S.A.
Education:	Smithfield, N. C., public schools A. B. in Physics, Harvard University, 1966 Ph. D. in Physics, Duke University, 1972
Married:	Elizabeth Booker Lawson, July 9, 1966
Children:	Jonathan Dewey Lawson, born July 31, 1969 Neal Becton Lawson, born May 17, 1972

Professional Positions

1985-present: Senior Scientist, Neuroscience Program Office, Research Triangle Institute, Research Triangle Park, N. C. Research and development related to speech processors for multichannel intracochlear and brainstem implants and single channel extracochlear prostheses; signal processing hearing aids.

1982-1984: Consultant in architectural and environmental acoustics and computer applications. Clients included architectural firms, professional associations, and private and governmental institutions. A principal client was Research Triangle Institute, continuing the projects mentioned below.

1979-1982: Senior Physicist, Center for Technology Applications, Research Triangle Institute, Research Triangle Park, N. C. Research on machine decoding of speech, ultrasonic and audible acoustics, hearing. Design and development of digital speech database, computer modeling of speech and speech decoding, computer modeling of ultrasonic experiments on flowing gas mixtures. Evaluation of research and development projects.

1980-present: Adjunct Associate Professor, Department of Physics, Duke University, Durham, N. C. Teaching "Acoustics and Music", a course offered jointly by the Physics and Music departments; occasional supervision of independent study students.

1974-1979: Assistant Professor and Research Associate, Department of Physics, Duke University, Durham, N. C. Teaching courses in physics, acoustics, and music. Supervision of graduate students in Low Temperature Physics. Research on collective mode excitations in superfluid helium-3. Developed an integrated system for control, data acquisition, analysis, and results presentation by a single computer.

1977-1978: Offered a Fulbright/Hays Senior Fellowship at the University of Sussex, but was unable to interrupt Duke research program at that time.

1972-1974: Research Associate, Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, N. Y. (postdoctoral fellowship). Research on collisionless ("zero") sound and hydrodynamics of superfluid helium-3. Developed a computer experimental control and data acquisition system.

1967-1971: Research Assistant and Associate, Department of Physics, Duke University, Durham, N. C. Research on heat transport and sound propagation in dielectric crystals at low temperatures. Developed an automated crystal growth apparatus and computer data analysis system.

Member:
American Physical Society
American Association of Physics Teachers
Acoustical Society of America
Sigma Xi

University and Community Activities:

Former chairman, Duke University Environmental Concerns Committee (composed of faculty, student, administrative, and community representatives; charged with advising the Chancellor on off-campus matters of concern to the University.)

First Presbyterian Church, Durham, N. C. Elder; deacon; member and assistant conductor of choir; teacher; former chairman, Worship, Music and Lecture Committee and Task Force on Church and the Arts.

Former tympanist and principal of percussion, assistant conductor, chairman of the Orchestra Committee, and member of the board of directors, the Durham Symphony, Inc.

Former Durham YMCA soccer coach.

Boy Scouting: District committeeman, camporee chief, Order of the Arrow advisor, Cubmaster, Webelos Den Leader, troop committeeman, Scoutmaster; Eagle, Wood Badge, District Award of Merit, Vigil, Scouter's Key.

Member of the Board of Directors and President-elect, Triangle Greenways Council; coordinating activities of local government and private groups in planning for and preserving greenways through and among regional urban areas, and developing foot, equestrian, and canoe trails along such corridors.

Other Academic Interests:

Relationships between psychophysical and musical theory regarding consonance and dissonance.

The organ works of Lambert Chaumont as a test of the use of statistical methods to infer the specific tuning/temperament system intended by a composer.

The social, political, and art history of the City of Florence; especially art patronage during the republican administration of Piero Soderini (1502-1512).

Liturgics, in both historical and comparative aspects; especially the roles of music in liturgy.

Recent Publications

Wilson, B.S., C.C. Finley, D.T. Lawson and R.D. Wolford: Speech processors for cochlear prostheses. Invited paper accepted for publication in the special issue of Proc. IEEE on "Emerging Electromedical Systems," September, 1988.

Wilson, B.S., C.C. Finley, J.C. Farmer, Jr., D.T. Lawson, B.A. Weber, R.D. Wolford, P.D. Kenan, M.W. White, M.M. Merzenich and R.A. Schindler: Comparative studies of speech processing strategies for cochlear implants. Laryngoscope, in press.

Wilson, B.S., C.C. Finley, M.W. White and D.T. Lawson: Comparisons of processing strategies for multichannel auditory prostheses. In Proc. Ninth Ann. Conf. Engineering in Medicine and Biology Soc., IEEE Press (CH2513-0/87/0000), 1987, pp. 1908-1910.

Recent Abstracts and Presentations

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

Wilson, B.S., C.C. Finley, M.W. White and D.T. Lawson: Comparisons of processing strategies for multichannel auditory prostheses. Invited paper presented in the special session on cochlear implants, 1987 IEEE/EMBS Meeting, Boston, MA, Nov. 13-16, 1987.

Wilson, B.S., C.C. Finley, J.C. Farmer, Jr., B.A. Weber, D.T. Lawson, R.D. Wolford, P.D. Kenan, M.W. White, M.M. Merzenich and R.A. Schindler: Comparative studies of speech processing strategies for cochlear implants. Abstracts of the 90th Annual Meeting of the Triological Society, Denver, CO, April 28-30, 1987.

Lawson, D.T.: Cochlear implants. Invited presentation in the UNC-

Greensboro series of Psychology Colloquia, April 10, 1987.

Lawson, D.T.: Cochlear implants. Invited luncheon address at the Annual Meeting of the NC Regional chapter of the Acoustical Society of America, Tanglewood Park, NC, Oct. 9-10, 1986.

Recent Major Reports

Wilson, B.S., C.C. Finley and D.T. Lawson: Speech processors for auditory prostheses. Quarterly Progress Reports 1, 2, 4, 5, 6 and 8, NIH project NO1-NS-5-2396, September, 1985 to September, 1987.

Wilson, B.S., C.C. Finley and D.T. Lawson: Efficacy of single-channel coding strategies for extracochlear auditory prostheses. Final Report, Storz Instrument Company, June, 1987.

Finley, C.C., B.S. Wilson and D.T. Lawson: Speech processors for auditory prostheses. Quarterly Progress Reports 3 and 7, NIH project NO1-NS-5-2396, March to June, 1986 and March to June, 1987.

Wilson, B.S., C.C. Finley and D.T. Lawson: Speech processors for auditory prostheses. Final Report, NIH project NO1-NS-3-2356, September, 1985.

Wilson, B.S., C.C. Finley and D.T. Lawson: Speech processors for auditory prostheses. Quarterly Progress Reports 6, 7 and 8, NIH project NO1-NS-3-2356, December, 1984 to September, 1985.

Manuscripts in Preparation

Wilson, B.S., D.T. Lawson, C.C. Finley, R.D. Wolford, D.K. Kessler and R.A. Schindler: Direct comparisons of analog and pulsatile coding strategies with six cochlear implant patients. To be submitted for publication in J. Acoust. Soc. Am.

Wilson, B.S., D.T. Lawson, C.C. Finley, R.D. Wolford and M.W. Skinner: Evaluation of two channel, "Breeuwer/Plomp" processors for cochlear implants. To be submitted for publication in J. Acoust. Soc. Am.

Earlier Publications

"Phonon Scattering by Isolated Isotopic Lattice Perturbations in Single Crystals of Helium" (with H. A. Fairbank) Proc. of the 12th Internat. Conf. on Low Temp. Phys., Acad. Press of Japan, Tokyo, 1971, p.147 (abstract only).

"Phonon Scattering by Isolated Isotopic Impurities in Helium-4 Single Crystals" (with H. A. Fairbank) Bull. Am. Phys. Soc. 16, 638 (1971) (abstract only).

"Phonon Scattering by Isolated Isotopic Impurities in Single Crystals of Helium" dissertation, Duke University, 1971.

"Phonon Scattering by Isotopic Impurities in Helium Single Crystals" (with H. A. Fairbank) Low Temp. Phys. LT-13, Vol. II, Plenum, New York, 1973, p.85.

"A Technique for Growing Helium Crystals in Preferred Orientations" Cryogenics 13, 276 (1973).

"Thermal Conductivity and Isotopic Impurities in Single Crystals of Helium" (with H. A. Fairbank) J. Low Temp. Phys. 11, 363 (1973).

"Sound Propagation through Liquid Helium-3 in a Pomeranchuk Cell" (with W. J. Gully, S. Goldstein, R. C. Richardson, and D. M. Lee) Bull. Am. Phys. Soc. 18, 24 (1973) (abstract only).

"Attenuation of Zero Sound and the Low Temperature Transitions in Liquid Helium-3 (with W. J. Gully, S. Goldstein, R. C. Richardson, and D. M. Lee) Phys. Rev. Lett. 30, 541 (1973).

"The Effects of Magnetic Field on the 'A' Transition in Liquid Helium-3" (with W. J. Gully, D. D. Osheroff, R. C. Richardson, and D. M. Lee) Phys. Rev. A 8, 1633 (1973).

"Magnetic Effects in Liquid Helium-3 Below 3 mK" (with W. J. Gully, S. Goldstein, R. C. Richardson, and D. M. Lee) Bull. Am. Phys. Soc. 18, 642 (1973) (abstract only).

"The Viscosity of Liquid Helium-3 in the Fermi Liquid Region" (with W. J. Gully, S. Goldstein, J. D. Reppy, D. M. Lee, and R. C. Richardson) Bull. Am. Phys. Soc. 18, 642 (1973) (abstract only).

"The Low Temperature Viscosity of Normal Liquid Helium-3" (with W. J. Gully, S. Goldstein, R. C. Richardson, J. D. Reppy, and D. M. Lee) J. Low Temp. Phys 13, 503 (1973).

"Attenuation of Zero Sound and the Several Low Temperature Phases of Liquid Helium-3" (with W. J. Gully, S. Goldstein, R. C. Richardson, and D. M. Lee) J. Low Temp. Phys. 15, 169 (1974).

"Anisotropic Attenuation of Zero Sound in Superfluid Helium-3" (with H. M. Bozler and D. M. Lee) Bull. Am. Phys. Soc. 19, 1114 (1974) (abstract only).

"Anisotropy in Superfluid Helium-3 and the Attenuation of Zero Sound" (with H. M. Bozler and D. M. Lee) Phys. Rev. Lett. 34, 121 (1975).

"Sound Propagation and Anisotropy in Liquid Helium-3-A" (with H. M. Bozler and D. M. Lee) in Quantum Statistics and the Many-body Problem; S. B. Trickey, W. P. Kirk, and J. W. Dufty, editors; Plenum, New York, 1975, p.19.

"Anisotropy and Sound Propagation in Superfluid Helium-3" (with H. M. Bozler and D. M. Lee) Low Temp. Phys. LT-14, Vol. I, North-Holland, Amsterdam, 1975, p.92.

"Superfluid Helium-3" in Yearbook of Science and Technology 1975; McGraw-Hill, New York, 1976, p.204.

"Church Acoustics: Implications for Organ Performance", The Organ Yearbook, Vol. XI, p.116 (1980).

"Interval-Based Representations of Complex Tones" Am. J. Phys. 48, 615, (1980).

"The Temperament of Lambert Chaumont" J. Acoust. Soc. Am. 67, S85 (1980) (abstract only).

"Graphic Representations of Complex Tones" J. Acoust. Soc. Am. 67, S98 (1980) (abstract only).

"Analysis of Zero Sound Attenuation Data for Helium-3-A in High Magnetic Fields (with D. R. Pape) Bull. Am. Phys. Soc. 25, 497 (1980) (abstract only).

March 1988

Biographical Data
for
MARK W. WHITE

Present Position and Address

Associate Professor
Electrical and Computer Engineering
Box 7911
North Carolina State University
Raleigh, NC 27695-7911

Telephone: (919) 737-2336 Ex. 77

Home Address

819 Summerwinds Dr.
Cary, NC 27511

Personal Data

Citizenship:	USA
Date of birth:	Nov. 9, 1947
Place of birth:	Lincoln, Nebraska

Education

University of Nebraska - 1971, BSEE with High Distinction
University of California, Berkeley - 1978, Ph.D. Electrical Engineering & Computer Science

Ph.D. Dissertation Title: "Design Considerations of a Prosthesis for the Profoundly Deaf"

Areas of Professional Experience

Research and Teaching:

- signal processing
- pattern classification
- biomedical engineering
- computer engineering

Administration

- Student Advisor
- Faculty Review

Employment Record

1. Associate Professor, Department of Electrical and Computer Engineering, North Carolina State University, August 1986 - present.
2. Associate Professor, University of California, San Francisco, 1985-1986.
3. Visiting Faculty Member - University of California, Berkeley, Electrical Engineering and Computer Science Department, 1983.
4. Assistant Professor, University California, San Francisco, 1978-1985.
5. Research Assistant. Design of laboratory instrumentation for research in saccadic rhythm. Entomology Dept., UC Berkeley, 1973-1974.
6. Research Assistant. Design and construction of a primate oculomotor neurophysiology laboratory, including primate training. Electrical Engineering and Computer Science Dept., UC Berkeley, 1972.
7. Design Engineer. Design of electronic surveillance equipment. Guard Systems Inc., Oakland, 1971-1972.
8. Design Engineer. Design of audio recording equipment. SECO Laboratory, Omaha, 1971.
9. Software Design Engineer. Software designed for automatic testing of computer subassemblies. Collins Radio Corp., Richardson, Texas, 1968.
10. Programmer. Fortran and Cobol languages. University of Nebraska Computer Center, Lincoln, Nebraska, 1968.
11. Television Broadcast Engineer. Maintenance and monitoring of television and audio broadcast facilities. KUON-TV, Lincoln, Nebraska, 1967-1968.
12. Broadcast Engineer. Monitoring and maintenance of AM and FM radio transmitters. KRVN Radio, Lexington, Nebraska, 1966. Held First Class Commercial FCC license.

Awards, Honors, and Recognition

Graduated with High Distinction, University of Nebraska
Regents Scholarship, Haskel Scholarship, Eta Kappa Nu Scholarship
Membership in honor societies: Sigma Tau, Eta Kappa Nu, and Phi Eta Sigma
National Institutes of Health Traineeship in Biomedical Graduate Study, 1972-7.

Professional Memberships

1978-Present Member, Institute of Electrical and Electronics Engineers
1980-Present Associate member, Acoustical Society of America
1981-1983 Member, International Society for Artificial Organs
1985-Present Association for research in Otolaryngology
1987-Present International Neural Network Society

Other Professional Activities

1979-Present	Reviewer, Journal of Biomedical Engineering, Institute of Electrical and Electronics Engineers
1981	Grant reviewer, Western Regional Veterans Administration.
1987-Present	Reviewer, *Hearing Research.*

University Activities

UCSF and UCB

Dept. of Otolaryngology Faculty Review Committee member, 1979.
Member, UCSF Biostatistics Group, 1982-1986.
University Ad Hoc Faculty Review Committee member, 1985-86.

Bioengineering, UCSF-UCB

Member, Joint UCSF-UCB Bioengineering Graduate Program, 1983-1986
Member, UCSF-UCB Bioengineering Training Grant Committee, 1984.
Member, UCSF-UCB Bioengineering Nominating Committee, 1984.
Participated in a 2-day organizational meeting of the newly-formed joint UCSF-UCB Bioengineering group, Asilomar, January, 1984.
Participated in a 2-day organizational meeting of the newly-formed joint UCSF-UCB Bioengineering group, Asilomar, January, 1986.

Speech and Hearing Science, UCSF

Member, UCSF-UCSB Speech and Hearing Science Group, 1979-1986.
Graduate Advisor, Speech and Hearing Science Group, 1984-1986.
Obtained grants for equipment necessary for graduate student training in Speech and Hearing Science: a computer graphics terminal and comprehensive software package for signal analysis (1980-1982). This software was integrated with our software to generate a complete laboratory system for the analysis of speech signals by students. Several students have used this system extensively throughout their doctoral and post-doctoral research (1981-1986).
Member, Speech and Hearing Science Curriculum Committee, 1983-1986.
Participated in two joint faculty UCSF-UCSB Speech and Hearing Science organizational meetings at Santa Barbara, 1983 & 1984.
Participated in a program to familiarize UCSB and UCSF students with the educational opportunities available on te UCSF campus, 1984.

Cochlear Prostheses Research Group, Dept. of Otolaryngology, UCSF

Executive Committee member, 1977-1979.
Psychophysical Committee member, 1978-1986.
Patient Selection Committee member, 1982-1983.
Engineering Review Committee member, 1984-1986.

NCSU

Participant, NCSU Engineering Advisory Council Meeting, NCSU, April 12-13, 1987.

Participant, regional IEEE leadership conference, Hickory, North Carolina, April 11, 1987.

Advisor, NCSU Student Branch of the IEEE, 1987-Present.

Member, Computer Engineering Curriculum Committee.

Chairman, Nominating Committee for an IBM sponsored graduate student fellowship in artificial intelligence, 1986-Present.

Participant, NCSU-SOE "Teaching Effectiveness Workshop for Engineering Professors", held at the McKimmon Center, August 17-19, 1987.

Member, MCNC-Video-Network Seminar Committee, 1987-Present.

Participant, "NCSU Open House" for prospective students and their parents, 1986 and 1987.

Chairman, ECE Department's committee for participation in the "State Employee's Combined Campaign". The combined campaign includes the United Way, a substantial group of health research agencies, and North Carolina charitable organizations.

Member, University-wide group of faculty involved in research in biomedical engineering.

Member, ECE faculty group working with the Bowman Gray Medical Center to form a joint Bioengineering Graduate Program in medical imaging and computer communications.

Teaching Activities

109	EECS-UCB	Electronic Circuits & Instrumentation System	1983
234	S&HS-UCSF	Auditory Psychophysics	
230	S&HS-UCSF	Speech Recognition and Reception	1980-1986
249	S&HS-UCSF	Pattern Classification Principals Applied to Medical Diagnosis Using Auditory Evoked Responses	1984-1986
212	S&HS-UCSF	Speech and Hearing Science Seminar	1983-1986
210	S&HS-UCSF	Journal Club	
299	S&HS-UCSF	Dissertation Research	1982-1986
318	ECE-NCSU	Computer Organ. & Microprocessors	1986-Present
318L	ECE-NCSU	Microcomputer Laboratory	1986-Present
6050		CSC-UNCC-MCNC	Neural Networks

(NCSU Research Project Advisor & Faculty Sponsor for course)

Sponsored Research Activities

(1) Co-investigator to study the application of a cochlear prosthesis with patients. NIH Grant Support: Comm. Disorders Inst. (NIH) 4 year and 3 year grants, $250-350,000 per year. Supported at the 70-90% level.

(2) NIH Contract Support: Neuroprosthetics Div. contract support over 8 years, at approx. $100,000 per year. Supported at the 10-30% level.

List of Publications

(1) Merzenich, M.M., Schinler, D.N., and White, M.W.: Symposium on cochlear implants. II. Feasibility of multichannel scala tympani stimulation. *Laryngoscope* 84:1887-1893, 1974.

(2) Schinler, R.A., Merzenich, M.M., White, M.W., and Bjorkroth, B: Multielectrode Intracochlear implants: Nerve survival and stimulation patterns. *arch Otolaryngol* 103:691-699, 1977.

(3) Merzenich, M.M., White, M.W., Leake, P.A., Schinler, R.A., and Michelson, R.P.: Further progress in the development of multichannel cochlear implants. *Trans. Amer. Acad. Ophth. Otol.* 84:181-182, 1977.

(4) Merzenich, M.M., and White, M.W.: Cochlear prosthesis: The interface problem. In: *Functional Electrical Stimulation.* (Hambrecht, F.T., and Reswich, J.B. eds.), Marcel Dekker, Inc., Vol 3, pp. 321-340, 1977.

(5) Michelson, R.P., Schubert, E., Walsh, S.W., and White, M.W.: Protocol for determining the auditory percepts of electrical stimulation of the cochlea. *Laryngoscope* 89:748-751, 1979.

(6) Merzenich, M.M., White M.W., Vivion, M.C. Leake-Jones, P.A., and Walsh, S.W.: Some considerations of multichannel electrical stimulation of the auditory nerve in the profoundly deaf: Interacing electrode arrays with the auditory nerve array. *Acta Otolaryngol. 87:196-203, 1979.*

(7) White, M.W., and Merzenich, M.M.: Aspect electro-physiologique de l'implant cochleaire a multi-electrodes. *Les Cahiers D'O.R.L.* T14 6:567-579, 1979.

(8) Merzenich, M.M., and White, M.W.: Coding considerations in design of cochlear prostheses. *Ann. Otol. Rhinol. Laryngol.* Suppl. 74, 89:84-87, 1980.

(9) Merzenich, M.M., Byers, C.L., White, M.W. and Vivion, M.C.: Cochlear implant prostheses: Strategies and progress. *Annals Biomedical Engineering* 8:361-368, 1980.

(10) Merzenich, M.M., Vivion, M.C. Leake-Jones, P.A. and White, M.W.: Progress in development of implantable multielectrode scala tympani arrays for a cochlear implant prosthesis: In: *Advances in Prosthetic Devices for the Deaf: A Technical Workshop.* (McPherson, D.L. ed.), The National Technical Institute for the Deaf, Rochester Institute of Technology, Rochester, N.Y., pp. 262-270, 1980.

(11) White, M.W., Merzenich, M.M. and Vivion, M.C.: A non-invasive recording technique for evaluating electrode and nerve function in cochleas implanted with a multichannel electrode array. In: *Advances in Prosthetic Devices for the Deaf: A Technical Workshop.* (McPherson, D.L. ed.), The National Technical Institute for the Deaf, Rochester Institute of Technology, Rochester, N.Y., pp. 330-334, 1980.

(12) Vivion, M.C., Merzenich, M.M., Leake-Jones, P.A., White, M.W. and Silverman, M.: electrode position and excitation patterns for a model cochlear prosthesis. *Ann. Otol., Rhinol. & Laryngol.* Suppl. 82, 90:19-20, 1981.

(13) Vurek, L.S., White, M.W., W. Fong, M., Walsh, S.M. Opto-isolated stimulators used for electrically evoked BSER. *Ann. Otol., Rhinol., & Laryngol.* Suppl. 82, 90:21-24, 1981.

(14) White, M.W.: Formant frequency discrimination in a subject implanted with an Intracochlear stimulating electrode. *Art. Organis* 5S:314-316, 1981.

(15) Loeb, G.E., White, M.W., Jenkins, W.M.: Biophysical considerations in electrical stimulation of the auditory system. *Annals of the New York Academy of Sciences,* 405:123-136, 1983.

(16) White, M.W.: Formant frequency discrimination and recognition in subjects implanted with an Intracochlear stimulating electrode. *Annals of the New York Academy of Science* 405:348-359, 1983.

(17) White, M.W.: Compression Systems for Cochlear Prostheses. *Mechanisms of Hearing. W.R. Webster and L.M. Aitkin, eds. Monash Press, Clayton,* Victoria, Australia, pp 184-189, 1983.

(18) Loeb G.E., White, M.W., Merzenich, M.M.. Spatial cross-correlation: A proposed mechanism for acoustic pitch perception. *Biol cybernetics* 47:149-163, 1983.

(19) White, M.W.: The cochlear implant: the coding of auditory information. *Proceedings of the First Vienna International Workshop on Functional Electrostimulation,* edited by Dr. H. Thoma, University of Vienna, Vienna, Austria, p. 240-243, 1983.

(20) White, M.W., Merzenich, M.M., Gardi, J.N.: Multichannel cochlear implants: channel interactions and processor design. *Archives of Otolaryngology* 110:493-501, 1984.

(21) White, M.W.: The Multichannel Cochlear Prosthesis: Channel Interactions. *Proceedings of the Sixth Annual Conference of the IEEE Engineering in Medicine and Biology Society—Frontiers of Engineering and Computing in Health Care,* Los Angeles, California, pp. 396-400, 1984.

(22) White, M.W.: Psychophysical and Neurophysiological Considerations in the design of a cochlear prosthesis. *Audiologia Italiana.* 1:77-117, 1984.

(23) White, M.W.: Speech and stimulus processing strategies for cochlear prostheses. In: *Cochlear Implants: Current Status and Future.* (R.A. Schinler and M.M. Merzenich, eds.) Raven Press, New York, pp. 243-268, 1985.

(24) White, M.W.: Compression systems for hearing aids and cochlear prostheses. *Journal of Rehabilitation Research and Development.* 23:25-39, 1986.

(25) White, M.W.: Neurophysiological and Psychophysical Considerations in the Design of a Cochlear Prosthesis, *Ann. of Otol. Rhinol. & Laryngol.,* 96(No 1, Part 2):42, 1987.

(26) White, M.W., Finley, C.C., Wilson, B.S.: Electrical Stimulation Model of the Auditory Nerve: Stochastic Response Characteristics. *Proceedings of the Ninth Annual Conference of the IEEE Engineering in Medicine and Biology Society,* Boston, MA, November 9-12, 1987.

(27) Finley, C.C., Wilson, B.S., White, M.W.: A Finite-Element Model of Bipolar Field Patterns in the Electrically Stimulated Cochlea - A Two Dimensional Approximation. *Proceedings of the Ninth Annual Conference of the IEEE Engineering in Medicine and Biology Society,* Boston, MA, November 9-12, 1987.

(28) Wilson, B.S., Finley, C.C., White, M.W., Lawson, D.T.: Comparisons of Processing Strategies for Multichannel Auditory Prostheses. *Proceedings of the Ninth Annual Conference of the IEEE Engineering in Medicine and Biology Society,* Boston, MA, November 9-12, 1987.

(29) Wilson, B.S., Finley, C.C., Farmer, J.C., Lawson, D.T., Weber, B.A., Wolford, R.D., Kenan, P.D., White M.W., Merzenich M.M., Schindler R.A.: Comparative Studies of Speech-Processing Strategies for Cochlear Implants. *Ann. Otol. Rhinol. & Laryngol.* (submitted).

(30) Ochs, M.T., White, M.W., Merzenich, M.M., Vurek, L., Schubert E.D.: Role of the Second Formant in Vowel Identification with a Multichannel Cochlear Implant. *Journal of the Acoustical Society of America* (submitted).

(31) Sininger Y., Gardi J., Don M., White M.: Modeling of the ABR from Subjects with Cochlear Impairment Using High-Pass Masked Derived Band ABRs, *Journal of the Acoustical Society of America* (in preparation).

(32) White, M.W.: Training a Speech Enhancement Network Using a Perceptual Model, *Proceedings of the IEEE Internatiional Conference on Neural Networks,* San Diego, July 24-27, 1988.

(33) Bilbro, G., Mann, R., Millter, T., Van den Bout, D., White, M.: Simulated Annealing Using the Mean Field Approximation (submitted to *Science*).

Technical Reports

(1) Merzenich, M.M., Jones, P., White, M.W. , Vivion, M., Silverman, M.: *Development of multichannel electrodes for an auditory prosthesis* — first quarterly progress report (Sept. - Nov. 1977). Report available through NIH, contract # N01-NS-7-2367.

(2) Merzenich, M.M., Vivion, M., Jones, P., White, M.W., McMillan, B., Silverman, M.: *Development of multichannel electrodes for an auditory prosthesis* — second quarterly progress report (Dec. 1977-Feb. 1978). Report available through NIH, contract # N01-NS-7-2367.

(3) Merzenich, M.M. Vivion, M., Jones, P., White, M., Silverman, M.: *Development of multichannel electrodes for an auditory prosthesis* — fourth quarterly progress report (Jun-Aug. 1978). Report available through NIH, contract # N01-NS-72367.

(4) Merzenich, M.M., Byers, C., Jones, P., Rebscher S., Walsh, S.M., White, M.: *Development of multichannel electrodes for an auditory prosthesis* — yearly progress report for 1979-1980. Report available through NIH, contract # N01-NS-7-2367.

(5) Merzenich, M.M., White, M., Shannon, R.V., Gray, R.F., Byers, C., Rebscher S., Casey, D.E.: *Development of multichannel electrodes for an auditory prosthesis* — quarterly progress report (Sept.-Nov. 1981). Report available through NIH, contract # N01-NS-7-2367.

(6) Rebscher, S.J., Wilkinson, D.R., Zimmerman, P.A., Byers, C.L., Merzenich, M.M., White, M.: *Development of multichannel electrodes for an auditory prosthesis* — 3rd quarterly progress report (April-May 1984). Report available through NIH, contract # N01-NS-3-2353.

(7) Wilson, B.S., Finley, C.C., White, M.W.: Speech Processors for Auditory Prostheses: Interleaved-Pulse Processors for Multichannel Devices. Invention Disclosure, Research Triangle Institute, July 15, 1987.

(8) Bilbro, G.L., White, M.W., Snyder, W.: Image Segmentation with Neurocomputers. Center for Comm. and Signal Proc., Electrical and Computer Engineering Department, North Carolina State University, CCSP-TR-87/12, August 1987.

Papers Presented

1976	Research Forum, American Academy of Opthalmology and Otolaryngology, Las Vegas, Presentation: Further Progress in the Development of Multichannel Cochlear Implants.
1977	Annual Meeting, Committee on Hearing, Bioacoustics and Biomechanics, National Research Council, Washington, D.C. Invited Presentation: Electrophysiological Experiments Relating to Electrical Stimulation of the Auditory Nerve in Man.
1977	Invited participant in a symposium to consider the feasibility of a cochlear implant as a medical benefit of the British National Health Service. Sponsored by the British National Health Service.
1978	First International Course on Multichannel cochlear Implants, Hopital Saint-Antoine, Paris. Invited Presentation: Some Electrophysiological Data Relevant to Excitation Control for a Cochlear Prosthesis.
1978	Acoustical Society of America, Waikiki, Hawaii. Presentation: Multichannel cochlear Prosthesis, Noninvasive Recording Methods for Estimating the Spatial Distribution of Functional Auditory Nerve Fibers.
1979	Acoustical Society of America, Salt Lake City. Invited Presentation: Progress in Electrical Stimulation of the Cochlea.
1980	West Coast Cochlear Prosthesis Conference, Seattle. Presentation: Formant Frequency Discrimination in a Subject Implanted with an Intracochlear Stimulating Electrode using Natural and Synthetic Speech.

1980	Society for Neuroscience, Cincinnati, Ohio. Presentation: On the Role of Auditory Nerve Inter-Fiber Discharge Timing in the Perception of Pitch.
1980	Acoustical Society of America, Los Angeles. Presentation: Formant Frequency Discrimination in a Subject Implanted with an Intracochlear Stimulating Electrode.
1981	West Coast Cochlear Prosthesis Conference, Pacific Grove, Ca. Presentation: Temporal Properties of Unit Responses in the Anteroventral Cochlear Nucleus due to Intra-Cochlear Electrical Stimulation.
1981	Third Congress of the International Society for Artificial Organs, Paris. Co-Chair of Neuroprosthesis Section of the Third International Congress on Artificial Organs. Presentation: Evaluation of Two Subjects Implanted with a Multielectrode Intracochlear Implant: Discriminable Features of Speech.
1982	New York Academy of Sciences: INternational Cochlear Implant Conference. Invited Presentation: Multielectrodes: single channel vs. multichannel results. Panel Member: Coding Considerations in the Transmission of Speech Information using a Cochlear Prosthesis.
1982	West Coast Cochlear Prosthesis Workshop, Seattle, Washington. Moderator: Neurophysiology session. Presentation: Methods for Measuring Channel Interaction: Single Unit, ABR, and Psychophysical Response Measures.
1983	Sixth Midwinter Research Meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, Florida. Presentation: Electrical Stimulation of the Auditory Nerve: Membrane Models Applied to the Interpretation of Psychophysical and Electrophysiological Response. Invited Presentation: Multichannel Electrical Stimulation of the Auditory Nerve: Channel Interaction and Processor Design . Panel Member: Maximizing Auditory Information via Single vs Multichannel Cochlear Prostheses.
1983	Tenth Anniversary Conference on Cochlear Implants: An International Symposium, San Francisco, California. Invited Presentation: Speech Processing Strategies.
1983	Gordon Research Conference on Cochlear Prostheses. Tilden, New Hampshire. Invited Presentation: Neurophysiological and Psychophysical Considerations in the Design of a Cochlear Prosthesis.
1983	Acoustical Society of America, San Diego, California. Presentation: Electrical Stimulation of the Auditory Nerve: Membrane Models Applied to the Interpretation of Electrophysiological and Psychophysical Response. Presentation: Electrical Stimulation of the Auditory Nerve in Man: Dynamic Range as a Function of Stimulus Duration.
1984	Seventh Midwinter Research Meeting of the Association for Research in Otolaryngology, St. Petersburg Beach, Florida. Presentation: Electrical Stimulation of the Auditory Nerve in Man: Compression Systems.

1984 West Coast Cochlear Prosthesis Conference, Seattle Washington. Presentation: Channel Interactions as a Function of Stimulus Amplitude and Waveform.

1984 XVII International Congress of Audiology, Santa Barbara, California. Presentation: The Cochlear Implant: Dynamic Range Functions and Compressors. Chairman: Cochlear prosthesis session.

1984 Sixth Annual Conference of the IEEE Engineering in Medicine and Biology Society, Los Angeles. Invited Presentation: The Multichannel Cochlear Prosthesis: Channel Interactions.

1984 Acoustical Society of America, Minneapolis, Minnesota. Presentation: Interactions in a Multichannel Cochlear Prosthesis.

1985 Eighth Annual Mid-Winter Research Meeting of the Association for Research in Otolaryngology, Clearwater, Florida. Presentation: Cochlear Implants: Psychophysics Related to Processor Design.

1985 Acoustical Society of America, 109th meeting, Austin, Texas. Presentation: Formant discrimination in a multichannel cochlear prosthesis.

1985 Acoustical Society of America, 109th meeting, Austin, Texas. Presentation: Cochlear prosthesis: Stochastic model of electrical excitation.

1985 International Cochlear Implant Symposium & Workshop, Melbourne, Australia. Presentation: Neurophysiological and psychophysical considerations in the design of a cochlear prosthesis.

1986 Ninth Annual Mid-Winter Research Meeting of the Association for Research in Otolaryngology, Clearwater, Florida. Presentation: Stochastic Properties of Neural Excitation in the Small-Diameter Nodes of the Auditory Nerve.

1986 International Union of Physiological Scientists, IUPS Satellite Symposium on Hearing, San Francisco, CA. Invited Presentation: Stochastic and passive properties of the auditory nerve.

1987 Ninth Annual Conference of the IEEE Engineering in Medicine and Biology Society, Boston. Invited Presentation: Electrical Stimulation Model of the Auditory Nerve: Stochastic Response Characteristics.

Graduate Student Thesis Direction

Supervision of Ph.D. graduate student research, UCSF:

D. Morledge, supervising student's research on: "Pattern classification theory applied to non-invasive medical diagnosis using auditory evoked response."

Y. Sinninger, supervised research on using auditory evoked responses to predict behavioral hearing thresholds as a function of stimulus frequency.

K. Doyle, supervised research on "the recognition of vowels by subjects implanted with a cochlear prosthesis."

L. D'Antonio, supervising student's research on: "The acoustic analysis of speech from cleft palate speakers."

M. Sutter, beginning Ph.D. graduate student; research assistant.

Supervision of post-doctoral research, UCSF:

M. Ochs, Ph.D.; Supervised post-doctoral research to determine what features of stimulation were contributing to the recognition of speech elements by patients implanted with a multichannel cochlear prosthesis. Vowel recognition was investigated using computer-synthesized stimuli.

K. Doyle, Ph.D.; Supervised a post-doctoral study to determine the usefulness of multichannel processing and stimulation in a cochlear prosthesis for the profoundly deaf.

NCSU

Co-Chair or member of the following students' dissertation committees:

William Edmonson, Ph.D.
Johngwhan Jang, Ph.D.
Gee-Gwo Mei, Ph.D.
Ron Holdaway, Ph.D.

Professional Consulting

1982	House Ear Institute, Los Angeles, CA
1987-Present	Research Triangle Institute, Neuroscience Program

Patents

1. United States Patent No. 4,701,953 titled "Signal Compression System," 1987.
2. United States Patent Application No. 07/120,145 titled "Speech Processor Apparatus and Method for Auditory Prosthesis," November 13, 1987.

CURRICULUM VITAE

Name: Wolford, Robert D.

Date and Place of Birth: October 3, 1957 --- Ligonier, PA

Home Address: 127 George Anderson Drive
Hillsborough, NC 27278

Office Address: Center for Speech and Hearing Disorders
Box 3887
Duke University Medical Center
Durham, NC 27710

CURRENT POSITION: Clinical Audiologist, Center for Speech and Hearing Disorders; Coordinator, Center for the Severely Hearing Impaired; Manager, Hearing Aid Dispensary, Department of Surgery, Duke University Medical Center, Durham, North Carolina.

OTHER PROFESSIONAL EXPERIENCE:

AUDIOLOGY:

Clinical Audiologist, Speech and Hearing Clinic, University of North Carolina, Chapel Hill, North Carolina, 1983-1985.

Speech Pathology/Audiology Resident, Duke University Medical Center, Durham, North Carolina, 1983.

Audiology Practicum, Speech and Hearing Clinic, Veterans Administration Hospital, Durham, North Carolina, 1982.

Audiology Practicum, Speech and Hearing Clinic, University of North Carolina, Chapel Hill, North Carolina, 1981-1982.

SPEECH PATHOLOGY:

Westmoreland Intermediate Unit #7, Greensburg, Pennsylvania, 1979-1980.

PAPERS PRESENTED:

Auditory Brainstem Response Testing in the Intensive Care Nursery. Division of Otolaryngology, UNC School of Medicine, Chapel Hill, NC, August, 1983.

Neonatal ABR Testing. Graduate Student Program, Division of Speech and Hearing Sciences, UNC School of Medicine, Chapel Hill, NC, October, 1983.

Auditory Brainstem Audiometry. Graduate Student Program, Division of Speech and Hearing Sciences, UNC School of Medicine, Chapel Hill, NC, October, 1983.

Auditory Assessment in Children. Department of Pediatrics, UNC School of Medicine, Chapel Hill, NC, June, 1984.

Diagnosis of Sensorineural Hearing Loss. Tarheel Sertoma Club, Chapel Hill, NC, June, 1984.

Special Auditory Test. Division of Otolaryngology, UNC School of Medicine, Chapel Hill, NC, September, 1984.

ABR and Its Use as Hearing Screening Technique in the Neonatal Nursery. Graduate Audiology Students, November, 1984.

ABR Threshold Evaluation. Graduate Audiology Students, November, 1984.

Cochlear Implants - Audiological Pre-implant Evaluation and Post-implant Rehabilitation. Grand Rounds, North Carolina Memorial Hospital, November, 1984.

Cochlear Implants Seminar. Northwest Area AHEC, Morganton, NC, March, 1985.

Hearing Aids: The Improved Technology. Wake County SHHH, Raleigh, NC, September, 1985.

Advanced Technologies for Hearing Aids and Assistive Devices for the Hearing Impaired, Durham County, SHHH, Durham, NC, October, 1985.

Recent Advances in Cochlear Implants and Hearing Aids. Project Enlightenment, Raleigh, NC, February, 1986.

Cochlear Implants and the Role of the Speech Pathologist. Murdoch Center, Butner, NC, March, 1986.

Cochlear Implants: Clinical Issues and Future Directions. NCSLHA, Charlotte, NC, March, 1986.

The Role of Audiology in the Otologic Practice. Department of Otolaryngology, Duke University Medical Center, Durham, NC, October, 1986.

Audiogram Interpretation and the Impact of Severe Hearing Loss. Durham Regional Hearing Impaired Parents Organization, Durham, NC, March, 1987.

Cochlear Implants and the Duke Center for the Severely Hearing Impaired. NC Memorial Hospital Cochlear Implant Team, Chapel Hill, NC, April, 1987.

ABSTRACTS:

Thomas, W.G., Wolford, R., McDonald-Bell, C., and McMurry, E., Auditory Brainstem Evoked Potentials and Acoustic Reflex Measures in Language Disordered Children. Communique, NCSHLA, Fall:2-13, 1984.

Wolford, R.D., Advances for the Hearing Impaired: Assistive Listening Devices. North Carolina Medical Journal, February, 1987.

EDUCATION:

University of North Carolina, Chapel Hill, NC, Masters of Science in Audiology, 1982.

Indiana University of Pennsylvania, Indiana, Bachelor of Science in Speech and Hearing, 1979.

PROFESSIONAL AFFILIATIONS AND LICENSURE:

Co-Investigator, Cochlear Implants, House Ear Institute, Los Angeles, CA 1983-1985.

American Speech-Language-Hearing Association, 1980-Present.

North Carolina Audiology License #1341.

Curriculum Vitae
Sigfrid D. Soli
April, 1988

Personal

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Home Address

7727 64 St. North
Pine Springs, Minnesota 55115
Telephone: 612/779-0636

Professional Experience

1984-present: Senior Speech Scientist, Communications Group, Hearing Research Laboratory, 3M Center, St. Paul, Minnesota

1984-1985: Associate Professor of Psychology, University of Maryland, College Park, Maryland

1983-1985: Research Associate, Haskins Laboratories, New Haven, Connecticut

1978-1984: Assistant Professor of Psychology, University of Maryland, College Park, Maryland

1977-1978: Research assistant in speech perception, Center for Research in Human Learning, University of Minnesota, Minneapolis, Minnesota

1974-1978: NIH Graduate Trainee, Center for Research in Human Learning, University of Minnesota, Minneapolis, Minnesota

Other Experience

1968-1972: US Air Force Officer, promoted to Captain in 1971

Education

Ph.D., Experimental Psychology, Center for Research in Human Learning, University of Minnesota, Minneapolis, Minnesota, 1978

B.A., summa cum laude, Psychology, University of Minnesota, Minneapolis, Minnesota, 1974

B.A., cum laude, Physics and Mathematics, St. Olaf College, Northfield, Minnesota, 1968

Honors and Awards

NIH Traineeship, Center for Research in Human Learning, University of Minnesota, 1974-1978

Inducted into Sigma Pi Sigma, National Physics Honor Society, 1967

Dean's Scholarship, St. Olaf College, 1965-1968

Professional Activities

Acting Chair for Seattle meeting, Technical Committee on Speech Communication, Acoustical Society of America, 1988

Member, Technical Committee on Speech Communication, Acoustical Society of America, 1985-1988

Co-chair, Engineering Research Foundation Conference on Implantable Auditory Prostheses, 1987-1989

Advisory Consultant in speech perception/production, NINCDS, 1983

Ad hoc grant reviewer, NIE, 1979

Frequent reviewer for speech perception, occassional reviewer for psychological acoustics, Journal of the Acoustical Society of America; occassional reviewer for Journal of Speech and Hearing Research, Perception and Psychophysics, Journal of Experimental Psychology: Human Perception and Performance

Membership in Professional Organizations

Acoustical Society of America
American Speech-Language-Hearing Association
Classification Society, North American Branch
Psychometric Society
Sigma Pi Sigma, National Physics Honor Society
Society of Mathematical Psychology

Publications in Acoustics

Van Tasell, D.J., Soli, S.D., Kirby, V.M., and Widin, G.P. (1987). "Speech waveform envelope cues for consonant recognition," Journal of the Acoustical Society of America 82, 1152-1161.

Dooling, R.J., Soli, S.D., Kline, R.M., Park, T.J., Hue, C.,

and Bunnell, T. (1987). "Perception of synthetic speech sounds by the budgerigar (Melopsittacus undulatus)," Bulletin of the Psychonomic Society 25, 139-142.

Dooling, R.J., Brown, S.D., Park, T.J., Okanoya, K., and Soli, S.D. (1987). "Perceptual organization of acoustic stimuli by the budgerigar (Melopsittacus undulatus): I. Pure tones," Journal of Comparative Psychology 101, 139-149.

Dooling, R.J., Park, T.J., Brown, S.D., Okanoya, K., and Soli, S.D. (1987). "Perceptual organization of acoustic stimuli by the budgerigar (Melopsittacus undulatus): II. Vocal signals," Journal of Comparative Psychology 101, 367-381.

Soli, S.D., Arabie, P., and Carroll, J.D. (1986). "Discrete representation of perceptual structure underlying consonant confusions," Journal of the Acoustical Society of America 79, 826-837.

Soli, S.D. (1982). "The role of spectral cues in the discrimination of voice onset time differences," Journal of the Acoustical Society of America 73, 2150-2165.

Soli, S.D. (1982). "Structure and duration of vowels together specify final fricative voicing," Journal of the Acoustical Society of America 72, 366-378.

Yeni-Komshian, G.H., and Soli, S.D. (1981). "Recognition of vowels from information in fricatives: Perceptual evidence of fricative-vowel coarticulation," Journal of the Acoustical Society of America 70, 966-975.

Soli, S.D. (1981). "Second formants in fricatives: The acoustic consequences of fricative-vowel coarticulation," Journal of the Acoustical Society of America 70, 976-984.

Soli, S.D. (1980). "Some effects of acoustic attributes of speech on the processing of phonetic feature information," Journal of Experimental Psychology: Human Perception and Performance 6, 622-638.

Yeni-Komshian, G.H., and Soli, S.D. (1979). "Extraction of vowel information from fricative spectra" in J.J. Wolf and D.H. Klatt (Eds.), Speech Communication Papers: 97th Meeting of the Acoustical Society of America, 37-40.

Soli, S.D., and Arabie, P. (1979). "Auditory versus phonetic accounts of observed confusions between consonant phonemes," Journal of the Acoustical Society of America 66, 46-59.

Patents in Acoustics

Soli, S.D., and van den Honert, C. "Signal processor for an auditory prosthesis utilizing channel dominance," application filed 1987.

Soli, S.D., and van den Honert, C. "Method and apparatus for fitting implanted prosthesis," application filed 1988.

Technical Reports in Acoustics

Soli, S.D. (1981). "Second formants in fricatives: Acoustic consequences of fricative-vowel coarticulation," Working Papers in Biocommunications 1, 43-64.

Soli, S.D. (1980). "Acoustic properties of speech required for normal perception: Some thoughts about perceptual cues to be enhanced for the hearing impaired listener," Center for Language and Cognition Report No. 18, University of Maryland.

Other Publications

Gingrich, G., and Soli, S.D. (1984). "Subjective evaluation and allocation of resources in routine decision making," Organizational Behavior and Human Performance 33, 188-203.

Chew, S.L., Larkey, L.S., Soli, S.D., Blount, J., and Jenkins, J.J. (1982). "The abstraction of musical ideas," Memory and Cognition 10, 413-423.

Arabie, P., and Soli, S.D. (1982). "The interface between type of regression and method of collecting proximities data," in R. Gollege and J.N. Raynor (Eds.), Proximity and Preference: Multidimensional Analysis of Large Data Sets, 90-115. University of Minnesota Press, Minneapolis, Minn.

Soli, S.D., Nuechterlein, K.H., Garmezy, N., Devine, V.T., and Schaefer, S.M. (1981). "A classification system for research in childhood psychopathology: Part I. An empirical approach using factor and cluster analyses and conjunctive decision rules," in B.A. Maher and W.B. Maher (Eds.), Progress in Experimental Personality Research, Vol. 10, 115-161. Academic Press, New York.

Nuechterlein, K.H., Soli, S.D., Garmezy, N., Devine, V.T., and Schaefer, S.M. (1981). "A classification system for research in childhood psychopathology: Part II. Validation research examining converging descriptions from the parent and from the child, in B.A. Maher and W.B. Maher (Eds.), Progress in Experimental Personality Research, Vol. 10, 163-202. Academic Press, New York.

Soli, S.D., and Devine, V.T. (1976). "Behavioral

correlates of achievement: A look at high and low achievers," Journal of Educational Psychology 68, 335-341.

Soli, S.D., and Balch, W.R. (1976). "Performance biases and recognition memory for semantic and formal changes in connected discourse," Memory and Cognition 4, 673-676.

Invited Presentations

Gordon Conference on Implantable Auditory Prostheses
Haskins Laboratories
Indiana University
Johns Hopkins University
Massachusetts Institute of Technology
Midwest Psychological Association
Rutgers University
University of Michigan
University of Minnesota

CURRICULUM VITAE

Robert V. Shannon

CURRENT TITLE & DEPARTMENT:

Laboratory Coordinator, Sensory Aids
Boys Town National Institute for Communication Disorders in Children
555 North 30th Street, Omaha, NE 68131
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and

Associate Professor, Department of Otolaryngology
Creighton University School of Medicine
Omaha, NE 68178

EDUCATION:

1971 University of Iowa, Iowa City, IA. B.A., Mathematics & Psychology

1975 University of California, San Diego. Ph.D., Psychology

PRINCIPAL POSITIONS HELD:

1973-75 Laboratory of Psychophysics, Harvard University, Cambridge, MA. Research Assistant.

1975-76 Institute for Perception, TNO, Soesterberg, Netherlands. NIH Postdoctoral Research Fellow.

1976-78 Department of Psychobiology, University of California, Irvine. Postdoctoral Research Associate.

1978-82 Department of Otolaryngology, University of California, San Francisco. Assistant Research Psychoacoustician.

1982-85 Department of Otolaryngology, University of California, San Francisco. Assistant Professor in Residence.

1985 Department of Electrical Engineering, Stanford University. Visiting Research Associate.

GRANTS

1987-92 "Temporal processing in cochlear implants," R.V. Shannon, Principal Investigator (NIH R29 NS24754), $349,253.

HONORS and AWARDS:

1967-71 National Water Works Foundation Scholarship
1971 National Science Foundation, Undergraduate Research Trainee
1975-76 NIH Postdoctoral Fellowship

MEMBERSHIP IN PROFESSIONAL ORGANIZATIONS:

1971-present Acoustical Society of America
1982-present Association for Research in Otolaryngology
1982-present American Association for the Advancement of Science
1983-present American Auditory Society
1983-present American Speech, Language, and Hearing Association

PROFESSIONAL ACTIVITY: Service to Organizations

1975-present Reviewer, Journal of the Acoustical Society of America
1978-present Grant Proposal Reviewer, NIH
1984-present Editorial Board, Random House series on Audiology
1986, 1988 American Speech, Language, and Hearing Association, Hearing Science Program Subcommittee

MEETINGS AND WORKSHOPS ATTENDED:

Acoustical Society of America: 1978 (paper), 1979 (organized and chaired symposium), 1980 (3 papers), 1981 (paper), 1983 (3 papers), 1984 (paper).
American Speech, Language, and Hearing Association: 1981 (short course), 1983 (invited presentation), 1984 (organized and chaired 2 special sessions), 1986 (organized and chaired 1 special session), 1987 (invited presentation, 1 contributed paper).
Association for Research in Otolaryngology: 1982 (paper), 1983 (invited panelist, 2 papers), 1985 (paper), 1986 (2 papers), 1988 (1 paper).
Academy of Rehabilitative Audiology: 1983 (invited presentation)
Gordon Research Conference on Implantable Auditory Prostheses: 1983 (invited presentation), 1985 (invited presentation, discussion leader), 1987 (invited presentation).
International Congress of Audiology: 1984 (invited panelist).

Regional:

National Institutes of Health, Neural Prosthesis Workshop: 1979 (participant).
West Coast Auditory Prosthesis Workshop: 1980 (paper), 1981 (paper), 1984 (paper).
Western Psychological Association: 1981 (invited presentation).
California Speech, Language, and Hearing Association: 1984 (invited presentation).
American Association for the Advancement of Science, Pacific Division: 1984 (invited presentation).
Nebraska Educators of the Hearing Impaired: 1986 (invited presentation).
Midwest Deaf Womens Conference: 1987 (invited presentation).

INVITED PAPERS, LECTURES, PRESENTATIONS not listed above:

1976 Institut voor Sonologie, Utrecht, Netherlands, lecture
1977 University of California, Irvine, lecture
1981 University of California, Irvine, lecture
1983 University of California, Berkeley, lecture
1983 INRS Telecom.- University of Quebec, Montreal, presentation
1983 3M Surgical Products Division, presentation
1984 Scott Reger Memorial Conference on Sensorineural Hearing Loss, Iowa City, invited presentation
1985 Kresge Hearing Research Institute, invited presentation
1985 Invited article in Otobrief, European Edition
1986 Northwestern University Cochlear Implant Conference, invited presentation.
1986 University of Kansas Medical Center, 2 invited presentations.
1987 Dept. of Psychology, University of Texas, presentation.

UNIVERSITY SERVICE:

1978-80 Chair, UCSF Implant Psychophysical Testing Committee
1978-80 Coordinator, UCSF Implant Patient Testing
1983-85 Chair, Curriculum Committee, UCSF Speech and Hearing Sciences
1984-85 Graduate Advisor, UCSF Speech and Hearing Sciences

PUBLICATIONS:

Shannon, R.V. (1975). Suppression of Forward Masking. Ph.D. Thesis, University of California, San Diego.

Shannon, R.V. (1976). Two-tone unmasking and suppression in a forward masking situation. J. Acoust. Soc. Am. 59, 1460-1470.

Shannon, R.V. and Houtgast, T. (1980). Psychophysical measurements relating suppression and combination tones. J. Acoust. Soc. Am. 68, 825-829.

Kettner, R.E., Shannon, R.V., Nguyen, T.M. and Thompson, R.F. (1980). Simultaneous behavioral and neural (cochlear nucleus) measurement during signal detection in the rabbit. Percept. Psychophys. 28, 504-513.

Shannon, R.V. (1981). Growth of loudness for sinusoidal and pulsatile electrical stimulation. Ann. Otol. Rhinol. Laryngol. Suppl. 82, 90, 13-14.

Shannon, R.V. (1983). Multichannel electrical stimulation of the auditory nerve in man: Basic psychophysics. Hearing Res. 11, 157-189.

Shannon, R.V. (1983). Multichannel electrical stimulation of the auditory nerve in man: Channel interaction. Hearing Res. 12, 1-16.

Shannon, R.V. (1983). Comparison of normal hearing to the auditory percepts evoked by cochlear implants. J. Acad. Rehab. Audiol. 16, 114-127.

Shannon, R.V. (1985). Loudness summation as a measure of channel interaction in a multichannel cochlear implant. In *Cochlear Implants,* R.A. Schindler and M.M. Merzenich, Eds. Raven Press, pp. 323-334

Shannon, R.V. (1985). Threshold and loudness functions for pulsatile stimulation of cochlear implants. Hearing Res. 18, 135-143.

Shannon, R.V. (1986). Temporal processing in cochlear implants. In *Sensorineural Hearing Loss: Mechanisms, Diagnosis, and Treatment,* M.J. Collins, T.J. Glattke and L.A. Harker, Eds. Univ. of Iowa Press, pp. 349-368.

Shannon, R.V. and Houtgast, T. (1986). Growth of pulsation threshold of a suppressed tone as a function of its level. Hearing Res. 21, 251-255.

Shannon, R.V. (1986). Psychophysical suppression of selective portions of pulsation threshold patterns. Hearing Res. 21, 257-260.

Shannon, R.V. (1986). Review of *Cochlear Implants,* Roger F. Gray, Ed. J. Acoust. Soc. Am. 80, 1859-1860.

Shannon, R.V. (1987). Psychophysics of cochlear implant stimulation: Implications for the implantation of children. In *Cochlear Implants in Children,* E. Owens and D. Kessler (Eds.), College-Hill Press, in press.

ABSTRACTS:

Shannon, R.V. (1974). Suppression in forward masking. J. Acoust. Soc. Am. 55, s32.

Shannon, R.V. (1975). Suppression at high frequencies. J. Acoust. Soc. Am. 57, s4.

Shannon, R.V. (1976). On the growth of the pulsation threshold of a suppressed tone. J. Acoust. Soc. Am. 60, s117.

Shannon, R.V. (1976). Suppression in pulsation threshold patterns. J. Acoust. Soc. Am. 60, s117.

Shannon, R.V. (1977). Relationship between combination tones and psychophysical suppression. J. Acoust. Soc. Am. 62, s59.

Shannon, R.V. (1979). A model of psychophysical suppression. J. Acoust. Soc. Am. 65, s56.

Shannon, R.V. (1980). A two-process model of suppression. J. Acoust. Soc. Am. 68, s37.

Shannon, R.V. (1980). The interaction of two suppressors. J. Acoust. Soc. Am. 68, s37.

Shannon, R.V., Owens, E. and Kessler, D. (1980). Preliminary psychophysical results of electrically stimulating the auditory nerve in man. J. Acoust. Soc. Am. 67, s102.

Shannon, R.V. and Schreiner, C.E. (1981). Phase effects in forward masking. J. Acoust. Soc. Am. 70, s86.

Shannon, R.V. (1983). Basic psychophysics of cochlear implant stimulation: Limitations for single-channel stimulation. Abstracts of ARO Midwinter Res. Meeting (D.J. Lim, ed.).

Shannon, R.V. (1983). Two techniques for assessing channel independence in a multichannel cochlear implant. Abstracts of ARO Midwinter Res. Meeting (D.J. Lim, ed.).

Shannon, R.V. (1983). Temporal processing in cochlear implants. J. Acoust. Soc. Am. 74, s110.

Divenyi, P.L. and Shannon, R.V. (1983). Auditory time constants unified. J. Acoust. Soc. Am. 74, s10.

Divenyi, P.L., Shannon, R.V. and Saunders, S.R. (1983). Neural response patterns to speech sounds - A model. J. Acoust. Soc. Am. 74, s68.

Shannon, R.V. (1983). Comparison of perceptions from acoustic and electrical stimulation of the 8th nerve. ASHA 25(10), 95.

Shannon, R.V. (1984). A model of temporal processing in cochlear implants. J. Acoust. Soc. Am. 76, s48.

Shannon, R.V. (1984). Comparison of temporal psychophysical measures in normal listeners and cochlear implant patients. ASHA, 26.

Shannon, R.V. (1985). Psychophysics of cochlear implant stimulation: Implications for the implantation of children. ASHA, 26.

Shannon, R.V. (1985). A model of threshold and loudness for pulsatile electrical stimulation of cochlear implants. Abstracts of ARO Midwinter Research Meeting (D.J. Lim, Ed.).

Shannon, R.V. (1986). A phenomenological model of psychophysics for cochlear implants. Abstracts of ARO Midwinter Research Meeting (D.J. Lim, Ed.).

Shannon, R.V. (1986). Modulation detection in cochlear implants. Abstracts of ARO Midwinter Research Meeting (D.J. Lim, Ed.).

Shannon, R.V. (1987). Software for psychophysical experiments on PC-compatible computers. ASHA, 29, p 65.

Shannon, R.V. (1987). Gap detection and gap discrimination with cochlear implants. ASHA, 29, p 81.

Shannon, R.V. (1988). Gap detection in noise with cochlear implants. Abstracts of ARO Midwinter Research Meeting (D.J. Lim, Ed.).

CURRICULUM VITAE

Bryan Ernest Pfingst, Ph.D.
Kresge Hearing Research Institute
University of Michigan
Ann Arbor, Michigan 48109-0506
(313) 763-2292

PERSONAL

Birth: June 28, 1943
Fort Wayne, Indiana

EDUCATION

Waggener High School, Louisville, Kentucky, 1957-1961

University of Louisville, 1961-1963

University of North Carolina at Chapel Hill, Psychology, B.A. 1963-1965

University of North Carolina at Chapel Hill, Psychology, Neurobiology, M.A. 1965-1968

University of North Carolina at Chapel Hill, Psychology, Neurobiology, Ph.D. 1968-1971

POSITIONS HELD

1965-1966: Research Assistant, Department of Psychology, University of North Carolina at Chapel Hill. Worked with Dr. Kurt Schlesinger (Psychology) and Drs. John Wilson and Edward Glassman (Biochemistry) on experiments concerned with biochemical bases of memory storage.

1966-1967: Teaching Assistant, Department of Psychology, University of North Carolina at Chapel Hill. Lectured and conducted a laboratory in Physiological Psychology.

1967-1970: Neurobiology Predoctoral Fellow, University of North Carolina at Chapel Hill. Continued research on the biological bases of memory storage including work with Dr. Richard King on amnesic effects of electroconvulsive shock. Studied single unit activity in cat visual cortex with Dr. Paul Shinkman.

1971-1973: Neurophysiology Postdoctoral Fellow, Department of Physiology and Biophysics, University of Washington School of Medicine. Research and study with Dr. Josef Miller on the physiology of audition.

1973-1975: Research Associate, Department of Otolaryngology, University of Washington School of Medicine. Research in physiology and psychophysics of audition. Teaching classes in sensory processes.

1975-1980: Research Assistant Professor, Department of Otolaryngology School of Medicine; and Research Affiliate, Regional Primate Research Center, University of Washington. Research and teaching in auditory physiology and psychophysics.

1980-1984: Research Associate Professor, Department of Otolaryngology School of Medicine; and Research Affiliate, Regional Primate Research Center, University of Washington. Research and teaching in auditory physiology and psychophysics.

1984-present: Associate Professor, Kresge Hearing Research Institute, Department of Otorhinolaryngology, University of Michigan Medical School, and Adjunct Associate Professor, Department of Psychology, University of Michigan. Research and teaching in auditory physiology and psychophysics. Emphasis on psychophysics of electrical stimulation via cochlear implants and on neural (single unit) encoding of speech signals in the CNS of behaving primates.

CURRENT GRANTS

Studies of the Cochlear Prosthesis

NIH NS 21440
July 1, 1987 - June 30, 1991
Co-Investigator; Principal Investigator on Project 1 - Cochlear Prosthesis Psychophysics
Percent time: 45% on Project 1; 15% on Core
Annual Direct Costs (year 1): Program Project: $678,172; Project 1: $118,998

Applications Pending:

Nonspectral Frequency Discrimination
NSF and NIH
For summer 1988

OTHER PROFESSIONAL ACTIVITIES

Reviewer:
Association for Research in Otolaryngology
Hearing Research
Journal of Acoustical Society of America
Journal of Neurophysiology
Journal of Speech and Hearing Research
Neuroscience Letters
Science

Ad Hoc Reviewer:
National Institutes of Health
National Science Foundation
Medical Research Council of Canada

SOCIETY MEMBERSHIPS

Acoustical Society of America
Association for Research in Otolaryngology
Society for Neuroscience
Sigma Xi

TEACHING ACTIVITIES

Co-organizer: Graduate seminar on processing of complex acoustic signals (speech) in the CNS. Fall 1984-Spring 1985.

Co-organizer: Kresge Hearing Research Institute Symposium Series: Cochlear Prostheses--Potentials and Limitations. Spring 1985.

Organizer: Physiological Acoustics 510: Kresge Hearing Research Institute and Physiological Acoustics Program Seminar Series. Fall 1985-Summer 1986.

Organizer-instructor: Psychology 500, section 002 - Brain Function and Hearing. Fall, 1986.

Guest faculty: Psychology 830 - Advanced Comparative Psychology: Perception in Animal Behavior. Winter, 1988

Advisor - resident and student research projects:
John Zappia, medical student. Summer-Fall, 1984
Mark Maslan, resident. 1984-85
Adelaide Park, Summer Research Fellow, 1986
James Sayer, psychology student. Fall, 1986
Robert Tumacder, Student Medical Research Fellow, Summer 1987

DEPARTMENTAL SERVICE

Chair:
Library Committee, KHRI

Member:
Education Committee, Department of Otorhinolaryngology
Open House Planning Committee, KHRI
Brochure Sub-Committee, Department of Otorhinolaryngology
Hands-on Museum Committee, KHRI
25th Anniversary Planning Committee, KHRI
Annual Report Subcommittee, KHRI

Ad hoc member:
Research Committee, Department of Otorhinolaryngology

UNIVERSITY SERVICE

Member: University Committee on Use and Care of Animals - July 1, 1986-present

PARTICIPATION IN RECENT NATIONAL AND INTERNATIONAL MEETINGS

International Cochlear Implant Symposium and Workshop, Melbourne, Australia, August 1985; invited speaker.

International Union of Physiological Sciences Satellite Symposium on Hearing, San Francisco, CA, July 1986; invited panel member.

Association for Research In Otolaryngology, Clearwater, FL, February 1987; workshop organizer and chair.

International Cochlear Implant Meeting, Düren, Germany, September, 1987; invited speaker and discussant.

Biennial Conference on Implantable Auditory Prostheses; participant 1987; elected chair 1989.

PUBLICATIONS

Journal Articles:

1. Pfingst, B. E. and King, R. A.: A one-trial response-choice technique for the biological study of memory. Psychol. Sci. 8:497-498, 1967.

2. Pfingst, B. E. and King, R. A.: Effects of post-training electroconvulsive shock on retention-test performance involving choice. J. Comp. Physiol. Psychol. 68:645-649, 1969.

3. Coleman, M. S., Pfingst, B. E., Wilson, J. E. and Glassman, E.: Brain function and macromolecules. VIII. Uridine incorporation into brain polysomes of hypophysectomized rats and ovariectomized mice during avoidance conditioning. Brain Res. 26:349-360, 1971.

4. Miller, J. M., Sutton, D., Pfingst, B. E., Ryan, A., Beaton, R. and Gourevitch, G.: Single cell activity in the auditory cortex of Rhesus monkeys: Behavioral dependency. Science 177:449-451, 1972.

5. Miller, J. M., Beaton, R. D., O'Connor, T. and Pfingst, B. E.: Response pattern complexity of auditory cells in the cortex of unanesthetized monkeys. Brain Res. 69:101-113, 1974.

6. Shinkman, P. G., Bruce, C. J. and Pfingst, B. E.: Operant conditioning of single-unit response patterns in visual cortex. Science 184:1194-1196, 1974.

7. Pfingst, B. E., Bruce, C. J. and Shinkman, P. G.: Quantitative analysis of unit response patterns in cat visual cortex. Exp. Neurol. 46:215-228, 1975.

8. Pfingst, B. E., Hienz, R., Kimm, J. and Miller, J. M.: Reaction-time procedure for measurement of hearing. I. Suprathreshold functions. J. Acoust. Soc. Am. 57:421-430, 1975.

9. Pfingst, B. E., Hienz, R. and Miller, J. M.: Reaction-time procedure for measurement of hearing. II. Threshold functions. J. Acoust. Soc. Am. 57:431-436, 1975.

10. Pfingst, B. E., O'Connor, T. A. and Miller, J. M.: Response plasticity of neurons in auditory cortex of the Rhesus monkey. Exp. Brain Res. 29:393- 404, 1977.

11. Pfingst, B. E., O'Connor, T. A. and Miller, J. M.: Single cell activity in the awake monkey cortex: Intensity encoding. Trans. Am. Acad. Ophthal. Otolaryngol. 84:217-222, 1977.

12. Spelman, F. A., Pfingst, B. E. and Miller, J. M.: A constant-current stimulator for use with chronic cochlear implants. Proceedings of the San Diego Biomedical Symposium 17:1-3, 1978.

13. Pfingst, B. E., Laycock, J., Flammino, F., Lonsbury-Martin, B. and Martin, G.: Pure tone thresholds for the Rhesus monkey. Hearing Res. 1:43-47, 1978.

14. Pfingst, B. E., Donaldson, J. A., Miller, J. M. and Spelman, F. A.: Psychophysical evaluation of cochlear prostheses in a monkey model. Ann. Otol. Rhinol. Laryngol. (Suppl. 66) 88:613-625, 1979.

15. Pfingst, B. E., Spelman, F. A. and Sutton, D.: Operating ranges for cochlear implants. Ann. Otol. Rhinol. Laryngol. 89:1-4, 1980.

16. Sutton, D., Miller, J. M. and Pfingst, B. E.: Comparison of cochlear histopathology following two implant designs for use in scala tympani. Ann. Otol. Rhinol. Laryngol. (Suppl. 66) 89:11-14, 1980.

17. Spelman, F. A., Clopton, B. M., Pfingst, B. E. and Miller, J. M.: Design of the cochlear prosthesis: Effects of the flow of current in the implanted ear. Ann. Otol. Rhinol. Laryngol. (Suppl. 66) 89:8-10, 1980.

18. Miller, J. M., Dobie, R. A., Pfingst, B. E. and Hienz, R. D.: Electrophysiologic studies of the auditory cortex in the awake monkey. Am. J. Otolaryngol. 1(2):119-130, 1980.

19. Pfingst, B. E. and O'Connor, T. A.: A vertical stereotaxic approach to auditory cortex in the unanesthetized monkey. J. Neurosci. Meth. 2(1):33- 45, 1980.

20. Spelman, F. A., Pfingst, B. E., Miller, J. M., Hassul, M., Powers, W. E. and Clopton, B. M.: Biophysical measurements in the implanted cochlea. Otolaryngol. Head Neck Surg. 88:183-187, 1980.

21. Pfingst, B. E. and O'Connor, T. A.: Characteristics of neurons in auditory cortex of monkeys performing a simple auditory task. J. Neurophysiol. 45(1):16-34, 1981.

22. Pfingst, B. E., Sutton, D., Miller, J. M. and Bohne, B. A.: Relation of psychophysical data to histopathology in monkeys with cochlear implants. Acta Otolaryngol. 92:1-13, 1981.

23. Spelman, F. A., Clopton, B. M. and Pfingst, B. E.: Tissue impedance and current flow in the implanted ear: Implications for the cochlear pros thesis. Ann. Otol. Rhinol. Laryngol. (Suppl. 98) 91:3-8, 1982.

24. Pfingst, B. E., Burnett, P. A. and Sutton, D.: Intensity discrimination with cochlear implants. J. Acoust. Soc. Amer. 73:1283-1292, 1983.

25. Clopton, B. M., Spelman, F. A., Glass, I., Pfingst, B. E., Miller, J. M., Lawrence, P. D. and Dean, D. P.: Neural encoding of electrical signals. Ann. N. Y. Acad. Sci. 405:146-158, 1983.

26. Pfingst, B. E. and Sutton, D.: Relation of cochlear implant function to histopathology in monkeys. Ann. N. Y. Acad. Sci. 405:224-239, 1983.

27. Miller, J. M., Duckert, L. G., Malone, M. A. and Pfingst, B. E.: Cochlear prostheses: Stimulation-induced damage. Ann. Otol. Rhinol. Laryngol. 92:599-609, 1983.

28. Ryan, A. F., Miller, J. M., Pfingst, B. E. and Martin, G. K.: Effects of reaction time performance on single-unit activity in the central auditory pathway of the Rhesus macaque. J. Neurosci. 4:298-308, 1984.

29. Pfingst, B. E.: Operating ranges and intensity psychophysics for cochlear implants. Implications for speech processing strategies. Arch. Oto laryngol. 110:140-144, 1984.

30. Pfingst, B. E.: Psychophysical data from cochlear implants: Relevance to strategies for rehabilitation. Seminars in Hearing 6:7-21, 1985.

31. Pfingst, B.E.: Encoding of frequency and level information in the auditory nerve. Seminars in Hearing 7:45-63, 1986.

32. Pfingst, B.E.: Stimulation and encoding strategies for cochlear prostheses. Otolaryngologic Clinics of North America 19:219-236, 1986.

33. Pfingst, B.E., and Rush, N.L.: Discrimination of simultaneous frequency and level changes in electrical stimuli. Annals of Otology, Rhinology, and Laryngology (St. Louis) 96: Supplement 128, 34-37, 1987.

34. Miller, J.M., Pfingst, B.E., Tjellström, A., Albrektsson, T., Thompson, P, and Kemink, J.L. Titanium implants in the otic capsule: Development of a new multichannel extracochlear implant. American Journal of Otology 8(3):230-233, 1987.

35. Pfingst, B.E. Comparisons of psychophysical and neurophysiological studies of cochlear implants. Hearing Research, in press.

Book Chapters:

1. Miller, J. M., Towe, A. L., Pfingst, B. E., Clopton, B. M. and Snyder, J. M.: The auditory system: Transduction and central processes. In: Physiology and Biophysics, 20th Edition, Volume 1, The Brain and Neural Function, Chapter 10, edited by T. C. Ruch and H. D. Patton, W. B. Saunders Co., Philadelphia, pp. 376-434, 1979.

2. Pfingst, B. E.: Psychophysical studies of cochlear prosthesis in animals. In: Advances in Prosthetic and Technical Devices for the Deaf: A Technical Workshop, edited by D. L. McPherson, National Technical Institute for the Deaf, Rochester, NY, pp. 275-280, 1979.

3. Spelman, F. A., Pfingst, B. E., Powers, W. E., Miller, J. M., Hassul, M. and Clopton, B. M.: Biophysics of the implanted ear: Electrical parameters. In: Advances in Prosthetic and Technical Devices for the Deaf: A Technical Workshop, edited by D. L. McPherson, National Technical Institute for the Deaf, Rochester, NY, pp. 312-323, 1979.

4. Larson, C. R. and Pfingst, B. E.: Neuroanatomic bases of hearing and speech. In: Speech, Language and Hearing, Volume 1, Chapter 1, edited by N. J. Lass, L. V. McReynolds, J. L. Northern and D. E. Yoder, W. B. Saunders Co., Philadelphia, pp. 3-52, 1982.

5. Miller, J. M., Pfingst, B. E. and Ryan, A. F.: Behavioral modification of response characteristics of cells in the auditory system. In: Advances in Behavioral Biology, Volume 26, Conditioning: Representations of Involved Neural Functions, edited by C. D. Woody, Plenum Press, New York, pp. 345-361, 1982.

6. Miller, J. M. and Pfingst, B. E.: Cochlear implants. In: Hearing Science-Recent Advances edited by C. I. Berlin, College-Hill Press, San Diego, CA, pp. 309-339, 1984.

7. Miller, J. M., Duckert, L., Sutton, D., Pfingst, B. E. and Malone, M.: Animal models: Relevance to implant use in humans. In: Cochlear Implants, edited by R. A. Schindler and M. M. Merzenich, Raven Press, New York, pp. 35-54, 1985.

8. Pfingst, B. E., Glass, I., Spelman, F. A. and Sutton, D.: Psychophysical studies of cochlear implants in monkeys: Clinical implications. In: Cochlear Implants, edited by R. A. Schindler and M. M. Merzenich, Raven Press, New York, pp. 305-322, 1985.

9. Donaldson, J. A. and Pfingst, B. E.: Cochlear implants: Experience with nonhuman primates. In: Reger Symposium on Sensorineural Hearing Loss: Mechanisms, Diagnosis, and Treatment, edited by M.J. Collins, T.J. Glattke, and L.A. Harker, U. Iowa, Iowa City, pp. 341-348, 1985.

10. Pfingst, B.E., Altschuler, R.A., Watkin, K.L., and Larson, C.R. Neuroanatomic bases of hearing and speech. In: Handbook of Speech-Language Pathology and Audiology, edited by N. Lass, L. McReynolds, J.L. Northern, D.E. Yoder., pages 79-131; and Review Manual for Speech-Language Pathology and Audiology, edited by J. L. Northern. Burlington, Ontario: B.C. Decker, in press.

11. Pfingst, B.E. Stimulus parameters affecting the discrimination of temporal frequency cues. In: Cochlear Implants 1987, edited by P. Banfai, C.-H. Chouard, E. Douek, P. Finkenzeller, S. Iurato. Berlin: Springer-Verlag, in press.

Presentations:

1. Pfingst, B. E. and King, R. A.: Time course of consolidation as measured by response-choice behavior. Proceedings, 76th Annual Convention, American Psychological Association, 327-328, 1968.

2. Pfingst, B. E. and Shinkman, P. G.: Patterns of responsiveness of neurons in cat visual cortex. Psychonomic Science 21:281, 1970.

3. Pfingst, B. E., Hienz, R. and Miller, J. M.: Reaction time as a measure of threshold and suprathreshold hearing. I. Normal man and monkey. J. Acoust. Soc. Am. 55:450, 1974.

4. Pfingst, B. E., Hienz, R., Snyder, J. and Miller, J. M.: Reaction-time as a measure of threshold and suprathreshold hearing. II. Subject with impaired hearing. J. Acoust. Soc. Am. 55:4504-51, 1974.

5. O'Connor, T., Pfingst, B. E. and Miller, J. M.: Intensity functions of neurons in the auditory cortex of the unanesthetized monkey. J. Acoust. Soc. Am. 57:S54, 1975.

6. Pfingst, B. E., O'Connor, T. A. and Miller, J. M.: Response plasticity of neurons in the auditory cortex of the unanesthetized monkey. J. Acoust. Soc. Am. 57:S54, 1975.

7. Pfingst, B. E., O'Connor, T. A. and Miller, J. M.: Representation of intensity and frequency information in auditory cortex of monkeys per forming a simple auditory task. J. Acoust. Soc. Am. 58:S65, 1975.

8. Miller, J. M., Pfingst, B. E. and Hienz, R.: Effects of behavior attention on unit responses in the auditory cortex. J. Acoust. Soc. Am. 58:S65, 1975.

9. O'Connor, T. A., Pfingst, B. E. and Miller, J. M.: Intensity functions of cortical auditory neurons in the awake monkey. J. Acoust. Soc. Am. (Suppl. 1) 6:S81, 1976.

10. Lonsbury-Martin, B. L., Martin, G. K., Pfingst, B. E. and Miller, J. M.: A neurobehavioral analysis of sound-induced hearing loss. Abstracts of the First Midwinter Research Meeting, Association for Research in Otolaryngology 12, 1978.

11. Pfingst, B. E., Donaldson, J. A. and Miller, J. M.: Behavioral evaluation of the cochlear prosthesis. Abstracts of the First Midwinter Research Meeting, Association for Research in Otolaryngology 22, 1978.

12. Sutton, D., Miller, J. M., Pfingst, B. E. and Donaldson, J. A.: Cochlear pathology associated with a silicon rubber implant in monkey and guinea pig scala tympani. Abstracts of the First Midwinter Research Meeting, Association for Research in Otolaryngology 22, 1978.

13. Pfingst, B. E. and Spelman, F. A.: Properties of electrical stimulation relevant to the design of a cochlear prosthesis. J. Acoust. Soc. Am. (Suppl. 1) 64:S65, 1978.

14. Sutton, D., Pfingst, B. E., Miller, J. M. and Webster, D. B.: Cochlear and CNS histopathology in monkeys with chronic cochlear implants. Abstracts of the Second Midwinter Research Meeting, Association for Research in Otolaryngology 13, 1979.

15. Miller, J. M., Clopton, B. M., Donaldson, J. A., Pfingst, B. E., Schuknecht, H. F., Simmons, F. B., and Sutton, D.: Cochlear prostheses: Indications, implications, and complications. Presentation and Panel Discussion. Great Debates in Otolaryngology. Continuing Medical Education, University of Washington School of Medicine, August 1979.

16. Pfingst, B. E. and Burnett, P. A.: Intensity discrimination with cochlear prostheses. Abstracts of the Third Midwinter Research Meeting, Association for Research in Otolaryngology 39-40, 1980.

17. Miller, J. M., Sutton, D. and Pfingst, B. E.: CNS Degeneration associated with chronic scala tympani implants in the monkey. West Coast Cochlear Prosthesis Workshop, Battelle Institute, July 1980.

18. Pfingst, B. E. and Burnett, P. A.: Initial comparisons of modiolar and scala tympani implants. West Coast Cochlear Prosthesis Workshop, Battelle Institute, July 1980.

19. Pfingst, B. E.: Cochlear implants in severely damaged ears: Functional implications. Alumni Day Symposium, Department of Otolaryngology, University of Washington, May 1981.

20. Pfingst, B. E., Sutton, D. and Miller, J. M.: Electrode-place discrimination by monkeys with cochlear and modiolar implants. Abstracts of the Fourth Midwinter Research Meeting, Association for Research in Otolaryngology 64, 1981.

21. Pfingst, B. E. and Miller, J. M.: Effects of behavior and attention on the electrophysiology of the auditory pathway. Winter Conference on Brain Research, Keystone, Colorado, January 1981.

22. Pfingst, B. E.: Auditory cortex: Some functional characteristics in search of structural bases. Symposium on "Implications of Functional Studies for Structure, and Vice Versa, in the Cerebral Cortex", Neurological Sciences Institute, Good Samaritan Hospital and Medical Center, Portland, Oregon, May 1981.

23. Sutton, D. Pfingst, B. E. and Miller, J. M.: Histopathology associated with chronic cochlear implants in monkeys. West Coast Cochlear Prosthesis Conference, Asillomar Conference Center, August 1981.

24. Pfingst, B. E. and Sutton, D.: Hearing with cochlear implants in severely damaged ears. West Coast Cochlear Prosthesis Conference, Asillomar Conference Center, Pacific Grove, California, August 1981.

25. Miller, J. M., Pfingst, B. E., Clopton, B. M. and Spelman, F. A.: Loudness growth functions for electrical stimulation of scala tympani implants. West Coast Cochlear Prosthesis Conference, Asillomar Conference Center, Pacific Grove, California, August 1981.

26. Pfingst, B. E. and Clopton, B. M.: Detection of complex electrical stimuli. West Coast Cochlear Prosthesis Conference, Asillomar Conference Center, Pacific Grove, California, August 1981.

27. Glass, I. and Pfingst, B. E.: Discrimination of complex electrical signals with single- and multiple-channel stimulation in the monkey. West Coast Cochlear Prosthesis Conference, Asillomar Conference Center, Pacific Grove, California, August 1981.

28. Pfingst, B. E. and Clopton, B. M.: Detection thresholds for complex electrical stimuli delivered to cochlear implants. Abstracts of the Fifth Midwinter Research Meeting, Association for Research in Otolaryngology 51, 1982.

29. Miller, J. M., Pfingst, B. E., Clopton, B. M., Spelman, F. A. and Sutton, D.: Loudness growth functions for electrical stimulation of scala tympani implants. Abstracts of the Fifth Midwinter Research Meeting, Association for Research in Otolaryngology 51-52, 1982.

30. Pfingst, B. E.: A proposed procedure for prediction of the number of surviving neural elements in cochlear implant candidates. Alumni Day Symposium, Department of Otolaryngology, University of Washington, May 1982.

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X.F. General Qualifications of Research Triangle Institute

Rev. 3/3/88

RESEARCH TRIANGLE INSTITUTE
General Qualifications

A. Introduction

Research Triangle Institute (RTI) is a not-for-profit contract research corporation located on a 180-acre campus in North Carolina's Research Triangle Park. RTI is a freestanding corporate entity created in 1958 by joint action of the University of North Carolina at Chapel Hill, Duke University, and North Carolina State University.

RTI conducts applied and basic research and provides technical services in the United States and abroad for national, State, and local governments, public service organizations, trade associations, and private-sector clients ranging from small companies to international corporations.

B. Organization and Staff

RTI's organization facilitates the formation of multidisciplinary teams to address complex research issues in many scientific, technical, and social subjects.

RTI's staff of more than 1,260 people includes approximately 60 percent professionally trained research personnel. Of these, about 33% have doctoral degrees and another 33% have master's degrees. The backgrounds of this staff cover more than 115 degree fields and provide a firm base for multidisciplinary studies. Major areas of training and experience include:

Chemical and Biological Sciences: analytical, organic, inorganic, physical, polymer, and medicinal chemistry, toxicology, pharmacology, genetics, neuroscience, biology, biochemistry, and microbiology.

Engineering and Physics: electrical, electronics, systems, computer, semiconductors, chemical, biochemical, energy, industrial, mechanical, materials, biomedical, aerosol, civil, petroleum, nuclear, aeronautical, and transportation engineering.

Environmental Sciences and Engineering: environmental controls and engineering, environmental chemistry, environmental health, industrial hygiene, hazardous materials management, hydrogeological and earth and mineral sciences, epidemiology, meteorology, and oceanography.

Mathematics, Statistics and Computer Sciences: data management and analysis, statistical methods development, statistical analysis, biostatistics, clinical trials, computer-aided engineering, CAD/CAM, systems software, software verification, computer security, numerical modeling, and operations research.

Survey Research: sample design and selection, survey planning and execution, data collection and management, and research and development (R&D) on survey methodology.

Social Sciences: economics, econometrics, evaluation research, urban and regional planning, international development, health services and health policy research, agricultural development, sociology, psychology, social psychology, education, business administration, public administration, municipal financial management, criminology, law, political science and the humanities.

C. University Affiliations

RTI was created as the focal point for growth in North Carolina's Research Triangle Park, an industrial and governmental scientific center built around the resources of the area's three major research universities (UNC-Chapel Hill, Duke, and NC State).

RTI research projects frequently involve collaboration with university and medical center scientists, who greatly expand the available capabilities. Additional relationships include RTI participation in university-led research, joint faculty-staff appointments, cooperative research programs, and other professional contact.

D. Laboratory and Office Facilities

RTI's 16 buildings contain nearly 400,000 square feet of space, with laboratory, computer, and other facilities for all RTI programs. RTI also maintains offices in Washington, DC; Newport News, VA; Cocoa Beach, FL; and at project locations in Africa and Asia.

The main campus includes laboratory, computer, and related facilities for all of RTI's programs.

E. Computer Facilities

In-house facilities include up-to-date minicomputers and microcomputers for data management and analysis, statistical research, simulation and modeling, computer-aided engineering, electronic systems development, software research and development, and laboratory management.

An important resource for RTI and the nearby universities is the Triangle Universities Computation Center, with mainframe facilities shared by various North Carolina educational institutions.

RTI also has daily traffic with computer networks such as the Department of Defense Advanced Research Projects Agency Network (ARPANET), NASA's AIRLAB research facility, Microelectronics Center of North Carolina, COMNET, the Environmental Protection Agency, the Health Care Financing Administration, the National Institutes of Health, and the National Center for Health Statistics.

F. Library Facilities

The RTI central library provides on-line computerized literature searches via more than 250 data bases relevant to RTI research programs. The library maintains approximately 600 subscriptions to professional periodicals.

RTI has full access to the combined libraries of the nearby universities, which have been cross-cataloged and shared since 1934. Access is facilitated by computerized catalog links and daily truck service.

The combined university collection includes more than 7.1 million bound volumes, 78,000 current serials and periodicals, 4.4. million microforms, and 14.1 million manuscripts. In addition, the UNC-Chapel Hill library is the regional repository for U.S. Government documents.

Another valuable resource is the North Carolina Science and Technology Research Center, which is adjacent to RTI. The Center provides computerized searches of more than 200 data bases, including important government data bases.

G. Administrative Information

RTI's administrative contract office is Defense Contract Administration Services Management Area-Atlanta, 805 Walker Street, Marietta, GA 30060, Code: DCRA-DAB, Attention: Louise Donald, Administrative Contracting Officer, Telephone: (404) 429-6017.

RTI's accounting and purchasing practices may be confirmed by contacting OIG Audit, P.O. Box 27443, Raleigh, NC 27611, Attention: Roy C. Wainscott; Telephone: (919) 856-4226.

RTI's top secret facility clearance, held since July 5, 1961, may be verified through the Defense Investigative Service, New Orleans Region, Directorate of Industrial Security, 805 Walker Street, Marietta, GA 30060; Telephone: (404) 429-6000.

RTI's address is P.O. Box 12194 (or: 3040 Cornwallis Road), Research Triangle Park, NC 27709-2194; Telephone (919) 541-6000. RTI's cable address is RESTRINS, Raleigh, NC and its Telex number is 802509 (RTI RTPK).

RESEARCH TRIANGLE INSTITUTE'S R&D PROGRAMS

International Programs

The Office for International Programs serves as the focal point for RTI involvement in research, development, and technical assistance projects overseas. Staff disciplines include public finance, management information systems, municipal administration, urban and regional planning, and public health administration.

Population and Policy Studies

RTI conducts research in human resource development, population, demography, public policy analysis, program evaluation, and public service delivery. Staff specialties include political science, economics, sociology, demography, planning, and psychology.

Development Policy

Staff specialties include development economics and planning; agricultural economics, population economics; population policy and planning; econometrics; economic-demographic modeling; agricultural policy, marketing, and statistics; transportation economics; mainframe and microcomputer systems, simulation, and applications; computer graphics; and forest resources.

Social Research and Policy Analysis

RTI conducts research on social and economic behavior of individuals, groups, and populations. Staff capabilities include sociology, social psychology, psychology, criminology, social policy planning, statistics, economics, public administration, and political science.

Economics Research

RTI provides economic analysis of public and private policies for both government and business clients. Staff capabilities include sociology, social psychology, psychology, criminology, social policy planning, statistics, economics, public administration, and political science.

Educational Studies

RTI conducts educational research, evaluates education programs, and provides technical assistance on educational activities. RTI leads and coordinates complex educational studies involving survey and statistical methodologies. Staff skills include quasi-experimental design, text, and questionnaire development, evaluability assessment, needs analysis, process evaluation, histographical and case study analysis, cost-effectiveness studies, programmed instruction design, and longitudinal analysis.

Medical, Environmental, and Energy Statistics

RTI designs studies and analyzes data for investigations related to medicine, the environment and energy. Capabilities include analyzing weighted data from complex survey and data collection designs.

Health Research

RTI designs and conducts evaluations and analytical studies of programs for delivering health care services and the efficacy and safety of pharmaceutical products and biomedical technology systems.

Computer Applications

RTI conducts research in software design, systems analysis, and computer applications and supports data collection projects with programming, data base management, and data analysis.

Survey Statistics

RTI designs, specifies, and selects samples, estimation procedures, and analysis procedures for RTI sample surveys; specifies and performs inferential analyses, including development of analytic and data management computer software; and conducts research related to statistical sampling theory and practices. Staff experience includes projects in social sciences, education, economics, energy, health, behavior, medical care, environmental monitoring and measurement, and engineering applications.

Analytical and Chemical Sciences

RTI develops and applies analytical techniques to trace organic and inorganic chemical measurements in biomedical, environmental, energy, and manufacturing processes.

Physical Sciences

RTI specializes in polymer research and has broad capabilities in polymer synthesis, characterization, and application. In addition, RTI addresses both physical and chemical aspects of problems and applications involving polymers.

Life Sciences and Toxicology

RTI designs and executes testing protocols to solve problems presented by efforts to develop products and processes for health care, industrial products/processes, and consumer products. RTI also conducts toxicology testing required by regulatory agencies.

Organic and Medicinal Chemistry

RTI researches and develops pharmaceutical, agricultural, and other chemical products.

Bioorganic Chemistry

RTI conducts molecular-level studies on the interactions between chemicals and biological systems.

Digital Systems Research

RTI designs and develops microelectronic systems, including very large-scale, integrated (VLSI) circuits and software. RTI also develops theoretical concepts, analyzes systems, designs circuitry, and verifies function and reliability.

Semiconductor Research

RTI conducts basic and applied research on materials and fabrication technologies used to construct microelectronic devices; develops new designs for microelectronic devices; and improves device and material production processes.

Systems Engineering

RTI performs systems research, exploratory systems development, and engineering to define, design, implement, test, and evaluate electronic systems.

Engineering Sciences

RTI assists industry and government to analyze and develop new energy, materials, and mechanical technologies. RTI examines energy supply technologies, conservation technologies, innovative energy use and conversion technologies, and employs methods such as modeling and simulation, failure analysis, conceptual design, cost analysis, and engineering economics.

Engineering Handbook

RTI edits and administers to an Engineering Design Handbook series published by the U.S. Army Material Command. The handbooks provide fundamental design information and up-to-date records of advancing technologies that are contributed by scientists nationwide. The manuscripts are prepared at industrial and government laboratories, universities, and other scientific organizations, prior to submission to RTI.

Technology Applications

RTI performs interdisciplinary research in the application of advanced technology in industrial automation and robotics, biomedical products, and rehabilitation devices. Programs involve development, modeling, and evaluation of computer-aided logistics systems for material handling and manufacturing.

Biomedical Engineering

RTI develops electronic, optical, mechanical, and biomedical instrumentation. Staff capabilities include electrical and biomedical engineering and computer science and engineering. RTI's experience includes speech processing research and development for hearing prostheses and speech recognition.

Geoscience

RTI's basic and applied research programs involve applications of remote satellite data, expert systems, and numerical modeling of atmospheric and oceanic processes. RTI's laboratory facilities include dedicated image processing systems and a digital satellite receiver; staff capabilities include meteorology, oceanography, geology, and artificial intelligence.

Neuroscience

RTI's capabilities include neurobiology, neurophysiology, electrical engineering, and speech analysis. Its neuroscience staff collaborate with medical researchers, particularly at Duke University Medical Center and the University of California at San Francisco, in the development of speech processing strategies for cochlear implant hearing prosthesis and related research.

Environmental Measurements

RTI develops, evaluates, and applies analytical methods for measurement of ambient air, source emissions, hazardous wastes, and groundwater and industrial hygiene pollutants. In addition, RTI conducts field measurement programs in the areas of atmospheric chemistry, acid precipitation, groundwater, earth and mineral sciences, and hazardous waste.

Environmental Quality Assurance

RTI provides technical support to ensure that environmental research and data collection yield accurate, defensible results. Areas of expertise include guidelines preparation, project reviews, systems and performance audits, methods assessment and standardization, and preparation/validation of reference material.

Environmental Systems

RTI conducts engineering and scientific analyses of environmental regulations in support of government agencies and private clients; performs environmental impact analyses of proposed facilities and engineering projects; and conducts studies that form the basis for decision making in the areas of air and water quality control, water resource management, and hazardous waste management.

Aerosol Technology

RTI provides engineering services to transfer fundamental aerosol technology to practical application in environmental and personnel protection, clean-room technology, industrial processes, and defense. RTI also conducts basic research in aerosol science.

Process Research

RTI conducts bench and pilot-scale studies of unit operations and transport processes in chemical engineering. Additionally, RTI conducts research in catalytic and biochemical reaction engineering, synthetic chemical and fuel production, chemical feedstock production, and vapor-phase decontamination.

Separation Processes

RTI develops methods to separate components in mixed systems for engineering operations such as environmental control, product recovery, and mineral enrichment. RTI conducts research, development, and engineering evaluations of chemical engineering separation techniques such as distillation, absorption, and extraction and of novel techniques such as supercritical extractors, membranes, and biological separation. RTI also conducts research in colloid science and particle technology related to solid-liquid separation and particle adhesion and dispersion.

Hazardous Materials Research

RTI conducts research on hazardous waste management, treatment, and disposal technologies and provides engineering studies for land disposal, control technologies for air emissions, waste treatment, land reclamation, and regulatory activities.