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Speech Processors for Auditory Prostheses

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I. Introduction

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

1. Completion of a series of studies with Ineraid patients who have poor outcomes with their clinical devices. The studies have included comparisons of the clinical *compressed analog* (CA) processors with various implementations of *continuous interleaved sampling* (CIS) processors. Subjects SR9 and SR11 participated in the studies of this quarter, increasing to four the total number of subjects in the "poor performance" series (see QPR 11 for a preliminary report of results for the other two subjects in the series, SR1 and SR10).
2. Continued analysis of data from prior and current studies, to evaluate effects of single parameter changes on the performance of CIS processors.
3. Continued studies with subjects using the new MiniMed device.
4. Preparation of a chapter on "Signal processing," for the book *Cochlear Implants: Audiological Foundations* (edited by R. Tyler).
5. Preparation and submission of an invited manuscript on "Design and evaluation of a continuous interleaved sampling (CIS) processing strategy for multichannel cochlear implants."
6. Continued preparation of other manuscripts for publication.

In this report we present results from the completed series of studies with Ineraid patients who have poor outcomes with their clinical devices (point 1 above). In addition, we present a summary of results obtained in earlier studies with a patient using the Auditory Brainstem Implant (ABI) device. Work related to points 2 and 3 above will be described in future reports.

II. Completion of "Poor Performance" Series

Recent studies in our laboratory have focused on comparisons of *compressed analog* (CA) and *continuous interleaved sampling* (CIS) processors (Lawson et al., 1992; Wilson et al., 1990b and 1991a). Both use multiple channels of intracochlear electrical stimulation, and both represent waveforms or envelopes of speech input signals. No specific features of the input, such as the fundamental or formant frequencies, are extracted or explicitly represented. CA processors use continuous analog signals as stimuli, whereas CIS processors use nonsimultaneous pulses. The CA approach is used in the widely-applied Ineraid device (Eddington, 1980 and 1983) and in the now-discontinued UCSF/Storz device (with some differences in details of processor implementation, see Merzenich et al., 1984). Wearable devices capable of supporting the CIS approach are just becoming available for use in clinical settings.

We have completed a study of eleven subjects -- seven selected for their high levels of speech recognition with the Ineraid CA processor and four selected for their relatively poor performances with that processor. The "high performance" subjects were representative of the best patients, in terms of their speech recognition scores, using any commercially-available implant system (Wilson et al., 1991a). The purpose of this report is to provide a summary of results for both sets of subjects.

Processing Strategies

Distinctions between CA and CIS processors are illustrated in Figs. 1 and 2. In CA processors a microphone signal varying over a wide dynamic range is compressed or restricted to the narrow dynamic range of electrically-evoked hearing (Pfingst, 1984; Shannon, 1983) using an automatic gain control. The resulting signal then is filtered into four contiguous frequency bands for presentation to each of four electrodes. As shown in Fig. 1, information about speech sounds is contained in the relative stimulus amplitudes among the four electrode channels and in the temporal details of the waveforms for each channel.

A concern associated with this method of presenting information is that substantial parts of it may not be perceived by implant patients (Wilson et al., 1990a). For example, most patients cannot perceive frequency changes in stimulus waveforms above about 300 Hz (see, e.g., Shannon, 1992). Thus, many of the temporal details present in CA stimuli are not likely to be accessible to the typical user.

In addition, the simultaneous presentation of stimuli may produce significant interactions among channels through vector summation of the electric fields from each electrode (e.g., White et al., 1984). The resulting degradation of channel independence would be expected to reduce the salience of channel-related cues. That is, the neural response to stimuli from one electrode may be significantly distorted, or even counteracted, by coincident stimuli from other electrodes.

The CIS approach addresses the problem of such channel interactions through the use of interleaved nonsimultaneous stimuli (Fig. 2). Trains of balanced biphasic pulses are delivered to each electrode with temporal offsets that eliminate any overlap across channels. The amplitudes of the pulses are

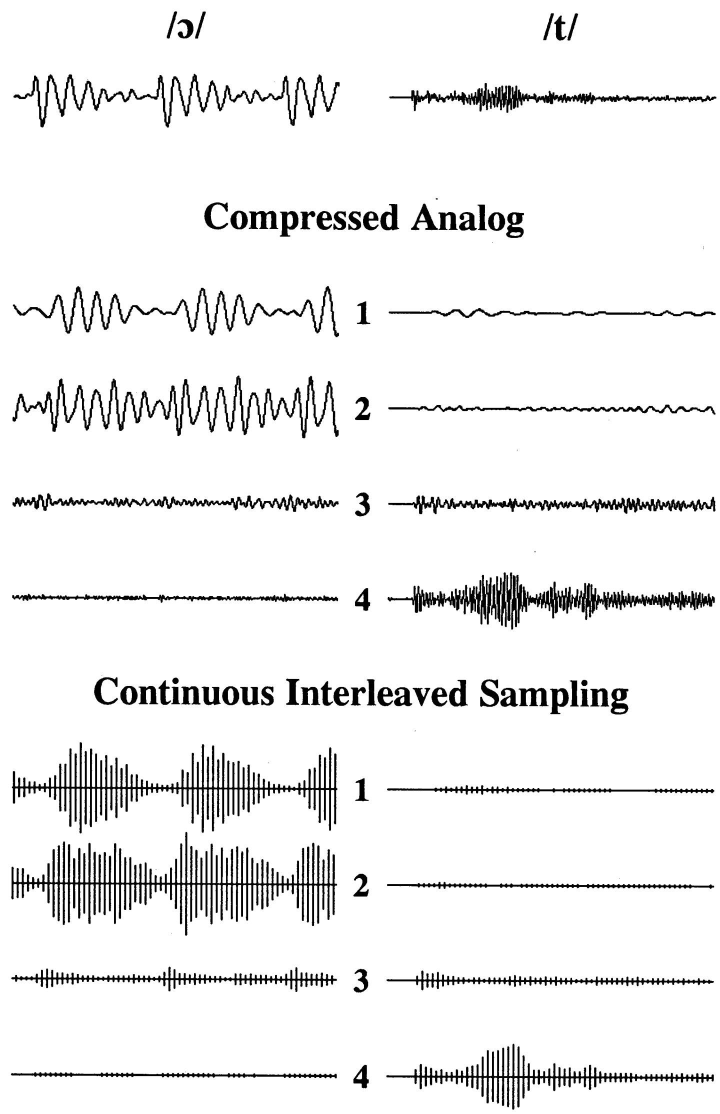

Figure 1. Waveforms produced by simplified implementations of CA and CIS strategies. The top panel shows preemphasized (6 dB/octave attenuation below 1.2 kHz) speech inputs. Inputs corresponding to a voiced speech sound ("aw") and an unvoiced speech sound ("t") are shown in the left and right columns, respectively. The duration of each trace is 25.4 ms. The remaining panels show stimulus waveforms for CA and CIS processors. The waveforms are numbered by channel, with channel 1 delivering its output to the apical-most electrode. To facilitate comparisons between strategies, only four channels of CIS stimulation are illustrated here. In general, five or six channels have been used for that strategy. The pulse amplitudes reflect the envelope of the bandpass output for each channel. In actual implementations the range of pulse amplitudes is compressed using a logarithmic or power-law transformation of the envelope signal.

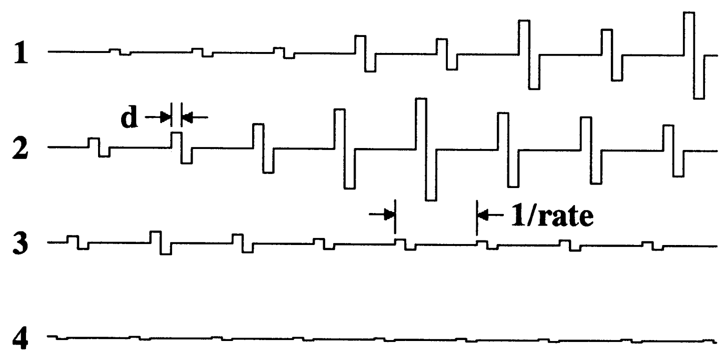

Figure 2. Expanded display of CIS waveforms. Pulse duration per phase ("d") and the period between pulses on each channel ("1/rate") are indicated. The sequence of stimulated channels is 4-3-2-1. The total duration of each trace is 3.3 ms.

derived from the envelopes of bandpass filter outputs. In contrast to the four-channel clinical CA processors, five or six bandpass filters (and channels of stimulation) generally have been used in CIS systems to take advantage of additional implanted electrodes and reduced interactions among channels. The envelopes of the bandpass outputs are formed by rectification and lowpass filtering. Finally, the amplitude of each stimulus pulse is determined by a logarithmic or power-law transformation of the corresponding channel's envelope signal at that time. This transformation compresses each signal into the dynamic range appropriate for its channel.

A key feature of the CIS approach is its relatively high rate of stimulation on each channel. Other pulsatile strategies present sequences of interleaved pulses across electrodes at a rate equal to the estimated fundamental frequency during voiced speech and at a jittered or fixed (often higher) rate during unvoiced speech (Clark, 1987; Wilson, 1992; Wilson et al., 1991b). Rates of stimulation on any one channel rarely have exceeded 300 pulses per second (pps). In contrast, CIS processors generally use brief pulses and minimal delays, so that rapid variations in speech can be tracked by pulse amplitude variations. The rate of stimulation on each channel usually exceeds 500 pps and is constant during both voiced and unvoiced intervals. A constant high rate allows relatively high cutoff frequencies for the lowpass filters in the envelope detectors. With a stimulus rate of 800 pps, for instance, lowpass cutoffs can approach (but not exceed) 400 Hz without introducing aliasing errors in the sampling of the envelope signals at the time of each pulse (see Rabiner and Shafer, 1978, for a complete discussion of aliasing and its consequences).

Methods

Each subject has been studied for a one-week period during which (a) basic psychophysical measures were obtained on thresholds and dynamic ranges for pulsatile stimuli, (b) a variety of CIS processors (with different choices of processor parameters) were evaluated with preliminary tests of consonant identification, and (c) performance with the best of the CIS processors and the clinical CA processor was documented with a broad spectrum of speech tests. Experience with the clinical processor exceeded one year of daily use for all subjects. In contrast, experience with the CIS processors was limited to no more than several hours before formal testing. All comparisons within this eleven-subject study are on the basis of a single week of CIS optimization. In subsequent visits by some of the same subjects a potential for significant further optimization has been demonstrated.

Tests. The comparison tests included open-set recognition of 50 one-syllable words from Northwestern University Auditory Test 6 (NU-6), 25 two-syllable words (spondees), 100 key words in the Central Institute for the Deaf (CID) sentences of everyday speech, and the final word in each of 50 sentences from the Speech Perception in Noise (SPIN) test (presented in our studies without noise). All tests were conducted with hearing alone, using single presentations of recorded material, and without feedback as to correct or incorrect responses.

Processor parameters. Each subject's own clinical device was used for the tests with the CA processor. As mentioned above, selection of parameters for the CIS processor was guided by preliminary tests of consonant identification. The standard four channels of stimulation were used for the clinical CA processors (Eddington, 1980 and 1983), whereas five or six channels were used for the CIS processors. Additional parameters of the CIS processors are presented in Table 1. As indicated there, all CIS processors for the "high performance" subjects, SR2-8, had pulse durations of 102 μs/phase or less, zero delay between the sequential pulses on different channels, pulse rates of 817 pps or higher on each channel, and a cutoff frequency for the lowpass filters of 400 Hz or higher. The best processor for subject SR1 also fit this description, except that a delay of 172 μs was interposed between sequential pulses. The best processors for subjects SR9-11 used long-duration pulses (167 μs/phase), paired with a relatively low rate of stimulation on each channel (500 pps) and a relatively low cutoff frequency for the lowpass filters (200 Hz).

Evaluation of practice and learning effects. Because the tests with the CA processor preceded those with the selected CIS processor for each subject, we were concerned that practice or learning effects might favor the latter in comparisons of the two strategies. To evaluate this possibility, the CID and NU-6 tests were repeated with the CIS processor for five of the "high performance" subjects (subjects SR3, SR4 and SR6-8), using a different recorded speaker and new lists of words and sentences. Practice or learning effects would be demonstrated by significant differences in the test/retest scores. However, no such differences were found ($p > 0.6$ for paired t comparisons of the CID scores; $p > 0.2$ for the NU-6 scores), and the scores from the first and second tests were averaged for all subsequent analyses.

Table 1. Parameters of CIS processors. The parameters include number of channels, pulse duration, the rate of stimulation on each channel (Rate), and the cutoff frequency of the lowpass integrating filters for envelope detection (Integrating Filter Cutoff). The subjects are listed in the chronological order of their participation in the present studies. SR2 through SR8 are the "high performance" subjects while SR1 and SR9-11 belong to the "low performance" group.

Subject	Channels	Pulse Duration (μs/phase)	Rate (pps)	Integrating Filter Cutoff (Hz)
SR2	6	55	1515	800
SR3	6	31	2688	400
SR4	6	63	1323	400
SR5	6	31	2688	800
SR6	6	102	817	400
SR7	5	34	2941	400
SR8	6	100	833	400
SR1	5	34	833	400
SR10	6	167	500	200
SR9	5	167	500	200
SR11	6	167	500	200

Results

The results from one-week studies of each of the eleven subjects are presented in Table 2 and Fig. 3. CA and CIS scores for each of the "high performance" subjects are connected by the light lines near the top of each panel in Fig. 3, and scores for the four "low performance" subjects are connected by the dark lines closer to the bottom of each panel. We note that low-performance subject SR1 had participated in an earlier study not involving CIS processors (Wilson et al., 1991b). Results from his first week of testing with CIS processors are presented here. This is also true of high-performance subject SR2, who has returned to the laboratory for many additional studies with various implementations of CIS processors (see, e.g., Lawson et al., 1992). In those subsequent tests SR2 has achieved even higher scores using a variety of six-channel CIS processors, with NU-6 percentages ranging from the high 80s to the low 90s.

As is evident from the figure, scores for all eleven subjects are improved with the use of a CIS processor. The average scores across subjects increased from 57 to 80% correct on the spondee test ($p < 0.002$), from 62 to 84% correct on the CID test ($p < 0.005$), from 34 to 65% correct on the SPIN test ($p < 0.001$), and from 30 to 47% correct on the NU-6 test ($p < 0.0005$). Note that the range of difficulty among our four tests provides sensitivity to performance differences across the rather wide range of absolute performance represented in this eleven-subject study.

Table 2. Individual results from the open-set tests.

	Spondee		CID		SPIN		NU-6	
Subject	CA	CIS	CA	CIS	CA	CIS	CA	CIS
SR2	92	96	100	100	78	96	56	80
SR3	52	96	66	98	14	92	34	58
SR4	68	76	93	95	28	70	34	40
SR5	100	100	97	100	94	100	70	80
SR6	72	92	73	99	36	74	30	49
SR7	80	100	99	100	66	98	38	71
SR8	68	100	80	100	36	94	38	66
SR1	40	60	25	70	2	30	6	32
SR10	0	56	1	55	0	26	0	14
SR9	8	34	9	34	2	2	2	4
SR11	46	66	40	71	12	30	18	22

Perhaps the most encouraging of these results are the improvements for the four low-performance subjects. SR1, for instance, achieved scores with the CIS processor that would have qualified him for membership in the high performance group (with the clinical CA processor). Similarly, SR10 achieved relatively high scores with the CIS processor. The score on the spondee test increased from 0 to 56% correct, on the CID test from 1 to 55% correct, on the SPIN test from 0 to 26% correct, and on the NU-6 test from 0 to 14% correct. These increases were obtained with no more than several hours of aggregated experience with CIS processors, compared to more than a year of daily experience with the clinical CA processor.

Note that while these gains for SR10 are large, they are not atypical of results for the other subjects. His improvements follow the pattern of the other subjects, i.e., generally large gains in the scores of tests that are not limited by ceiling effects. The distinctive aspect of SR10's results is that he enjoys such gains even though he started at or near zero on all four tests. Thus, the relative improvements for SR10 are larger than those for any other subject in the series.

Discussion

The findings presented above demonstrate that use of CIS processors can produce large and immediate gains in speech recognition for a wide range of implant patients. Indeed, the sensitivity of some of the administered tests has been limited by ceiling (or saturation) effects: five of the seven "high performance" subjects scored 96% or higher for the spondee test using CIS processors; all seven scored 95% or higher for the CID test; and five scored 92% or higher for the SPIN test. Scores for the NU-6

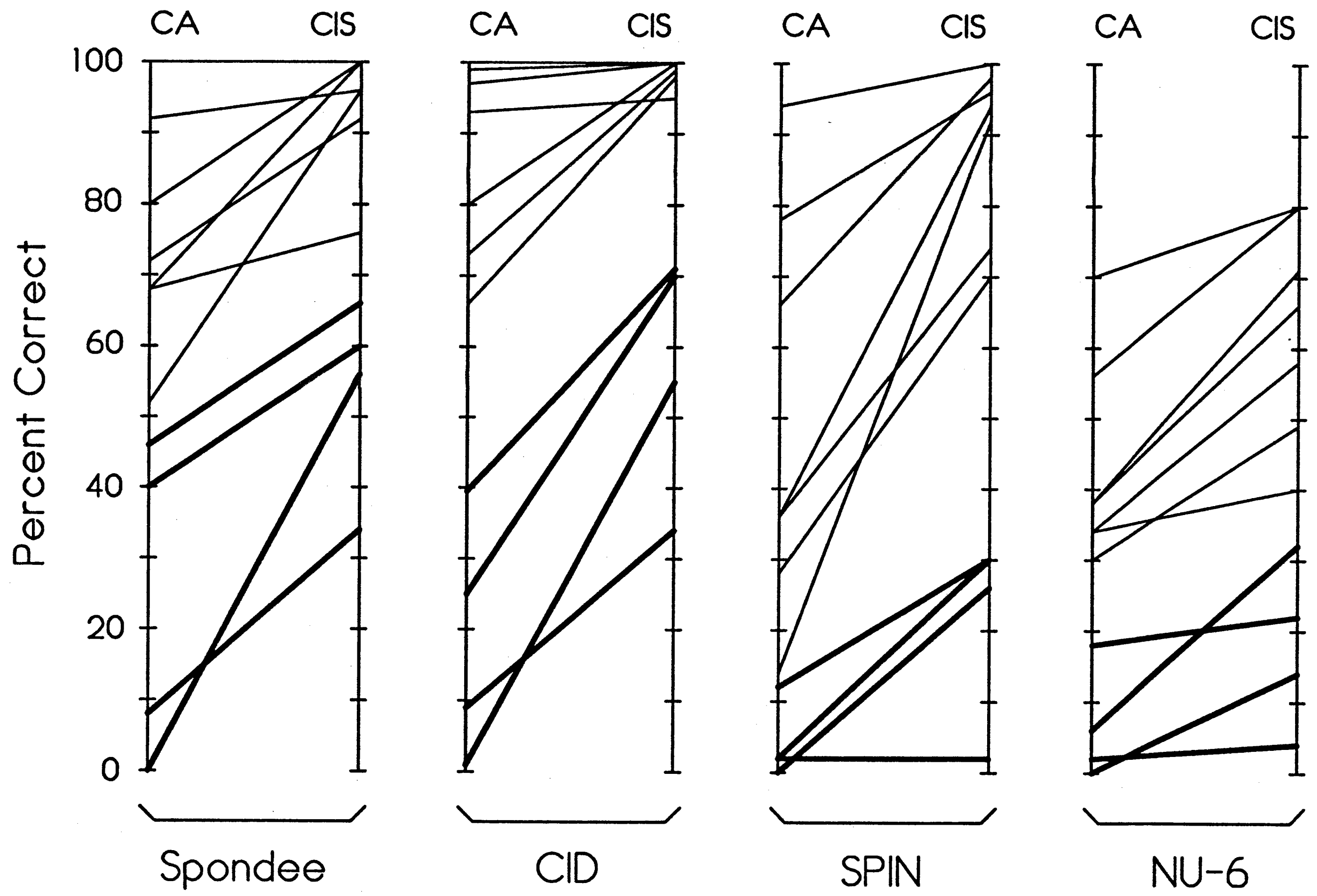

Figure 3. Speech recognition scores for CA and CIS processors. A line connects the CA and CIS scores for each subject. Light lines correspond to the seven subjects selected for their excellent performance with the clinical CA processor, while the heavier lines correspond to the four subjects selected for relatively poor performance.

test, while not approaching the ceiling, still were quite high. The 80% score achieved by two of the subjects corresponds to the middle of the range of scores obtained by people with mild-to-moderate hearing losses when taking the same test (Bess and Townsend, 1977; Dubno and Dirks, 1982).

The improvements are even more striking when one considers the large disparity in experience with the two processors. At the time of our tests each subject had 1 to 5 years of daily experience with the CA processor, but only several hours over a few days with CIS. In previous studies involving within-subjects comparisons, such differences in experience have strongly favored the processor with the greatest duration of use (Dowell et al., 1987; Dowell et al., 1990; Tyler et al., 1986).

Factors contributing to the performance of CIS processors might include (a) reduction in channel interactions through the use of nonsimultaneous stimuli, (b) use of five or six channels instead of four, (c) representation of rapid envelope variations through the use relatively high pulse rates, (d) preservation of amplitude cues with channel-by-channel compression, and (e) the shape of the compression function.

An interesting aspect of the studies with low-performance subjects is that the best CIS processors seem to involve parameters distinct from those of the best processors for subjects in the high-performance group. The best processor for SR1 used short-duration pulses (34 μs/phase) presented at a relatively low rate (833 pps), and the best processors for SR9-11 used long-duration pulses (167 μs/phase) presented at an even lower rate (500 pps). The subjects in the high-performance group, however, often obtained their best scores with processors tending to minimize pulse widths and maximize pulse rates (e.g., 31 μs/phase pulses presented at 2688 pps).

The use of such shorter pulses and higher rates allows representation of higher frequencies in the modulation waveform for each channel, i.e., the cutoff frequency of the lowpass filter in the envelope detectors for each channel may be raised to 1/2 the pulse rate without introducing aliasing effects. In addition, the dynamic range (DR) of electrical stimulation -- from threshold to most comfortable loudness -- typically is a strong function of pulse rate and a weaker function of pulse duration (Shannon, 1992; Wilson et al., 1991c). Large increases in DR generally are found with increases in pulse rates from about 400 pps to 2500 pps. Smaller increases often (but not always) are observed with increases in pulse duration (at a fixed rate of stimulation) from roughly 50 μs/phase to higher values (e.g., out to 200 μs/phase for practical CIS designs).

For some patients, though, these advantages may be outweighed by other factors. For several subjects in our Ineraid series, for instance, we have observed that the salience of channel ranking can decline with decreases in pulse widths below 100 μs/phase. A favorable tradeoff for such subjects might involve the use of long-duration pulses (e.g., 100 μs/phase or greater) to preserve channel cues, while foregoing any additional DR obtainable with shorter pulses and higher rates of stimulation.

Another possible advantage of relatively low rates of stimulation is further reduction of channel interactions. Providing time between pulses on sequential channels can reduce the "temporal integration" component of channel interactions (a component produced by the accumulation of charge at neural membranes from sequential stimuli, see, e.g., White et al., 1984). Thus, use of time delays between short-duration pulses in the stimulation sequence across electrodes may reduce interactions. Alternatively, use of long-duration pulses with no time delay also might reduce temporal interactions in that a relatively long period still is realized between the excitatory phases of successive pulses.

Collectively the present results indicate that (a) the performance of at least some patients with poor clinical outcomes can be improved substantially with the use of a CIS processor, (b) use of long-duration pulses produced large gains in speech test scores for three such subjects, (c) use of short-duration pulses presented at a relatively low rate produced similar improvements in another such subject, and (d) the optimal tradeoffs among pulse duration, pulse rate, interval between sequential pulses, and cutoff frequency of the lowpass filters appear to vary from patient to patient.

Acknowledgements

We thank the subjects of the described studies for their enthusiastic participation. We also are pleased to acknowledge the important scientific contributions of Michael F. Dorman, Donald K. Eddington, William M. Rabinowitz and Robert V. Shannon. This report is an updated version of a paper that has been submitted for publication in the *Journal of Rehabilitation Research and Development*, "Design and evaluation of a continuous interleaved sampling (CIS) processing strategy for multichannel cochlear implants."

References

Bess FH, Townsend TH (1977). Word discrimination for listeners with flat sensorineural hearing losses. *J Speech Hear Disorders* 42: 232-237.

Clark GM (1987). The University of Melbourne-Nucleus multi-electrode cochlear implant. *Adv Oto-Rhino-Laryngol* 38: 1-189.

Dowell RC, Brown AM, Mecklenburg DJ (1990). Clinical assessment of implanted deaf adults. In *Cochlear Prostheses*, G.M. Clark, Y.C. Tong and J.F. Patrick (Eds.), 193-205. Edinburgh: Churchill Livingstone.

Dowell RC, Seligman PM, Blamey PJ, Clark GM (1987). Evaluation of a two-formant speech-processing strategy for a multichannel cochlear prosthesis. *Ann Otol Rhinol Laryngol* 96 (Suppl. 128): 132-134.

Dubno JR, Dirks DD (1982). Evaluation of hearing-impaired listeners using a nonsense syllable test. I. Test reliability. *J Speech Hear Res* 25: 135-141.

Eddington DK (1980). Speech discrimination in deaf subjects with cochlear implants. *J Acoust Soc Am* 68: 885-891.

Eddington DK (1983). Speech recognition in deaf subjects with multichannel intracochlear electrodes. *Ann NY Acad Sci* 405: 241-258.

Lawson DT, Wilson BS, Finley CC (1992). New processing strategies for multichannel cochlear prostheses. *Prog Brain Res*, in press.

Merzenich MM, Rebscher SJ, Loeb GE, Byers CL, Schindler RA (1984). The UCSF cochlear implant project. State of development. *Adv Audiol* 2: 119-144.

Pfingst BE (1984). Operating ranges and intensity psychophysics for cochlear implants. *Arch Otolaryngol* 110: 140-144.

Rabiner LR, Shafer RW (1978). *Digital Processing of Speech Signals*. Englewood Cliffs, NJ: Prentice-Hall.

Shannon RV (1983). Multichannel electrical stimulation of the auditory nerve in man. I. Basic psychophysics. *Hear Res* 11: 157-189.

Shannon RV (1992). Psychophysics. In *Cochlear Implants: Audiological Foundations*, R.S. Tyler (Ed.), Chapter 3. San Diego, CA: Singular Publishing Group, in press.

Tyler RS, Preece JP, Lansing CR, Otto SR, Gantz BJ (1986). Previous experience as a confounding factor in comparing cochlear-implant processing schemes. *J Speech Hear Res* 29:282-287.

White MW, Merzenich MM, Gardi JN (1984). Multichannel cochlear implants: Channel interactions and processor design. *Arch Otolaryngol* 110: 493-501.

Wilson BS (1992). Signal processing. In *Cochlear Implants: Audiological Foundations*, R.S. Tyler (Ed.), Chapter 2. San Diego, CA: Singular Publishing Group, in press.

Wilson BS, Finley CC, Lawson DT (1990a). Representations of speech features with cochlear implants. In *Cochlear Implants: Models of the Electrically Stimulated Ear*, J.M. Miller and F.A. Spelman (Eds.), 339-376. New York: Springer-Verlag.

Wilson BS, Finley CC, Lawson DT, Wolford RD, Eddington DK, Rabinowitz WM (1991a). Better speech recognition with cochlear implants. *Nature* 352: 236-238.

Wilson BS, Lawson DT, Finley CC (1990b). Speech processors for auditory prostheses. Fourth Quarterly Progress Report, NIH project N01-DC-9-2401.

Wilson BS, Lawson DT, Finley CC, Wolford RD (1991b). Coding strategies for multichannel cochlear prostheses. *Am J Otol* 12 (Suppl. 1): 56-61.

Wilson BS, Lawson DT, Finley CC, Zerbi M (1991c). Speech processors for auditory prostheses. Ninth Quarterly Progress Report, NIH project N01-DC-9-2401.

III. Auditory Brainstem Implant

The Auditory Brainstem Implant (ABI) has been used to restore some hearing for people with bilateral loss of the cochlear nerve. To date, approximately 20 people have been implanted with the ABI device, following the removal of acoustic tumors resulting from neurofibromatosis II.

We have studied two of these patients, in collaboration with Robert V. Shannon and others at the House Ear Institute. The studies were conducted in our laboratory at Duke University Medical Center, beginning in the fall of 1989.

The ABI was placed in the first patient immediately after removal of his second acoustic tumor. In contrast, the device was placed in the second patient immediately after removal of her first tumor. This second patient still had normal hearing in her second ear at the time of our tests and no experience with prosthetic stimulation of her implant. The first patient was totally deaf without his prosthesis, and had approximately five months of experience with his ABI at the time of our tests. Both subjects had percutaneous access to their implanted electrodes, and in both cases only one of the two implanted electrodes offered the possibility of stimulating purely auditory percepts.

Results for the first subject are shown in Fig. 4. A single-channel *continuous sampling* (CS) processor was compared with the subject's clinical HEI processor (identical in most respects to the 3M/House processor). The stimuli presented by the CS processor, a single-channel variation of CIS processors, consisted of a train of short duration pulses whose amplitudes were modulated (via a logarithmic mapping function) with the envelope of the broadband speech signal. The tests included identification of 16 consonants, using male and female speakers; identification of 8 vowels, using male and female speakers; the segmental tests of the Minimal Auditory Capabilities (MAC) battery (Owens et al., 1985); and all open-set tests of the MAC battery except for the SPIN test, which was omitted for this subject. All tests were conducted with hearing alone, with no feedback as to correct or incorrect responses.

As is obvious from the figure, use of the CS processor produced large gains in the transmission of consonant information. In particular, scores for the temporal features of voicing, frication, duration, and envelope cues are much higher with the CS processor. In addition, the score for place of articulation is more than doubled with the application of the CS processor. The only score not improved with the CS processor is the one for nasality, which is about the same for the two processors.

Transmission of vowel features is about the same for the two processors. Also, the scores for the vowel test in the MAC battery are essentially equivalent for the two processors.

In contrast to the vowel scores, remarkable gains in open-set recognition are produced with the use of the CA processor. The score for spondee recognition is increased from 2 to 40% correct, for CID sentences from 11 to 25% correct, and for NU-6 words from 2 to 12% correct.

These increases, particularly for open-set recognition, are all the more remarkable when one considers the disparity in experience with the two processors. This subject had five months of daily experience with his HEI processor, but only several hours of (aggregated) experience with CS processors before

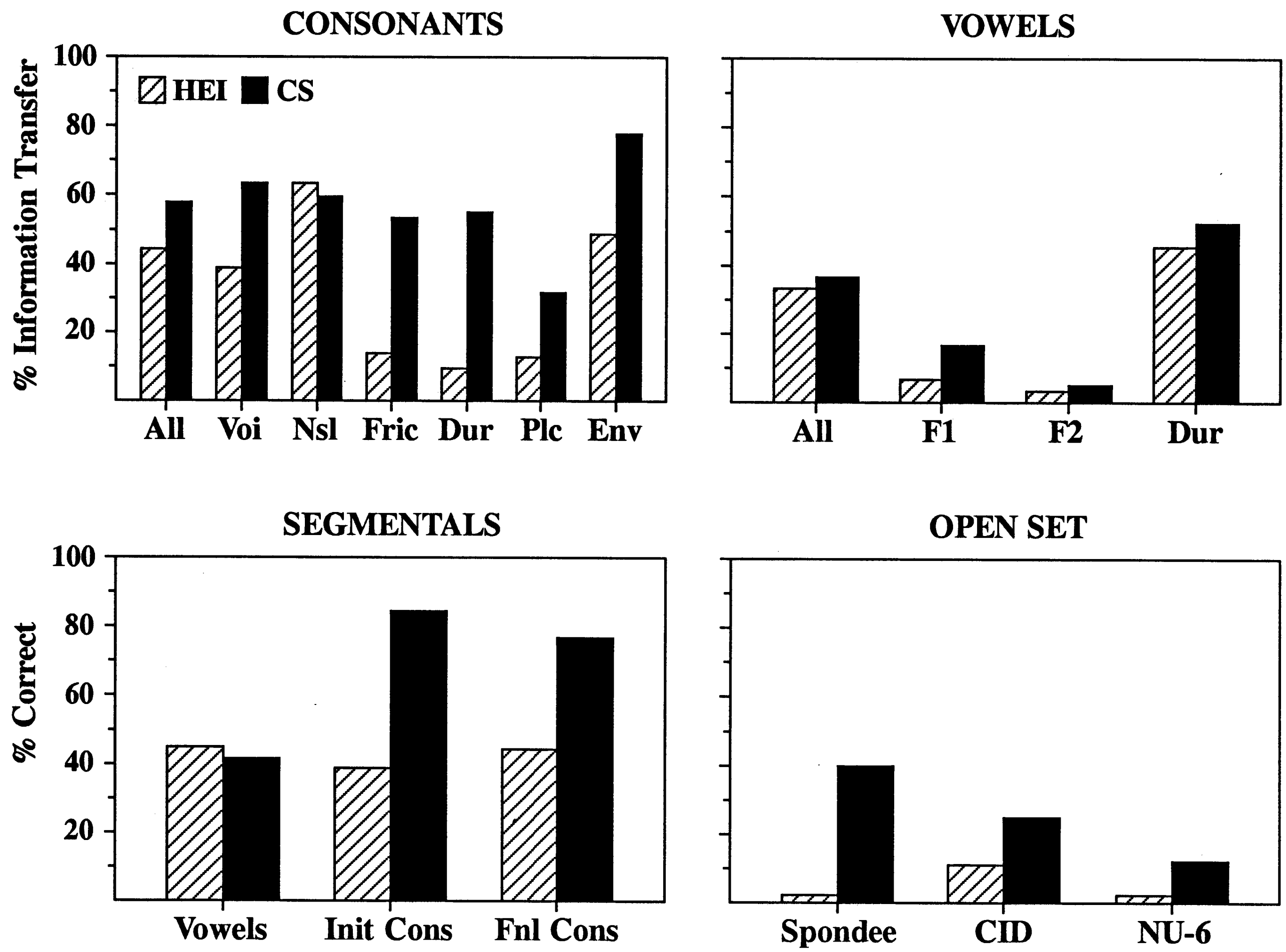

Figure 4. Comparison of speech test scores for the first ABI patient. Scores for the HEI processor are indicated by the striped bars, and those for the CS processor by the solid bars. The top panels show relative information transfer for articulatory and acoustic features of consonants and vowels (see Miller and Nicely, 1955). The features for consonants include overall transmission (All), voicing (Voi), nasality (Nsl), frication (Fric), duration (Dur), place of articulation (Plc), and envelope cues (Env). The features for vowels include overall transmission (All), first formant frequency (F1), second formant frequency (F2), and duration (Dur). Twenty presentations of each of 16 consonants were used in the consonant identification tests for both processors, and eighteen presentations of each of 8 vowels were used in the vowel identification tests for both processors. Presentations for both the consonant and vowel tests were equally divided between male and female speakers. The bottom panels show scores from the segmental and open-set tests of the Minimal Auditory Capabilities (MAC) battery. The CS processor (processor SS2B) used 110 μs/phase pulses, presented at the rate of 1818 pps. The cutoff frequency of the lowpass filter in the envelope detector was 400 Hz.

these tests were conducted.

Studies with the second subject were complicated by the fact that she had normal hearing, and that she lacked any experience with electrical stimulation.

Most studies with her were directed at acclimating her to electrically evoked percepts and to initial evaluations of the CS strategy as an adjunct to lipreading. As indicated in detail in QPR 6 for this project (in the section on "Parametric Variations and the Fitting of Speech Processors for Single-Channel Brainstem Prostheses"), use of the CS strategy in conjunction with lipreading (from the Iowa laser videodisc images) produced consonant identification scores in the high 90s. Such scores are compatible with high levels of open-set speech recognition. Thus, even in a totally naive listener, the CS strategy demonstrated its potential as an adjunct to lipreading.

While these findings are most encouraging, recent results from studies with CIS processors suggest that substantial improvements in speech recognition might be obtained with additional channels. In particular, consonant identification increased almost linearly with increases in channel number from 1 to 6 for a subject using a scala tympani implant (Lawson et al., 1992). Effective use of such additional channels for the ABI device would of course depend on the number of perceptually distinct sites of stimulation.

The present HEI Implant has two large electrode surfaces that overlie the dorsal cochlear nucleus. In most cases, only one of these electrodes is useful, in that (monopolar) stimulation of the other produces various nonauditory percepts such as dizziness. In the few cases in which both electrodes produce auditory sensations, the percepts have been described as identical (Shannon, personal communication).

Although distinct auditory percepts have not been demonstrated in ABI patients, studies of Frederickson and Gerken (1977) indicate that penetrating electrodes, properly positioned (in the ventral cochlear nucleus), can produce tonotopically restricted patterns of activation in the central auditory system. Use of such electrodes may allow the effective application of multichannel CIS processors.

Electrodes under development include the penetrating electrodes at the University of Michigan and at HEI/Huntington. In addition, Cochlear Corporation has developed an array of surface electrodes (including 8 contacts) in a cooperative effort with HEI. We plan to continue our collaborative studies with Bob Shannon and others at HEI to (a) study additional patients with the present electrode system and (b) study patients who might be implanted in the future with one of the new electrode systems.

Acknowledgements

We thank the subjects of the described studies for their enthusiastic participation. This work was conducted in collaboration with investigators at the House Ear Institute, including Robert V. Shannon, John Wygonski, and Albert Maltan.

References

Frederickson CJ, Gerken GM (1977). Masking of electrical by acoustic stimuli: Behavioral evidence for tonotopic organization. *Science* 198: 1276-1278.

Lawson DT, Wilson BS, Finley CC (1992). New processing strategies for multichannel cochlear prostheses. *Prog Brain Res*, in press.

Miller, GA, Nicely, PE (1955). An analysis of perceptual confusions among some English consonants. *J Acoust Soc Am* 27: 338-352.

Owens E, Kessler DK, Raggio M, Schubert ED (1985). Analysis and revision of the Minimal Auditory Capabilities (MAC) battery. *Ear Hear* 6: 280-287.

IV. Plans for the Next Quarter

An extensive series of studies is planned for Ineraid subject SR2, who will visit the laboratory for two weeks in June, 1992. The studies will include a detailed evaluation of tradeoffs among pulse duration, pulse rate, and interval between sequential pulses, as used in CIS processors. In addition, studies to evaluate several techniques for reducing deleterious effects of noise on processor performance will be initiated.

Our plans also include (a) continued studies with subjects using the new MiniMed device, (b) continued preparation of manuscripts for publication, and (c) preparation of the final report for this project.

Appendix 1

Summary of Reporting Activity for the Period of

February 1 through April 30, 1992

NIH Project N01-DC-9-2401

Reporting activity for the last quarter included preparation of two invited papers and presentation of one invited lecture. The citations are:

Wilson BS: Signal processing. To be published in R. Tyler (Ed.), *Cochlear Implants: Audiological Foundations*, Singular Publishing Group, San Diego, CA, 1992.

Wilson BS, Finley CC, Lawson DT, Wolford RD, Zerbi M: Design and evaluation of a continuous interleaved sampling (CIS) processing strategy for multichannel cochlear implants. Submitted for publication in the *Journal of Rehabilitation Research and Development*.

Wilson BS: Processing strategies for multichannel cochlear implants. Invited lecture presented at the *Fourth Symposium: Cochlear Implants in Children*, Kansas City, MO, Feb. 14-15, 1992.