Final Report

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NIH Project N01-DC-5-2103

Speech Processors for Auditory Prostheses

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I. Introduction

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

Major activities and achievements of the project

Work in the project has included a substantial effort and investment of other resources to equip and improve two new laboratories at the Research Triangle Institute (RTI), one dedicated to evoked potential studies and the other to psychophysical and speech reception studies. (We have retained our laboratory at Duke University Medical Center, principally for studies with recipients of the Auditory Brainstem Implant, who may require prompt medical care should stimuli delivered through the implant affect nearby non-auditory structures in the brainstem.)

The many and various upgrades to the laboratories at RTI have allowed us to ask or begin asking questions that could not be asked before. For example, we now can evaluate the efficacy of high rates of stimulation with implants, using a bank of 24 high-speed current sources developed for use in the psychophysics/speech reception laboratory. Similarly, new equipment and procedures in the evoked potentials laboratory allow studies with a quite wide range of stimuli, including modulated and unmodulated pulse trains with pulse rates up to 10000/s and stimuli with amplitudes that approach auditory thresholds and that are representative of amplitudes used in speech processor designs.

We also have conducted a wide range of psychophysical, speech reception and evoked potential studies in the course of the project. Many of these are described in our quarterly progress reports (see Table 1 below) and in recent publications (see section III of this report). Results from these studies provide a foundation for further work and advances in the upcoming project, to begin on September 30, 1998.

Table 1. Topics of the quarterly progress reports for NIH project N01-DC-5-2103.

QPR	Topic(s)
1	Learning effects with extended use of CIS processors

	22 electrode percutaneous study: Results for the first subject
	Upward extension of the CIS processed frequency spectrum
2	Manipulations in spatial representations with implants
3	22 electrode percutaneous study: Results for the first five subjects
4	New stimulator system for the speech reception laboratory
5	Bilateral cochlear implants controlled by a single speech processor
6	Intracochlear evoked potentials in response to pairs of pulses: Effects of pulse amplitude and interpulse interval
7	High rate studies, subject SR2
8	Relationships between temporal patterns of nerve activity and pitch judgments for cochlear implant patients
9	Further development of instrumentation in the evoked potentials laboratory
10	Effects of upward extension of the frequency range analyzed by CIS processors
11	Design of new speech test materials and comparisons with standard materials

Specific activities and achievements of the project included:

- Creation of two laboratories at RTI, one for evoked potential (EP) studies and the other for psychophysical and speech reception studies.
- Upgrades and improvements for the psychophysics/speech reception laboratory, including a bank of 24 high-speed current sources with a capability of simultaneous stimulation across electrodes, a system for continuous monitoring of electrode connection status, a multichannel monitoring system for evaluation and documentation speech processor outputs, separate interface systems for simultaneous laboratory control of bilateral Nucleus CI22, Nucleus CI24M, or Med El COMBI 40 or COMBI 40+ implants, incorporation of new Motorola 563001 DSPs for high-speed emulation of speech processor designs, coding of speech processor designs and psychophysical test procedures for execution with the new DSP system and with the new interface systems, uninterruptable power supplies, and new and greatly improved audio mixing equipment.
- Upgrades and improvements for the EPs laboratory, including custom high-speed current sources that can disconnect after delivery of stimulus pulses to improve the signal-to-noise ratio of recordings, custom "head stage" amplifiers with rapid recovery from saturation and low noise, better optical isolators for both the stimulating and recording sides with high bandwidth and low noise, implementation of a new "template subtraction" procedure that may allow routine recordings of responses for single polarities of stimulation, and development of a system for simultaneous or nonsimultaneous stimulation of two electrodes in conjunction with EP recordings on another electrode. Work is underway to develop a system for multichannel stimulation with more than two electrodes and for multichannel recording with as many as six unstimulated electrodes. Work also is underway to develop a capability for recording with the same electrode(s) used for stimulation.
- Studies with subjects specifically selected for their low levels of speech reception performance with their commercial speech processors and implant systems (Ineraid subjects SR9, SR10, SR15 and SR16, with multiple one- or two-week visits for each). The studies included evaluation of various processing strategies, some specifically designed for use by patients in the "low performance" category, such as processors with new types of mapping functions and/or relatively low rates of stimulation. The studies also included wide ranges of psychophysical and evoked potential measures, as indicated below, to characterize and understand the

psychophysical and neurophysiological substrates for these subjects.

- Completion of studies with five subjects implanted with an experimental version of the Cochlear Ltd. ("Nucleus") implant, that includes a percutaneous connector for direct electrical access to the implanted electrodes. Studies with these subjects included
- Comparisons among
    - *Continuous interleaved sampling* (CIS) processors using different numbers of channels (4, 6, 8, 11 and 21 channels for all subjects, and also 1, 2 and 3 channels for three subjects, with various channel-to-electrode assignments for processors with 6 and fewer channels).
    - CIS processors using different rates of stimulation (e.g., 250 versus 833 pulses/s on each channel for a six channel processor).
    - CIS processors using different ranges of spanned frequencies for the bandpass channels (standard range of 350 to 5500 Hz versus an alternative range of 350 to 9500 Hz).
    - n-of-m processors using relatively low (250 pulses/s) and somewhat higher (833 pulses/s) maximum rates of stimulation on the selected electrodes.
    - The clinical *spectral peak* (SPEAK) processor used by the subjects in their daily lives.
- Recordings of intracochlear EPs, with special emphasis on measures of spatial patterns of stimulation and neural responses (the relatively large number of electrodes in the Nucleus array provides an advantage for such measures).
- Additional studies with Ineraid subjects to evaluate effects of manipulations in channel number and channel-to-electrode assignments. These studies covered quite wide parametric spaces for each of three subjects, and a narrower but still wide space for another, with many tested processors using 1, 2 and 3 channels and a variety of channel-to-electrode assignments for each.
- Studies with three recipients of bilateral implants, one with Nucleus CI22 devices on both sides, one with Nucleus CI24M devices on both sides, and one with Med El COMBI 40+ devices on both sides. The studies included
- Psychophysical measures of electrode ranking within each implant and across the two implants.
- Psychophysical measures of sensitivities to amplitude and timing differences across the two sides, using loudness and pitch balanced stimuli for the two ears.
- Studies with the first and third of the above subjects also included evaluation of a wide range of speech processing strategies, including the two independent clinical processors, laboratory versions of CIS or CIS-like (for the subject with CI22 implants we were limited to the relatively low rates of stimulation that can be supported with the standard Nucleus transcutaneous link) for each side, laboratory versions of CIS or CIS-like processors designed to exploit the larger number of sites of stimulation provided by bilateral implants, and laboratory versions of CIS or CIS-like processors designed to present coordinated stimuli to the two sides in order to restore if possible sound lateralization abilities and the signal-to-noise advantages supported by such abilities. We expect to evaluate speech processor designs in studies with the second subject above during a subsequent visit to the laboratory by her in December, 1998.
- Design and evaluation of new processing strategies and fitting procedures, including
- Processing strategies for coordinated stimulation of bilateral implants, mentioned above
- Further development of n-of-m processors, in support of the studies with the "Nucleus percutaneous" subjects, also mentioned above.
- Initial design and evaluation of processors using rates of stimulation in excess of 2525 pulses/s/channel (the limit of our prior equipment for a 6 channel CIS processor).
- Evaluation of alternative fitting procedures for Innsbruck/RTI "CIS-LINK" wearable speech processors.
- Use of threshold and MCL measures obtained in the context of multichannel stimulation, as opposed to measures obtained with stimulation of single electrodes only.
- Evaluation of various mapping functions, for transforming the outputs of envelope detectors in CIS processors into pulse amplitudes. The studies included manipulations in the amount of compression provided by the mapping functions, evaluation of compression functions other than the standard logarithmic or power functions, evaluation of a procedure originally described by the Geneva team to specify mapping functions according to the results of loudness scaling measures for each channel, and preliminary evaluation of mapping functions designed to replicate loudness growth characteristics found in normal hearing, as originally described by the team at the Massachusetts Eye and Ear Infirmary (MEEI).
- Continued development of a new type of mapping function for use in CIS processors based on physiological considerations. In particular, this new function is designed to mimic principal features of the noninstantaneous compression found in normal hearing at the synapse between inner hair cells and adjacent terminations of

auditory nerve fibers.

- Continued development of a variety of approaches designed to improve neural representations of temporal events in speech and other signals. Several of the approaches attempt to restore a normal pattern of "spontaneous like" activity within and among fibers in the auditory nerve (*e.g.*, processors using high-rate "conditioner pulses" in conjunction with standard CIS stimuli).
- Additional speech reception studies, such as evaluation of a series of single-channel, *continuous sampling* processors, with systematic manipulation in pulse rate and in the cutoff frequency of the lowpass filter in the envelope detector, over wide ranges. (One purpose of these studies was to evaluate effects of rate of stimulation in the absence of electrode interactions.)
- Psychophysical studies with Ineraid subjects, including
- Measures of forward masking across electrodes, to infer spatial patterns of stimulation using a variety of stimulus types and electrode configurations (the procedure of Lim *et al.*, 1989, was used).
- Measures of forward masking on single electrodes, principally to investigate effects of pulse rate and modulation on recovery from prior stimulation (measures made with the procedure of Lim *et al*.)
- Magnitude estimations of loudness, in part for use in designing channel-by-channel mapping functions for CIS processors, as originally described by the Geneva team.
- Magnitude estimations of pitch, using unmodulated and sinusoidally amplitude modulated (SAM) pulse trains, with wide ranges of pulse rates, modulation frequencies, and carrier rates, including carrier rates as high as 10162 pulses/s.
- Recordings of intracochlear EPs, for subjects who have implant devices with percutaneous connectors. The stimuli and studies have included
- Measures of forward masking on single electrodes, for comparison to the psychophysical measures above using the same masker and probe stimuli.
- Measures of spatial patterns of stimulation and neural responses, mentioned above (principally with the Nucleus percutaneous subjects, but also with six of the Ineraid subjects).
- Measures of responses to unmodulated and SAM pulse trains, for pulse rates at and below 1016/s (all subjects with percutaneous connectors).
- Measures of responses to unmodulated and SAM pulse trains, for pulse rates above 1016/s, including rates as high as 10162 pulses/s (four Ineraid subjects and two Nucleus percutaneous subjects).
- Measures of responses to the unmodulated and SAM pulse trains used in the psychophysical experiments above, to evaluate possible relationships between the psychophysical judgments and recorded patterns of responses at the auditory nerve for the same stimuli.
- Measures of responses to the outputs of single-channel speech processors, using a relatively low rate of stimulation (824 pulses/s, three Ineraid subjects).
- Measures of responses to pairs of pulses, using various combinations of pulse amplitudes and interpulse intervals (all subjects).
- Measures of responses to low rate (*e.g.*, 1016 pulses/s) pulse trains with and without the presence of high rate (*e.g.*, 5081 pulses/s) "conditioner" or "biasing" pulses (Ineraid subject SR2).
- Measures of input/output functions for a single pulse preceded by a train of conditioner pulses, with various amplitudes (including zero) for the conditioner pulses (Ineraid subject SR2).
- Measures of simultaneous and nonsimultaneous channel interactions, using programmed control of two independent current sources (most of the subjects with percutaneous connectors).
- Measures of electrically evoked auditory brainstem responses (EABRs), for comparison with measures of intracochlear EPs for the same stimuli, electrodes and subjects (several Ineraid subjects and one Nucleus percutaneous subject).
- Recordings of intracochlear EPs using the "Neural Response Telemetry" (NRT) system of the new Cochlear CI24M device. (Several Ineraid subjects; studies included direct comparisons of recordings obtained with the NRT system versus recordings made with our standard laboratory system, using direct percutaneous access.)
- Comparisons among psychophysical, electrophysiological, and speech reception measures for each of six Ineraid subjects. (Preliminary results from such comparisons were presented in QPR 8 for the present project, and additional results will be presented in an upcoming progress report for the next project.)
- Design, recording and calibration of a new CV syllable test, for studies with the growing number of cochlear implant subjects enjoying levels of speech reception performance that are too high to be sensitively measured by other tests. This work included development of new software for the administration of the test and for automated analysis of test results. Calibration included cross-calibration with standard tests and materials using the same subjects.

- Development of additional speech test materials, including
- Italian- and German-language versions of our standard VCV consonant test, with each of the new versions including 16 consonants appropriate to the respective languages.
- A tape-recorded version of our standard VCV consonant test with 24 English consonants, for use by some of the participants in the field studies with wearable speech processors (see below).
- A German-language version of tests designed to measure possible advantages of binaural sound processing, for use in our studies with bilateral implant subject ME2 (this development was made possible with the tremendous assistance of Sigfrid Soli and Michael Nilsson of the House Ear Institute).
- Evaluation of possible learning effects with extended use of wearable CIS processors, following years of experience with either the clinical *compressed analog* (CA) processor of the Ineraid device or the SPEAK processor used with the Nucleus device. The Innsbruck/Med El/RTI wearable processor was used in studies with Ineraid subjects SR3, SR9, SR15 and SR16, and the Geneva/MEEI/RTI portable processor was used in a study with Nucleus percutaneous subject NP2.
- Further development and application of wearable speech processors, including
- Bench evaluation at RTI of the wearable processors developed in collaboration with investigators in Geneva and Boston, including detailed evaluation of processor outputs (e.g., symmetry, shape and timing of stimuli).
- Development of DSP and download software to implement RTI versions of CIS and other strategies in the Geneva/MEEI/RTI wearable processor.
- Development of fitting procedures for the Geneva/MEEI/RTI processor.
- Development of fitting procedures (some indicated above) for the Innsbruck/Med El/RTI wearable processor.
- Development of various tools and procedures for improved planning and coordination of project activities, including
- A Gantt Chart of tasks, schedules and resources for the project, using the Microsoft Project software package.
- A simpler scheduling chart to keep track of schedules for the three laboratories, for team meetings, for upcoming conferences, and for visits by subjects, consultants, guest scientists, and other guests. (We have found that this simple chart to be more useful for our work than the more elaborate and complex charts produced by Microsoft Project. The Microsoft Project charts have been abandoned in favor of the present chart.)
- Various archiving tools, such as spreadsheets containing details of all processors and processor conditions evaluated in our laboratories over the last decade, spreadsheets of speech reception test results, spreadsheets organized both across subjects and across stimuli for all evoked potential studies conducted to date, and a new and more accessible system for archiving notes and other materials for each subject visit.
- Highly detailed "straw man" lists of studies and objectives prior to each visit by each subject, for discussion and refinement by the team before the studies begin.
- Reporting for the project, which included 11 quarterly progress reports, this final report, 6 published papers (two of these reporting results from our prior project but published during the period of the present project), 1 paper in press, 2 papers submitted for publication, chapters in 2 books scheduled for publication, 28 invited presentations, and 3 additional presentations. (Please see section III of this report for detailed lists of these publications and presentations; please see Table 1 above for a list of the topics covered by the progress reports.)
- Hosting of two site visits for reviews of the project by Drs. Hambrecht and Heetderks (July, 1996 and August, 1998).

Additional efforts in the project have included ongoing analysis of prior and current psychophysical, speech reception and evoked potential data, and ongoing preparation of manuscripts for publication.

Awards and honors

A highlight of this project has been recognition of our work and contributions through major awards and honors, including

- The 1996 Discover Award for Technological Innovation in the category of "sound" (Wilson; award for the CIS processing strategy).
- Designation of Wilson as a Guest of Honor (along with Kurt Burian, M.D., retired Chairman of the OHNS Department at the University of Vienna) for the *International Workshop on Cochlear Implants*, held in Vienna, Austria, October 24-25, 1996.
- An invitation to write a guest editorial, on "The future of cochlear implants," in celebration of the 30th anniversary of the British Journal of Audiology (Wilson; editorial published in Brit J Audiol 31: 205-225, 1997).

- Election of Finley by his peers to serve as the Co-Chair for the *1997 Conference on Implantable Auditory Prostheses* (conference held in Pacific Grove, CA, August 17-21, 1997).
- The Presidential Citation, for "Major contributions to the restoration of hearing in profoundly deaf persons," on the occasion of the *130th Annual Meeting of the American Otological Society*, Scottsdale, AZ, May 10-11, 1997 (Wilson, Lawson, Finley and Zerbi).
- An invitation to present a keynote speech, on "New directions in implant design," at the *4th European Symposium on Paediatric Cochlear Implantation*, held in ‘s-Hertogenbosch, The Netherlands, June 14-17, 1998. (Wilson)

Introduction to the remainder of this report

Section II of this report provides an overview of the present status of cochlear implants and presents possibilities for the further development of implant systems. This section summarizes many aspects of work in the present project and relates that work to work elsewhere. Some of the material, such as the material on conditioner pulses, has not been presented in prior reports for the project. The text and illustrations in section II are from a chapter that will appear in a book on cochlear implants edited by Susan Waltzman and Noel Cohen (Wilson BS: New directions in implant design. In *Cochlear Implants*, edited by SB Waltzman and N Cohen, Thieme Medical and Scientific Publishers, New York, NY). Recommendations for further research are offered throughout this section.

A complete listing of publications, presentations, and other reporting activity for the project is presented in section III.

The success of this project was made possible by the contributions of many people and institutions. Acknowledgments of these contributions are presented in section IV.

II. New directions in implant design*

*This section reproduces a chapter that will be published in the book *Cochlear Implants*, edited by Susan Waltzman and Noel Cohen.

Remarkable progress has been made in recent years in the design and application of speech processing strategies for cochlear implants. In particular, use of the new *continuous interleaved sampling* (CIS) and *spectral peak* (SPEAK) strategies have produced large improvements in speech reception performance compared with prior strategies (Skinner *et al*., 1994; Wilson *et al*., 1991). According to the recent NIH Consensus Statement on Cochlear Implants in Adults and Children (1995), "...A majority of those individuals with the latest speech processors for their implants will score above 80-percent correct on high-context sentences, even without visual cues." Additional information on present levels of performance is presented in the chapter by Michael Dorman in this book.

Although great progress has been made, much remains to be done. Patients with the best performance still do not hear as well as people with normal hearing, especially in adverse listening situations such as attending to one speaker in competition with other speakers or background noise. Also, many patients do not enjoy high levels of performance even with the new processing strategies. Indeed, the range of performance across patients is large with any of the current multichannel implant systems

The purpose of this chapter is to indicate some directions for further improvements in performance. These include (1) an increase in the number of effective channels with CIS and other processors, (2) an increase in the amount of information represented and perceived within channels, and (3) coordinated stimulation of bilateral implants.

More channels

An increase in the number of effective channels might be obtained through new electrode designs, bilateral implants, and/or use of various techniques to reduce electrode interactions. Results from various recent studies have shown that 4-6 channels are adequate to support high levels of speech reception in quiet for some patients (Brill *et al.*, 1997; Fishman *et al*., 1997; Kiefer *et al*., 1996; Lawson *et al.*, 1996). Further increases in the number of channels usually do not produce increases in speech test scores. Such asymptotic performance may reflect a limitation in the number of effective channels available with present implant systems. An increase in the number of effective channels might raise the level of asymptotic performance and change the point at which asymptotic performance is reached. Also, a higher number of effective channels may be especially helpful for listening to speech in noise (see Dorman *et al.*, 1998;

Eddington *et al.*, 1997; Fu, 1997; Fu *et al.*, 1997).

Effects of manipulations in channel number with present implant systems are illustrated in Fig. 1, which shows results of a recent study conducted in our laboratory (Lawson *et al*., 1996; Wilson, 1997). Subject SR2 used the Ineraid implant, and subjects NP1-5 used a special version of the Nucleus implant that had a percutaneous connector. The Ineraid implant has 6 electrodes spaced 4 mm apart and the Nucleus implant has 22 electrodes spaced 0.75 mm apart. For the "Nucleus percutaneous" subjects, increases in channel (and electrode) number above 4 to 6 did not produce improvements in speech reception performance, as measured by identification of consonants in an /a/-consonant-/a/ context. Similarly, the difference in performance between 5 and 6 channels was not significant for the Ineraid subject, although the sensitivity of measures for him may have been limited by ceiling effects.

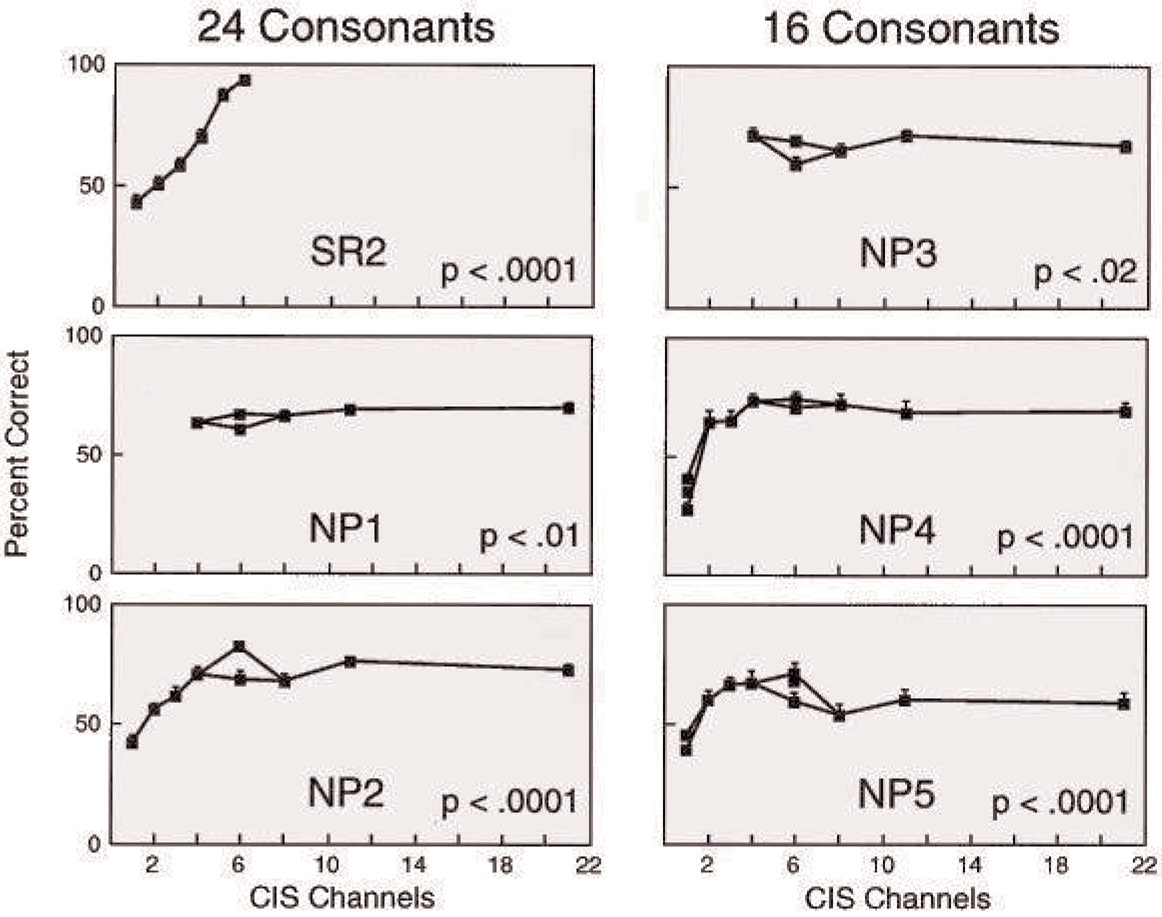


Figure 1. Effects of manipulations in number of channels and in channel-to-electrode assignments. The subjects included one patient with a 6-electrode Ineraid implant (subject SR2) and five patients with percutaneous connector versions of the 22-electrode Nucleus implant (subjects NP1-5). The rate of stimulation across all conditions for SR2 was 2525 pulses/s/channel on the selected electrodes. For NP1-5 the rate was 833 pulses/s/channel for all conditions except the 21-channel condition, where the rate was reduced to 721 pulses/s/channel to preserve nonsimultaneity of stimulation across channels. At least two variations of 6-channel processors, with different choices of electrodes, were included among the conditions for subjects NP1-5. In addition, different electrodes were used for three single-channel processors tested with subject NP4 and for two single-channel processors tested with subject NP5. The various processors were evaluated with tests of consonant identification, using recordings of a male and a female speaker. The 24 consonant test was used for three subjects whose high scores with the standard 16-consonant test reduced that test’s sensitivity. All tests were conducted with hearing alone and no feedback was given as to correct or incorrect responses. The error bars show standard deviations of the mean. Results from a one-way analysis of the variance of the data for each subject are indicated by the p values. (The present Fig. 1 was originally published in Wilson, 1997, and is reproduced here with the permission of the author and the British Journal of Audiology.)

As noted above, asymptotic performance at 4 to 6 channels also has been reported by others. The studies by Brill *et al.* (1997) and by Kiefer *et al.* (1996) involved subjects implanted with the Med El electrode array, and the study by Fishman *et al.* (1997) involved subjects implanted with the Nucleus electrode array (in conjunction with the standard transcutaneous link).

An additional aspect of the results presented in Fig. 1 is that choice of electrodes can affect the performance of CIS processors. For subjects NP1-5, at least two channel-to-electrode assignments were used for 6-channel CIS processors, and for subjects NP4 and NP5, at least two assignments were used for the single-channel processors. In most cases the different assignments produced highly significant differences in speech reception scores (*e.g.*, see the especially large differences in the scores for the 6-channel processors for subject NP2 and for subject NP5).

New electrode designs. The lack of improvements in performance with the addition of channels above 4 to 6 in these various studies may be due to a relatively broad spread of the electric fields and neural activation patterns produced by present electrode arrays. These arrays do not include any special provisions to position the electrode contacts close the inner wall of the scala tympani (ST). Indeed, the arrays are flexible and at least the Nucleus and Med El arrays tend to "rail out" against the lateral wall of the ST at the time of insertion (Gstöettner *et al*., 1998; Shepherd *et al.*, 1985 and 1993). Placements close to the inner wall can reduce thresholds, increase dynamic range, and increase the spatial specificity of stimulation (Cohen *et al*., 1998; Shepherd *et al.*, 1993). This last advantage may be the most important, as an increased spatial specificity (and accompanying reductions in electrode interactions) may increase the number of effective channels with the implant.

Major efforts are underway at several companies and at cooperating universities to develop electrode arrays that place the electrode contacts close to the inner wall of the ST (see, *e.g.*, Cohen *et al*., 1998; Jolly *et al*., 1998; Kuzma, 1996 and 1998; Spelman *et al.*, 1997). Such designs may increase the number of effective channels with unilateral implants.

Although close placement next to the inner wall is likely to improve spatial selectivity, it is important to note that the inner wall is not always close to the spiral ganglion (SG) throughout the length of the ST (Ariyasu *et al.*, 1989; Ketten *et al.*, 1997). Inasmuch as the spiral ganglion cells or the first central node of Ranvier are the most likely sites of stimulation with implants (see, *e.g.*, Klinke and Hartmann, 1997), electrodes next to the inner wall therefore may not be the ideal placement, particularly in regions where the distance between the inner wall and the SG is relatively large. The SG has 1 ¾ turns, whereas the ST has 2 ¾ turns. The SG reaches no higher than the middle of the second turn of the ST. The distance between the inner wall of the ST and the closest turn of the SG increases with increasing distance from the round window (towards the apex). These differences in the anatomic courses of the ST and SG preclude the possibility of close apposition of the structures throughout the length of the cochlea. The closest apposition is available along the basal turn.

While placements of electrodes next to the inner wall of the ST may not be a panacea, such placements may be much better than placements with present electrode arrays. Resulting improvements in the spatial specificity of stimulation may in turn produce improvements in the speech reception performance of implant systems.

Bilateral implants. An additional possibility for increasing the number of effective channels is to use bilateral implants. With full insertions on both sides, bilateral implants would double the number of electrodes and presumably increase the total number of independent or quasi-independent sites of stimulation compared with unilateral implants. Gains in speech reception might be produced by utilizing all such independent sites, without regard to the representation of binaural cues for sound localization. An implicit assumption in this approach is that the central auditory system will integrate or combine inputs from the two sides for speech reception tasks, even when channels are distributed across the two sides and even if the representation of normal bilateral timing and amplitude differences is absent. Preliminary results from our laboratory, obtained in studies with a subject with standard Nucleus 22 implants on both sides, are consistent with this assumption (Lawson *et al.*, 1998).

Further reduction in electrode interactions. Another possibility for increasing the number of effective channels is to reduce electrode interactions within any implanted ear. This might be accomplished through use of channel update sequences that minimize forward masking and temporal summation effects for nonsimultaneous stimuli, as measured with intracochlear evoked potentials (Finley *et al.*, 1997a). Alternatively, use of novel stimulus waveforms, such as triphasic pulses, may minimize temporal summation effects across sequentially stimulated electrodes (Eddington *et al.*, 1994). These reductions would be in addition to the large reductions that can be produced with nonsimultaneous stimulation of electrodes, at least with present electrode arrays.

Although electrode interactions might be reduced substantially with new electrode arrays, it seems likely that significant interactions will remain, especially for electrode positions beyond the basal turn. Use of nonsimultaneous stimuli, and use of customized update orders and/or novel stimulus waveforms in conjunction with nonsimultaneous stimuli, may help to reduce such remaining interactions and thereby produce further improvements in the spatial specificity of stimulation with implants.

Better channels

The quality of each channel in a multichannel implant system might be improved by increasing the range of frequencies represented and perceived within channels. This might be accomplished through use of high carrier rates or of high-rate "conditioner pulses" that are presented in conjunction with standard (relatively low-rate) outputs of CIS processors. Improvements in the quality of individual channels also might be produced with a closer mimicking of the noninstantaneous compression that occurs in the normal auditory periphery (present CIS and other processors use an instantaneous logarithmic or power function for compression, which differs in several respects from the compression function found in normal hearing).

High carrier rates. Effects of carrier rate on the neural representation of modulation waveforms and frequencies are illustrated in Figs. 2 and 3. The left column of Fig. 2 shows patterns of neural responses evoked at the auditory nerve of an implant subject by sinusoidally amplitude modulated (SAM) pulse trains, with the carrier rate of 1016 pulses/s and with modulation frequencies ranging from 100 to 600 Hz. The right column shows those patterns along with the modulation waveforms for the stimuli and the amplitudes of the individual stimulus pulses. Figure 3 compares patterns of neural responses for the carrier rates of 1016 and 4065 pulses/s. In both figures the magnitudes of evoked potentials (EPs) are shown, and these are normalized to the maximum EP magnitude across modulation conditions for the 1016 pulses/s carrier. The stimulus pulse amplitudes in Fig. 2 also are normalized to the maximum amplitude across conditions. Procedures used by our group for the recording of intracochlear evoked potentials are described in recent reports (*e.g.*, Finley *et al.*, 1997b; van den Honert *et al.*, 1997; Wilson, 1997; Wilson *et al.*, 1997a and b).

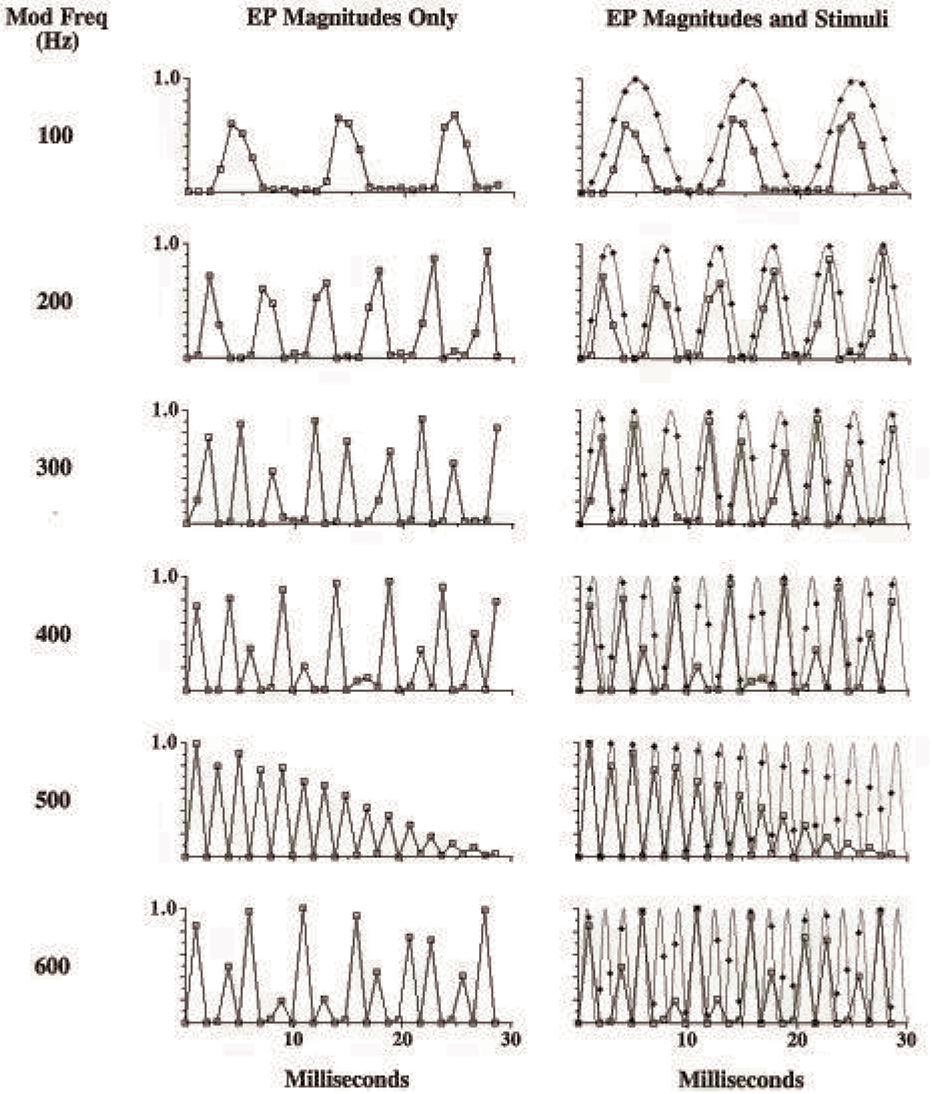


Figure 2. Magnitudes of evoked potentials (EPs) for sinusoidally amplitude modulated pulse trains, with the carrier rate of 1016 pulses/s and with modulation frequencies ranging from 100 to 600 Hz. The EP magnitudes are normalized to maximum value across all conditions. The left column shows the normalized EP magnitudes only, and the right column shows those along with normalized amplitudes of the stimulus pulses. The modulation waveforms for the stimuli are shown by the light lines in the right column. Data are from studies with Ineraid subject SR2. The carrier level for all conditions was 475 µA, and the pulse duration was 33 µs/phase. Stimuli were delivered to intracochlear electrode 3 and recordings were made with intracochlear electrode 4. These stimulus conditions elicited comfortably loud percepts for the subject.

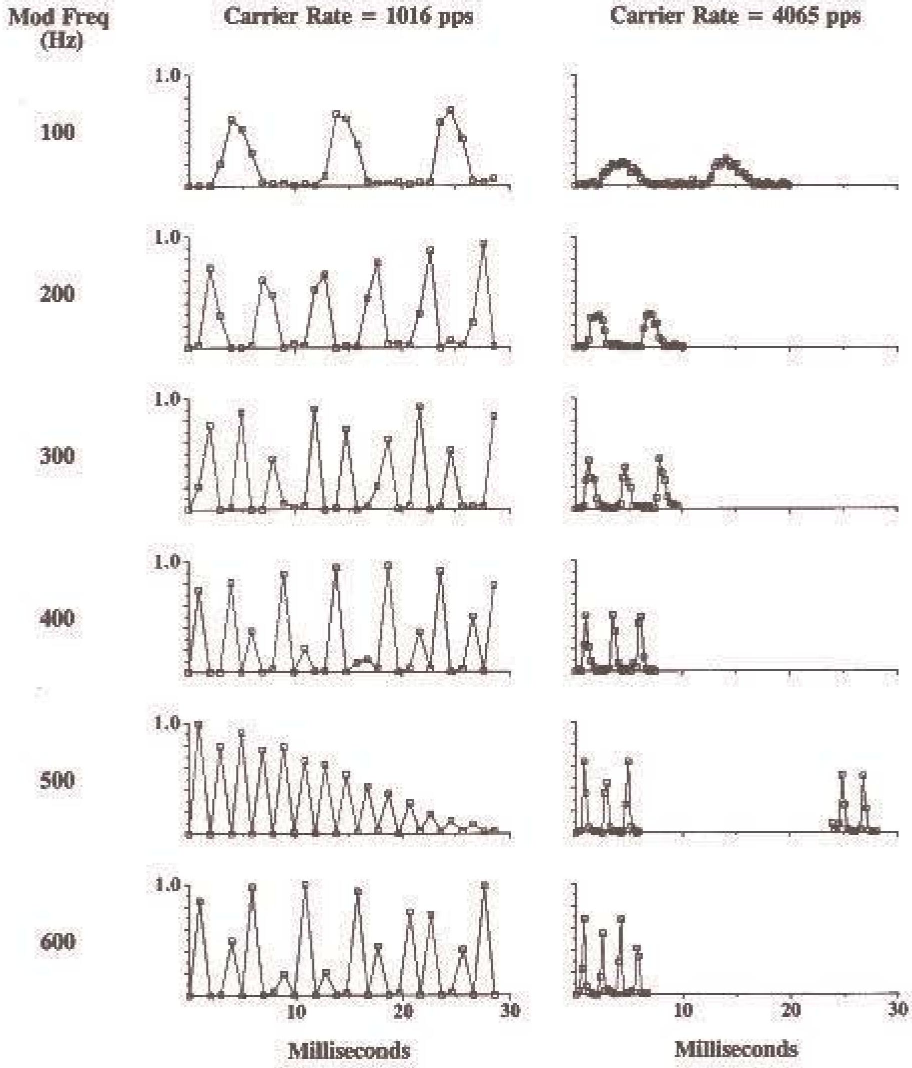


Figure 3. Magnitudes of evoked potentials for sinusoidally amplitude modulated pulse trains, as in Fig. 2, but now with the additional carrier rate of 4065 pulses/s. Evoked potentials for the high carrier rate were derived using the subtraction technique described in Wilson *et al.* (1997a). The subject, carrier level, stimulating electrode, and recording electrode are the same as those specified in the caption to Fig. 2. (The present Fig. 3 was originally published in Wilson, 1997, and is reproduced here with the permission of the author and the British Journal of Audiology.)

Note that for the lower pulse rate, the EP magnitudes correspond closely to the stimulus modulation only for the lowest modulation frequencies. With the higher pulse rate (Fig. 3), EP magnitudes correspond closely to higher frequency modulation waveforms as well. For the low-rate carrier, the pattern of responses is almost sinusoidal for the modulation frequency of 100 Hz (Fig. 2). The periodicity of the 200 Hz modulator also is clearly represented, although there are variations in the fine structure of the responses across cycles of the modulation waveform. At higher modulation frequencies the responses become more complicated and/or reflect gross sampling artifacts as the Nyquist frequency (one half of the carrier rate) is approximated or exceeded. The patterns of stimuli and responses are complex for the 300 Hz modulation condition, reflecting in part a sparse sampling of the modulation waveform by the carrier pulses. At 400 Hz the patterns are both complicated and no longer reflect the period of the modulation waveform. The first interval between major peaks in the response (peaks in the responses corresponding to pulses 2 and 5, see right column of Fig. 2) roughly approximates the period, but subsequent intervals are much longer than the period. At 500 Hz, an alternating pattern of responses is observed. This pattern corresponds to the pattern of stimulation, which is produced by the close approximation of the modulation frequency to the Nyquist frequency (508 Hz). The pattern of responses for the 600 Hz modulation condition condition is complex and similar in some ways to the pattern of responses for the 400 Hz modulation condition. The similarities, such as similar or identical intervals between peaks in the responses, are the result of similar differences between the modulation frequency and the Nyquist frequency for the two conditions. Detailed discussions of responses for the 1016 pulses/s carrier conditions, and of responses for lower carrier rates, are presented in Wilson (1997) and Wilson *et al.* (1997b).

The lack of a close correspondence between the stimulus modulation waveform and EP magnitudes for modulation frequencies above 200 Hz for the 1016 pulses/s carrier, and at lower modulation frequencies for lower carrier rates, has led us to suggest that the carrier pulse rates selected for cochlear implants should be at least 4 to 5 times higher than the highest modulation frequency for each channel (see, *e.g.*, Wilson, 1997). Busby *et al.* (1993) have offered this same suggestion, based on results from their psychophysical studies with subjects using the Nucleus-22 device.

Patterns of responses for the 4065 pulses/s carrier show simple representations for all of the tested modulation frequencies. The patterns of responses follow closely the patterns of stimulation for the modulation frequencies of 400 Hz and lower. The distortions noted above for 300 and 400 Hz modulation of the 1016 pulses/s carrier are eliminated with an increase in carrier rate to 4065 pulses/s. At the higher modulation frequencies of 500 and 600 Hz, the patterns of responses for the 4065 pulses/s carrier show a shallow alternation between high and low peaks for successive cycles of the modulation waveform. For the 500 Hz modulation condition, this alternation may be damped or absent after the initial cycles, as suggested by the pattern of responses for the two cycles beginning at about 24 ms after the onset of the SAM pulse train (use of a subtraction procedure allowed us to derive evoked potentials for rates of stimulation exceeding 1000/s and for any selected set of sequential pulses in trains of pulses; see Wilson *et al.*, 1997a and b).

Additional aspects of the results for the 4065 pulses/s carrier are that (1) the peak magnitudes are lower than those for the 1016 pulses/s carrier and (2) the responses from pulse to pulse are smooth and continuous within modulation cycles. As described in detail elsewhere (Wilson, 1997; Wilson *et al.*, 1994, 1997a and b), these aspects are consistent with the idea that high rate stimuli elicit a more random pattern of responses within and among neurons than low rate stimuli.

The results in Fig. 3 (and similar results obtained in evoked potential studies with four additional subjects) suggest that more of the frequency spectrum might be transmitted within channels using relatively high carrier rates. A possible drawback to high-rate stimulation, however, is that electrode interactions due to forward masking and to temporal summation at neural membranes are likely to increase with increases in rate of stimulation. Thus, the potential benefits of high rates may be counteracted by increases in electrode interactions. Application of techniques to reduce electrode interactions may alter the tradeoff in a favorable way. That is, a reduction in interactions may allow us to convey more information within channels (with high-rate stimuli) while preserving across-channel cues. Alternatively, use of new electrode designs may reduce interactions to a point at which the potential benefits of high-rate stimuli easily outweigh the deleterious effects of the (residual) interactions.

Another question about high-rate stimuli is whether the additional range of modulation frequencies represented at the auditory nerve with such stimuli can be perceived (as an increased range over which monotonic increases in pitch are produced with increases in modulation frequency). If not, then high-rate stimuli may not offer any advantage over lower rates that are just adequate to represent the upper end of the perceptual range. In fact, in such a case the lower rates may be better in that their use would help to minimize electrode interactions.

As described in detail in a recent report from our laboratory (Wilson *et al*., 1997c), access to frequency information presented within channels appears to vary widely across implant patients. This suggests that high-rate stimuli, and the accompanying increase in the range of modulation frequencies represented at the auditory nerve, may be helpful for some but by no means all patients. Patients who cannot perceive a broad range of frequencies within channels (even with high carrier rates) may be best served with relatively low rates of stimulation (*e.g.*, rates that are four to five times higher than the highest frequency represented in the modulation waveforms, with that highest modulation frequency set at the upper end of the perceptual range for such patients).

Preliminary studies have been conducted in several laboratories to evaluate CIS processors using high carrier rates in conjunction with present electrode arrays and without any special strategies for reducing interactions (see, *e.g.*, Brill *et al.*, 1997 and 1998; Kiefer *et al.*, 1996 and 1997; Pelizzone *et al.*, 1998). In some cases, large gains in speech reception scores have been produced with increases in carrier rate, especially for processors using small numbers of channels (*e.g.*, Brill *et al.*, 1997), whereas in others scores have remained the same or dropped with increases in rate (*e.g.*, Pelizzone *et al.*, 1998). Additional studies are needed to evaluate effects of (1) rate manipulations across more than a small number of subjects, (2) rate manipulations across a broader range of rates, (3) concomitant increases in the cutoff frequency of the lowpass filters in the envelope detectors with increases in carrier rate, and (4) various techniques to reduce electrode interactions for high-rate processors. Additional studies also are needed to evaluate the idea that performance might be optimized for different patients by using different carrier rates. Such studies are underway in our laboratory and elsewhere. We should know much more about the efficacy and best application of high-rate stimuli once these studies are completed.

Conditioner pulses. In normal hearing, single fibers of the auditory nerve exhibit spontaneous activity, which is produced by the random release of chemical transmitter into the synaptic clefts between inner hair cells and adjacent neurons, even in the absence of acoustic stimulation. The spontaneous activity of one fiber is not correlated with the spontaneous activity of another (Johnson and Kiang, 1976). Such stochastic independence among neurons may be required for the representation of high frequency information in the population responses of the auditory nerve (see Parnas, 1996, and Fig. 8 and the accompanying discussion in Wilson *et al.*, 1994).

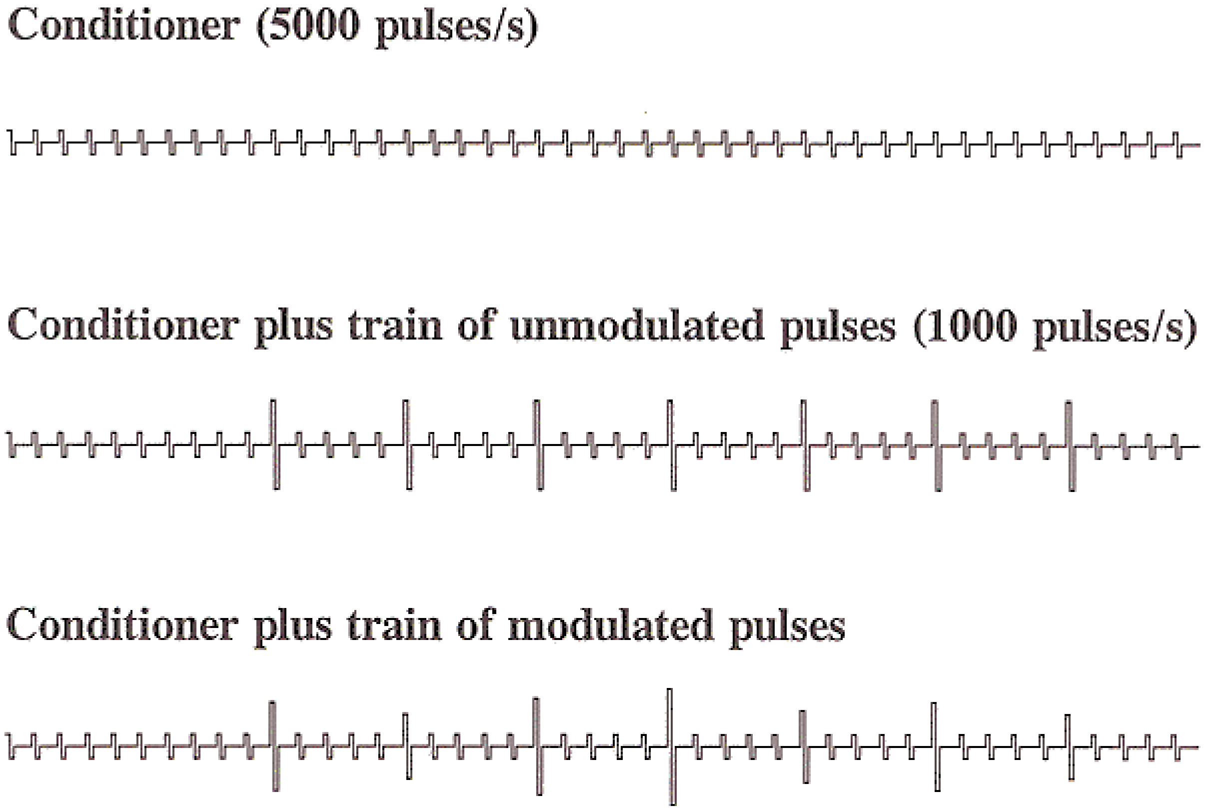
Spontaneous activity is absent in the auditory nerves of deafened animals (*e.g.*, Hartmann *et al.*, 1984). However, a relatively low level of noise (compared to synaptic noise) remains at nodes of Ranvier in surviving neurons. This level is insufficient to produce spontaneous discharges, but may be sufficient for a fortuitous interaction with pulses presented at high rates through a cochlear implant. Slight variations in neural threshold due to membrane noise may introduce a "jitter" in firing times within and across neurons for rapidly presented pulses (or for high-frequency sinusoids, see Dynes and Delgutte, 1992). The variations in threshold would be independent across neurons. Thus, for example, neuron A in the excitation field of an electrode might respond initially to pulse 15 in a train of pulses, whereas an adjacent neuron B might respond to pulse 17, and so on. The variability in response times would be expected to build upon itself with subsequent discharges. After a short period (*e.g.*, about 1-2 ms, see Wilson *et al.*, 1994 and 1997a), the discharge histories among neurons would be broadly distributed, with low correlations between the histories for any two neurons.

Rubinstein and coworkers (1997; 1998a and b; submitted) have suggested that continuous presentation of unmodulated pulses at high rates (*e.g.*, 5000 pulses/s or higher) could elicit in the nerve a background of spontaneous-like activity, which they call "pseudospontaneous" activity. With an appropriate adjustment in the amplitude of the pulses, the distribution of discharge rates among neurons might approximate the distribution in normal hearing. In addition, the activity in any one fiber would not be strongly correlated with the activity of any other fiber.

A background of spontaneous-like activity would be expected to alter in favorable ways the population responses of the auditory nerve to the standard types of stimuli used in cochlear implants. First, the stochastic independence among neurons would allow different subpopulations of neurons to share the load in representing high frequencies in the stimuli, as described in Parnas (1996) and Wilson *et al*. (1994). Second, random activity within a neuron can extend its dynamic range (see, *e.g.*, Collins *et al.*, 1995). This might also extend the dynamic ranges of the population responses and of perception from threshold to the maximum of comfortable loudnesses.

A reinstatement of spontaneous activity in the nerve might also improve the naturalness of percepts in that the hypersynchronization of neural responses normally produced with electrical stimuli would be reduced or eliminated. Afferent inputs to the cochlear nucleus would be less synchronous and perhaps more appropriate for processing within the CN and auditory structures central to the CN.

One way of combining conditioner pulses with information-carrying stimuli is illustrated in Fig. 4. The top panel shows conditioner pulses only, and the remaining panels show substitution of stimulus pulses for every fifth conditioner pulse, following an initial segment of conditioner pulses only. The conditioner pulses are presented at the rate of 5000/s and the stimulus pulses are presented at the rate of 1000/s. The conditioner and stimulus pulses could be combined in several other ways (*e.g.*, placing each stimulus pulse between two conditioner pulses), and different rates could be used for each. In all combinations, the intent would be to elicit in the nerve a steady background of spontaneous-like activity with the conditioner pulses, thus modifying the responses to the stimulus pulses, much like spontaneous activity in normal hearing modifies responses to acoustic stimuli.


Conditioner (5000 pulses/s)

Conditioner plus train of unmodulated pulses (1000 pulses/s)

Conditioner plus train of modulated pulses

Figure 4. Diagram of conditioner pulses and combinations of conditioner pulses with stimulus pulses.

We, in collaboration with the team at the University of Iowa, have begun studies to evaluate the use of conditioner pulses with cochlear implants. Studies to date have included recordings of intracochlear evoked potentials in our laboratory (Wilson and Finley, 1998; also see Rubinstein *et al.*, 1998b), in which effects of conditioner pulses on responses to stimulus pulses have been measured. Two experiments have been conducted with Ineraid subject SR2, using different types of stimuli in conjunction with various levels of the conditioning pulses. In the first experiment, unmodulated pulses presented at the rate of 1016/s were used as the stimulus (as in the middle panel of Fig. 4). The pulse duration was 33 μ s/phase and the pulse amplitude was 375 μ A. In the second experiment, the output of a single channel speech processor was used to modulate 33 μ s/phase pulses presented at the rate of 847/s, to form the stimulus (as in the bottom panel of Fig. 4). The rate of the conditioner pulses was 5081/s in both experiments. The conditioner pulses were presented during and 29 ms prior to the interval containing the stimulus pulses.

The presentation of the conditioner pulses prior to the onset of the stimulus pulses was designed to assure that the nerve would be in a state of equilibrium at the time of the first stimulus pulse.

Results from the first experiment are presented in Fig. 5. The figure shows magnitudes of intracochlear EPs for each of the 10 stimulus pulses. The parameter in the figure is the amplitude of the conditioner pulses. With no conditioner, the response to the stimulus pulses shows an alternating pattern, which probably reflects refractory properties of auditory neurons (see Wilson *et al.*, 1997a). As the amplitude of the conditioner pulses is increased, responses to the stimulus pulses become more uniform from pulse to pulse. This "smoothing" effect is consistent with the idea that the conditioner pulses act to desynchronize the nerve and produce a level of stochastic independence among neurons (also see Rubinstein *et al.*, 1998b and submitted).

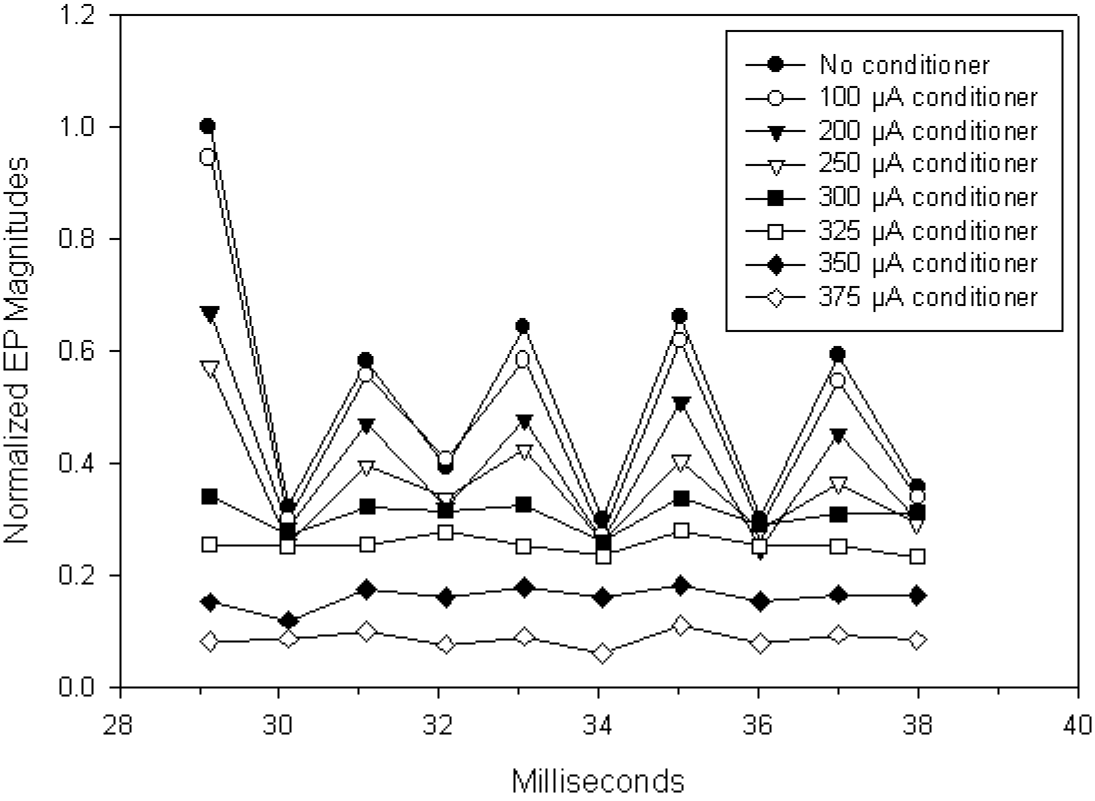


Figure 5. Effects of a 5081 pulses/s conditioner on responses to a train of 375 µA pulses presented at the rate of 1016/s. Magnitudes of intracochlear evoked potentials (EPs) for the stimulus pulses are shown. The subtraction technique described in Wilson *et al.* (1997a) was used to separate EPs following the stimulus pulses from (overlapping) EPs following the conditioner pulses. EP magnitudes are normalized to the magnitude of the EP following the first of the stimulus pulses for the "no conditioner" case. The subject, stimulating electrode, and recording electrode are the same as those specified in the caption to Fig. 2. (The present Fig. 5 is included in a manuscript submitted for publication by Rubinstein *et al.*, and is reproduced here with the permission of the authors and the journal Hearing Research.)

Figure 5 shows that the responses to the stimulus pulses are strongly affected by the conditioner pulses for conditioner pulse amplitudes of 200 µ A and higher. The responses are essentially uniform for the conditioner amplitudes of 300 µ A and higher. Increases in conditioner amplitude beyond 300 µ A produce reductions in the magnitudes of the EPs for the stimulus pulses, but do not alter the pattern of responses across pulses.

Results from the second experiment are presented in Fig. 6. This figure shows in the open squares the normalized magnitudes of intracochlear EPs for the pulses at the output of a single channel speech processor. Normalized amplitudes of the processor (stimulus) pulses are shown by the filled diamonds. The input to the speech processor for producing these stimulus pulses was the initial part of the vowel /a/, uttered by a male speaker. As in experiment 1, the conditioner pulses were presented during and 29 ms prior to the interval containing the stimulus pulses.

The four panels in the figure show patterns of neural responses to the stimulus pulses for various (uniform) amplitudes of the conditioner pulses. With no conditioner (top panel), the pattern of neural responses does not follow in detail the pattern of stimulus pulse amplitudes. Although the pattern of responses reflects the fundamental frequency of the /a/ sound, with peaks in the pattern at the first high amplitude pulse in each (approximately 10 ms) period, other features of speech stimulus do not appear to be represented. In the pitch period beginning at about 62 ms, for instance, a series of four pulses with nearly identical amplitudes is presented, followed by monotonic reductions in pulse amplitude. The responses to the first four pulses show an alternating pattern, rather than a uniform pattern, as might be anticipated from the prior recordings using unmodulated pulse trains as the stimuli (Fig. 5, responses without a conditioner). The temporal fine structure of the stimulus is not reflected in the pattern of neural responses.

In contrast, the pattern of neural responses closely approximates the pattern of stimulus pulse amplitudes with the addition of conditioner pulses, for the conditioner amplitudes of 300 and 350 μA. The neural representation of the stimulus is dramatically improved with the use of a conditioner.

Recordings of intracochlear EPs have shown that either high carrier rates or use of conditioner pulses can improve the correspondence of neural responses to stimulus modulation waveforms (Figs. 3 and 6). Both approaches probably produce spontaneous-like activity in the nerve, with at least some stochastic independence among neurons. However, the statistics and properties of the activity may be quite different between the approaches. With high-rate processors, for example, the overall level of spontaneous-like activity may well go up and down with the modulation waveforms for each channel. In contrast, use of conditioner pulses may produce a relatively uniform background of spontaneous-like activity, more like the uniform background of spontaneous activity in normal hearing. A possible disadvantage of processors using conditioner pulses is that the relatively low rates of the stimulus pulses reduce the range of frequencies that can be represented in the modulation waveforms for each channel. However, possible advantages associated with a close replication of normal spontaneous activity may offset or outweigh this limitation.

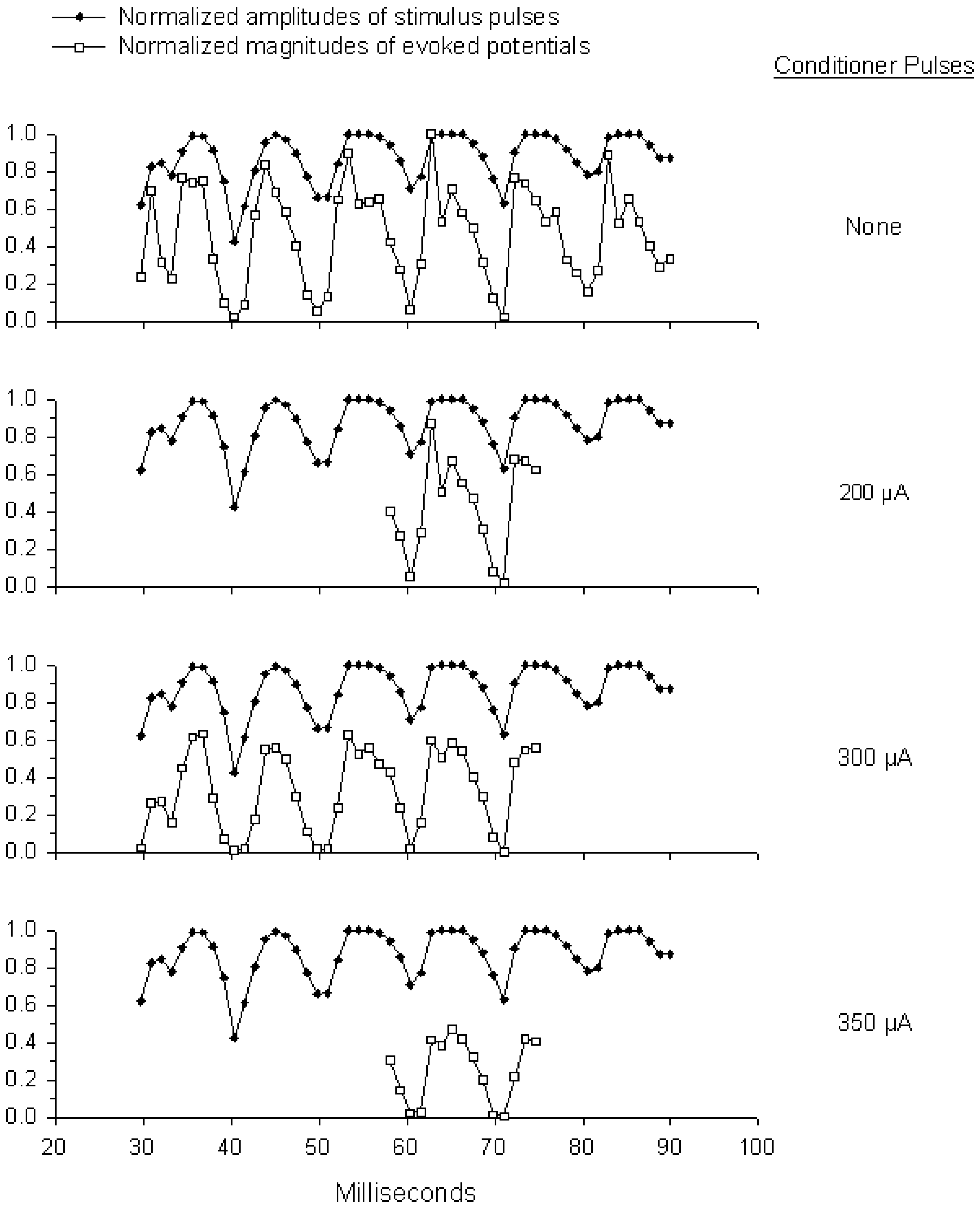


Figure 6. Pulse amplitudes (filled diamonds) and evoked potential (EP) magnitudes (open squares) for a processed speech token. Normalized values are shown, with pulse amplitudes normalized to the maximum pulse amplitude in the speech stimulus and with EP magnitudes normalized to the maximum magnitude across the four panels of the figure. The panels show effects of conditioner pulses on the patterns of neural responses to the stimulus pulses produced by the speech processor. Numbers at the right indicate the amplitude of the conditioner pulses for each panel. Pulses at the output of the speech processor were presented at the rate of 847/s and the conditioner pulses were presented at the rate of 5081/s. The subtraction technique described in Wilson *et al.* (1997a) was used to separate EPs following the speech processor pulses from EPs following the conditioner pulses. The EP magnitudes presented in the figure are those for

the speech processor pulses only. The subject, stimulating electrode, and recording electrode are the same as those specified in the caption to Fig. 2. Data are from unpublished observations by Wilson and Finley (1998).

Studies are just beginning in our laboratory to evaluate processors that use conditioner pulses. Results obtained with these processors will be compared with results obtained with high rate processors, using within-subject controls. A wide range of such processors will be tested, including processors with different amplitudes of the conditioner pulses and processors using various rates for the conditioner pulses and various rates for the stimulus pulses.

Compression functions based on physiological considerations. As indicated by recordings of intracochlear EPs for SAM pulse trains (*e.g.*, the recordings presented in the right column of Fig. 3 above), use of high carrier rates can improve the correspondence between stimulus modulation waveforms and evoked responses at the auditory nerve. Results from psychophysical studies (Wilson *et al.*, 1997c) show that such changes in neural representations are accompanied by changes in perception for some subjects, *e.g.*, pitch is scaled monotonically over a greater range of modulation frequencies with high rate carriers as compared with low rate carriers.

The correspondence between stimulus modulation waveforms and evoked responses also is improved by the use of conditioner pulses (Fig. 6). Studies are underway to evaluate effects of conditioner pulses on perception of modulation frequencies for SAM pulse trains.

The higher level of neural control provided by high-rate carriers, and through use of conditioner pulses, might be exploited to represent more complex and/or more realistic modulation signals with cochlear implants. The modulation signal used for present CIS processors (at the input to the mapping table for each channel) is a simple estimate of the envelope at the output of each bandpass filter. This estimate is derived using a rectifier followed by a lowpass filter. A better estimate might be provided with a Hilbert transform (see Oppenheim and Schafer, 1975), a more complicated signal processing technique. The relatively subtle changes in the estimates provided by the Hilbert transform might be conveyed with the use of high carrier rates or the use of conditioner pulses.

Use of high carrier rates or conditioner pulses also might allow representation of envelope signals that mimic stages of signal processing in the normal cochlea. These stages include a fast-acting and substantial compression in responses of the basilar membrane to acoustic stimuli (Johnstone *et al*., 1986; Moore *et al*., 1997; Ruggero, 1992), and a noninstantaneous compression at the synapses separating inner hair cells and the terminations of type I fibers in the auditory nerve (see, *e.g*., Meddis, 1986).

Models of these stages of signal processing in the normal cochlea could be substituted for the envelope detector and mapping table in CIS and other processors. Such substitution of a physiologically-based (and noninstantaneous) envelope extraction and mapping function might well improve the mimicking of normal auditory processing. This in turn might improve the perception of onsets of important speech sounds, the across-channel representation of envelope cues, and the representation of dynamic and steady-state intensities of stimuli. An improved representation of across-channel cues could be especially helpful for attending to a primary speech signal in the presence of interfering noise (see, *e.g*., Hall *et al*., 1984).

The key for entertaining application of these new types of modulation signals and compression functions is the improved correspondence between stimulus modulation waveforms and evoked responses obtained with high carrier rates or with conditioner pulses. The high frequency components in the more complex and/or more realistic modulation waveforms could not be well represented with conventional CIS processors. We plan to evaluate in the near future use of such modulation waveforms in conjunction with high-rate CIS processors.

Coordinated stimulation of bilateral implants

Two possibilities for coordinated stimulation of bilateral implants are (1) to represent interaural timing and amplitude cues and (2) to assign a single set of channels across the two sides. The first possibility is aimed at restoration of sound lateralization abilities and the second possibility is aimed at reduction of electrode interactions.

Recent results from studies in our laboratory with a subject implanted with Nucleus CI22 devices on both sides have provided encouragement for possibility 1 above (Lawson *et al.*, 1998). As shown in Fig. 7, this subject (NU4) is able to lateralize a sound image for pitch and loudness matched pairs of electrodes on the two sides, with differences in interaural timing as small as 150 μ s. Although this sensitivity is not as good as that of listeners with normal hearing (10 to 80 μ s, depending on the subject and the type of stimulus used, see Gabriel *et al.*, 1992, and Moore, 1989), it is much better than the sensitivities measured for other subjects with bilateral implants (*e.g.*, just noticeable differences of a millisecond or greater for the two subjects studied by van Hoesel *et al.*, 1993, and by van Hoesel and Clark, 1995 and 1997). A 150 μ s time delay corresponds to a 15 degree angle of incidence for a sound source with respect to the midline. This degree of sensitivity might be useful in situations involving directionally distinct multiple speakers or between a single speaker and various sources of interfering noise.

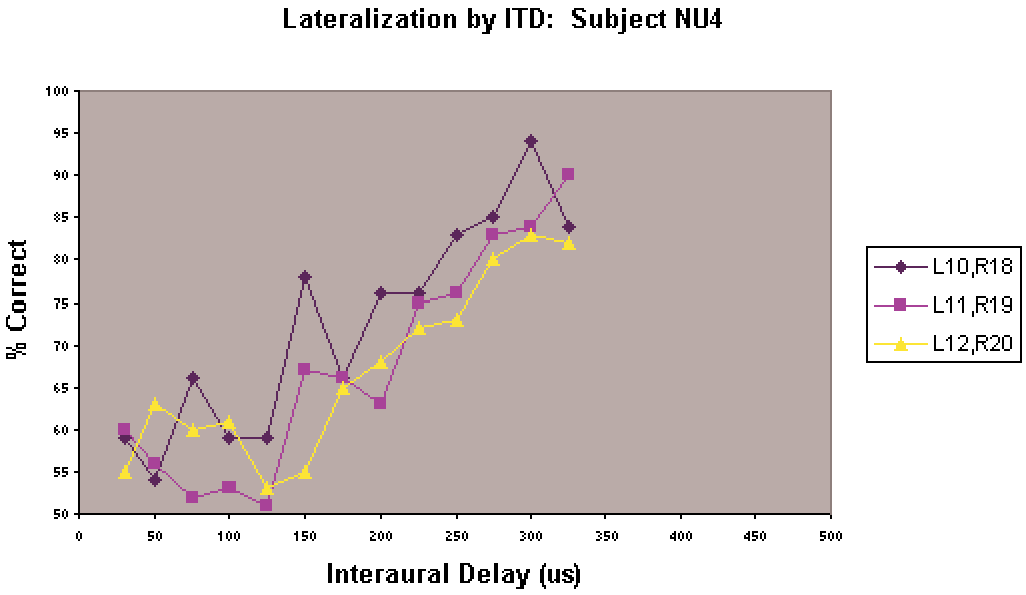


Figure 7. Percentage of lateralization judgments corresponding to the implant receiving the earlier stimulus, for bilateral implant subject NU4. Separate experiments were conducted for each of three pairs of electrodes on the two sides. Stimulation of either electrode in each pair produced a pitch and loudness that were indistinguishable from the pitch and loudness produced by stimulation of the other electrode (on the contralateral side). The stimuli were 50 ms bursts of pulses, with the pulse duration of 80 μ s/phase and the pulse rate of 480/s. (The present Fig. 7 was originally published in Lawson *et al.*, 1998, and is reproduced here with the permission of the authors and the American Journal of Otology.)

This subject also exhibits excellent sensitivity to differences in interaural amplitude. The sensitivity to a reduction in amplitude for one of the two electrodes in each of the three pairings indicated in Fig. 7 was 4 clinical units or better. For one of the pairings the sensitivity was 1 clinical unit, which corresponded to approximately 1/75th of the dynamic range (in terms of equivalent current levels) from threshold to most comfortable loudness for the electrodes in that pair.

An ability to lateralize sounds may be restored for some patients through representation of interaural timing and amplitude differences. This might be done in a variety of ways. We and others are evaluating such possibilities. Our plans include ongoing studies with subject NU4, with several subjects implanted with COMBI 40+ devices on both sides (in collaboration with investigators at the Julius-Maximilians Universität in Würzburg and at the University of Innsbruck and the Med El company in Innsbruck), and with as many as ten subjects implanted with CI24M devices on both sides (in collaboration with investigators at the University of Iowa). Hopefully, at least some of the subjects with the Med El and CI24M implants also will show good sensitivities to interaural timing and amplitude differences. (We should be able to determine, with this number of subjects, whether such sensitivities are rare or common among recipients of bilateral implants.)

An alternative way to exploit bilateral implants is to distribute one set of channels across the two sides, as mentioned above. With such distribution the spatial and/or temporal separation between active electrodes could be doubled for a given number of channels, compared with that for a unilateral implant and the same number of channels. The increased spacing on each side with bilateral implants should produce reductions in interactions among the electrodes. However, interaural timing and amplitude differences would be sacrificed in such a processor. It may be that representation of interaural differences will confer a greater advantage for some patients, whereas bilateral distribution of channels will confer a greater advantage for others. We would expect that patients with poor sensitivities to the interaural differences might fall into this second category.

Concluding remarks

Only a small subset of the possibilities for improving the performance of cochlear implants has been presented in this chapter. We are at an exciting point in the development of implant systems, with the advent of new electrode designs and new signal processing techniques. The likely increases in the number of effective channels with the new electrode designs may be especially helpful in listening to speech in noise. The likely increases in stochastic independence among neurons produced with new signal processing techniques may well extend for some patients the range of frequencies that can be perceived as different pitches within channels, and may well improve the naturalness of musical, speech and other sounds for most patients. Use of noninstantaneous compression functions, that mimic those of normal hearing, also may produce improvements in the naturalness and intelligibility of speech and in the naturalness and dynamics of music. In addition, coordinated stimulation of the two sides for recipients of bilateral implants may restore sound lateralization abilities and the signal-to-noise advantages supported by such abilities. The recent capability to record intracochlear evoked potentials for clinically relevant (low amplitude) stimuli has introduced a new era in speech processor design, in which the goal is to produce desired patterns of response at the auditory nerve rather than merely desired patterns of stimulation at the implanted electrodes. Implants of the near future are likely to be much better than those of today.

Acknowledgments

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Kiefer, J., von Ilberg, C., Rupprecht, V., Huber-Egener, J., Baumgartner, W., Gstöttner, W., & Stephan, K. (1997, May). Optimized speech understanding with the CIS-speech coding strategy in cochlear implants: The effect of variations in stimulus rate and numbers of channels. Presented at the Vth International Cochlear Implant Conference, New York, NY.

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Rubinstein, J. T., Wilson, B. S., & Abbas, P. J. (1998b, June). Restoration of acoustic-like patterns of auditory nerve activity with electrical stimulation. Presented at the 4th European Symposium on Paediatric Cochlear Implantation, 's-Hertogenbosch, The Netherlands. (Poster 44)

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Wilson, B. S., Finley, C. C., Zerbi, M., Lawson, D. T., & van den Honert, C. (1997b). Speech processors for auditory prostheses. Seventh Quarterly Progress Report, NIH project N01-DC-5-2103. Neural Prosthesis Program, National Institutes of Health, Bethesda, MD.

Wilson, B. S., Zerbi, M., Finley, C. C., Lawson, D. T., & van den Honert, C. (1997c). Speech processors for auditory prostheses. Eighth Quarterly Progress Report, NIH project N01-DC-5-2103. Neural Prosthesis Program, National Institutes of Health, Bethesda, MD.

III. Reporting activity for NIH project N01-DC-5-2103

Reporting activity for this project, covering the period of July 31, 1995 through September 29, 1998, included 11 quarterly progress reports, this final report, 6 published papers (two of these reporting results from our prior project but published during the period of the the present project), 1 paper in press, 2 papers submitted for publication, chapters in 2 books scheduled for publication, 28 invited presentations (including a keynote speech at the recent *4th European Symposium on Paediatric Cochlear Implantation*, held in ‘s-Hertogenbosch, The Netherlands, June 14-17, 1998), and 3 additional presentations. In addition, Finley served as the Co-Chair for the *1997 Conference on Implantable Auditory Prostheses*, Wilson served as the Chair for sessions at three international conferences, and Lawson served as a Co-Chair for a focus group at the *1997 Conference on Implantable Auditory Prostheses*. In the great majority of cases all expenses were reimbursed for the invited presentations, allowing us to present project results at no cost to the project.

Publications

Wilson BS, Lawson DT, Zerbi M, Finley CC, Wolford RD: New processing strategies in cochlear implantation. American Journal of Otology 16: 669-675, 1995. (This paper reports results from our prior "speech processors" project, but was published during the period of the present project.)

Wilson BS, Lawson DT, Zerbi M: Advances in coding strategies for cochlear implants. Advances in Otolaryngology – Head and Neck Surgery 9: 105-129, 1995. (This paper reports results from our prior "speech processors" project, but was published during the period of the present project.)

Wilson BS: The future of cochlear implants. British Journal of Audiology 31: 205-225, 1997 (invited guest editorial in celebration of the 30th anniversary of the journal).

Lawson DT, Wilson BS, Finley CC, Zerbi M, Cartee LA, Roush PA, Farmer JC Jr, Tucci DL: Cochlear implant studies at Research Triangle Institute and Duke University Medical Center. Scandinavian Audiology 26 (Suppl. 46): 50-64, 1997.

Wilson BS, Finley CC, Lawson DT, Zerbi M: Temporal representations with cochlear implants. American Journal of Otology 18: S30-34, 1997.

Wilson BS, Rebscher S, Zeng F-G, Shannon RV, Loeb GE, Lawson DT, Zerbi M. Design for an inexpensive but effective cochlear implant. Otolaryngol Head Neck Surg 118: 235-241, 1998.

Lawson DT, Wilson BS, Zerbi M, van den Honert C, Finley CC, Farmer JC Jr, McElveen JT, Roush PA: Bilateral cochlear implants controlled by a single speech processor. American Journal of Otology, in press.

Lawson DT, Wilson BS, Zerbi M, Roush PA, van den Honert C, Finley CC, Tucci DL, Farmer JC Jr: Within-patient comparisons among processing strategies for cochlear implants. American Journal of Otology, submitted.

Rubinstein JT, Wilson BS, Finley CC, Abbas PJ: Pseudospontaneous activity: Stochastic independence of auditory nerve fibers with electrical stimulation. Hearing Research, submitted.

Wilson BS: New directions in implant design. To be published as a chapter in *Cochlear Implants*, edited by SB Waltzman and N Cohen, Thieme Medical and Scientific Publishers, New York, NY.

Wilson BS: Cochlear implant technology. To be published as a chapter in *Cochlear Implants: Principles, Practice and Pitfalls*, by J Niparko, DF Boatman, KI Kirk, AM Robbins, DL Tucci and BS Wilson, Lippincott-Raven Publishers, Philadelphia, PA. (Wilson also is a contributor to several other chapters in the book.)

Invited presentations

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

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

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

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

Lawson DT: Electrical stimulation of the auditory system. *International Course on Hearing Aids, Vibrotactile Devices and Cochlear Implants in Profound Hearing Loss in Children*, Bolzano, Italy, December 13-16, 1995.

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

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

Wilson BS, Finley CC, Lawson DT, Zerbi M: Temporal representations with cochlear implants. *Third European Symposium on Paediatric Cochlear Implantation*, Hannover, Germany, June 6-8, 1996.

Wilson BS: Suggestions for the future development of cochlear implants. *Third European Symposium on Paediatric Cochlear Implantation*, Hannover, Germany, June 6-8, 1996. (This presentation was the penultimate summary lecture of the Symposium, preceding the concluding lecture by Professor Lenarz, General Chair.)

Wilson BS: Progress in the development of speech processing strategies for cochlear implants. University of Iowa, Department of Otolaryngology – Head and Neck Surgery, Iowa City, IA, July 29, 1996.

Wilson BS, Lawson DT: Speech processors for auditory prostheses. *27th Annual Neural Prosthesis Workshop*, Bethesda, MD, October 16-18, 1996.

Wilson BS: High rate coding strategies. *International Workshop on Cochlear Implants,* Vienna, Austria, October 24-25, 1996.

van den Honert C: Microstimulation of auditory nerve for estimating cochlear place of single fibers in a deaf ear. University of Iowa, Department of Otolaryngology – Head and Neck Surgery, Iowa City, IA, April 21, 1997

Lawson DT: Cochlear implant research. *Duke University Medical Center Symposium on "Excellence in Otolaryngology – Head and Neck Surgery,"* Durham, NC, April 25-26, 1997.

Wilson BS: Possibilities for the further development of speech processor designs. *Vth International Cochlear*

Implant Conference, New York, NY, May 1-3, 1997.

Lawson DT, Wilson BS, Zerbi M, Roush PA, van den Honert C, Finley CC, Tucci DL, Farmer JC Jr: Within patient comparisons among processing strategies for cochlear implants. *130th Annual Meeting of the American Otological Society*, Scottsdale, AZ, May 10-11, 1997 (lecture presented by Wilson).

Lawson DT, Wilson BS, Zerbi M, van den Honert C, Finley CC, Farmer JC Jr, McElveen JT, Roush PA: Bilateral cochlear implants controlled by a single speech processor. *130th Annual Meeting of the American Otological Society*, Scottsdale, AZ, May 10-11, 1997.

Wilson BS: Design of speech processors for cochlear prostheses. Johns Hopkins University, Department of Biomedical Engineering, May 30, 1997.

Wilson BS, Finley CC, Zerbi M, Lawson DT, van den Honert C: Representations of temporal information in responses of the human auditory nerve to electrical stimuli. *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-21, 1997.

Finley CC, Wilson BS, van den Honert C: Fields and EP responses to electrical stimulation: Spatial distributions, electrode interactions and regional differences along the tonotopic axis. *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-21, 1997.

Lawson DT, Wilson BS, Zerbi M, Finley CC: Design differences and parametric adjustments among CIS and related processors. *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-21, 1997.

Wilson BS: Speech processors for auditory prostheses. *28th Annual Neural Prosthesis Workshop*, Bethesda, MD, October 15-17, 1997.

Wilson BS: Review of studies at RTI with recipients of bilateral cochlear implants. University of Iowa, Department of Otolaryngology, Head & Neck Surgery, Iowa City, IA, January 27, 1998.

Lawson DT: Measures of thresholds in the context of multichannel stimulation and application of those measures in the fitting of speech processors for cochlear implants. University of Iowa, Department of Otolaryngology, Head & Neck Surgery, Iowa City, IA, February 20, 1998.

Wilson BS, Pierschalla M: Development of cochlear prostheses. Invited poster, NIH Bioengineering Symposium, *Building the Future of Biology and Medicine*, Bethesda, MD, Feb. 27 and 28, 1998. (This was one of five invited poster presentations to represent bioengineering research supported by the NIDCD.)

Wilson BS: New directions in implant design. Keynote speech, *4th European Symposium on Paediatric Cochlear Implantation*, ‘s-Hertogenbosch, The Netherlands, June 14-17.

Wilson BS: Possibilities for improving the performance of cochlear prostheses. University of Innsbruck, Innsbruck, Austria, June 18, 1998.

Lawson DT: Future trends in cochlear implant processing strategies. *Annual Meeting of the British Cochlear Implant Group*, Manchester, England, September 3-4, 1998.

Additional presentations

Finley CC, Wilson BS: Spatial distribution of stimulus fields and intracochlear evoked potentials as recorded from unstimulated electrodes of implanted cochlear prostheses. *Nineteenth Midwinter Research Meeting, Association for Research in Otolaryngology*, St. Petersburg Beach, FL, February 4-8, 1996. (Abstract is published in the ARO Abstracts for this meeting, page 108.)

Tucci DL, Roush PA, Lawson DT, Wilson BS, Zerbi M: Modified percutaneous Nucleus cochlear implant: Surgical experience and speech recognition results. *Vth International Cochlear Implant Conference*, New York, NY, May 1-3, 1997.

Rubinstein JT, Wilson BS, Abbas PJ: Restoration of acoustic-like patterns of auditory nerve activity with electrical stimulation. *4th European Symposium on Paediatric Cochlear Implantation*, ‘s-Hertogenbosch, The Netherlands, June 14-17.

Chaired conference

Skinner MW (Chair), Finley CC (Co-Chair): *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-21, 1997.

Chaired sessions

Wilson BS: Focus group on "Speech processing." *1995 Conference on Implantable Auditory Prostheses, Pacific Grove*, CA, August 20-24, 1995.

Wilson BS: Session on "Basic science and technical aspects." *Third European Symposium on Paediatric Cochlear Implantation*, Hannover, Germany, June 6-8, 1996.

Blamey P (Discussion Leader), James C (Discussion Co-Leader), Lawson DT (Discussion Co-Leader): Focus group on "Binaural stimulation – opportunities and limitations." *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-21, 1997.

Wilson BS (Discussion Leader), Böex-Spano C (Discussion Co-Leader), Svirsky M (Discussion Co-Leader): Focus group on "Issues in speech processor design." *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-21, 1997.

Web site

With the permission and encouragement of our NIH project officers, we now routinely post our progress reports on the RTI world wide web site http://www.rti.org/capr. This site is referenced by the home page for the Neural Prosthesis Program, http://www.ninds.nih.gov/npp.

IV. Acknowledgments

The work of this project was made possible by the generous and enthusiastic participation of our subjects. They included Ineraid subjects SR2, SR3, SR9, SR10, SR14, SR15 and SR16; Nucleus percutaneous subjects NP1, NP2, NP3, NP4 and NP5; Med El COMBI 40+ subjects ME1 (unilateral implant) and ME2 (bilateral implants); and Nucleus bilateral subjects NU4 (CI22 devices on both sides) and NU5 (CI24M devices on both sides). Most of these subjects visited the laboratory multiple times, with 1 or 2 weeks for each visit. Subject SR2 did this and also has worked with us on a weekly basis (usually a half day each week) since his move to the Research Triangle area in the winter of 1997.

The project also benefited greatly from contributions by our consultants and from collaborative efforts with investigators affiliated with other institutions. The contributions and collaborative efforts have included:

- An ongoing collaboration with investigators at the Hôpital Cantonal Universitaire and the l’Ecole d’Ingénieurs de Genève in Geneva, Switzerland, and at the MEEI in Boston, in the further development and application of the Geneva/MEEI/RTI wearable speech processor.
- An ongoing and similarly productive collaboration with investigators at the University of Innsbruck and Med El

GmbH also in Innsbruck, in the further development and application of the Innsbruck/Med El/RTI wearable speech processor (also called the "CIS-LINK" processor, for use by recipients of the Ineraid implant with its percutaneous connector).
- A collaborative effort among Cochlear Corporation, Duke University Medical Center and RTI, in support of the studies with the Nucleus percutaneous subjects.
- Essential contributions by Erwin Hochmair, Otto Peter and Stefan Brill, of the University of Innsbruck, in the development of the interface system for simultaneous laboratory control of bilateral Med El COMBI 40 or COMBI 40+ implants.
- A key contribution by consultant Sigfrid Soli and his associate Michael Nilsson, of the House Ear Institute, in (a) making available for use in our laboratory a new system they have developed for evaluating possible benefits of binaural signal processing and stimulation, and (b) incorporating into that system German-language test materials for our studies with a patient from Aachen, Germany, implanted with Med El COMBI 40+ devices on both sides (subject ME2).
- Direct participation in the three weeks of studies with that patient by Stefan Brill of the University of Innsbruck (all three weeks), Joachim Müller of Julius-Maximilians-Universität in Würzburg, Germany (two weeks), and Sigfrid Soli of the House Ear Institute (one week). The contributions of these individuals made our studies with subject ME2 possible.
- Key contributions by consultant William Rabinowitz, then with the Massachusetts Institute of Technology and Massachusetts Eye and Ear Infirmary, in the design and validation of our new CV syllable test.
- Direct participation in and important contributions by Michael Dorman and Philip Loizou of Arizona State University, in the initial studies with Ineraid subject SR15. (This was one of the four subjects specifically selected for low levels of speech reception performance with her or his commercial speech processor and implant system.)
- Direct participation in and important contributions by Susan Waltzman of New York University Medical Center, in the initial studies with Ineraid subject SR16. (This was another of the subjects specifically selected for low levels of speech reception performance with their commercial speech processors and implant systems.)
- Direct participation in and important contributions by Aaron Parkinson of the University of Iowa, in studies with Ineraid subject SR14, principally to investigate alternative mapping functions and fitting procedures for CIS processors in general and for the Innsbruck/RTI "CIS-LINK" processor in particular.
- Detailed advice and inputs from Colette Böex-Spano, of the Massachusetts Eye and Ear infirmary (and formerly with the Hôpital Cantonal Universitaire in Geneva) in replicating her procedures for measures of loudness growth with increases in stimulus amplitude, and subsequent use of those measures in the design of mapping functions for CIS processors, in our laboratory. Marian Zerbi of our group traveled to Boston for several days, during which Ms. Böex-Spano graciously provided her advice and inputs.
- Direct participation in and important contributions by Philip Loizou, initially with Arizona State University and later with the University of Arkansas at Little Rock, in (a) the development of DSP software for use in studies with the Geneva/MEEI/RTI wearable speech processor and (b) evaluation of outputs produced by that processor to verify presence of intended patterns of stimulation and to verify the safety, *e.g.*, charge symmetry, of the processor outputs.
- A collaborative effort with investigators at the University of Iowa, principally Jay Rubinstein and Paul Abbas, to develop the theory and application of new processing strategies using high-rate "conditioner" pulses.
- Essential contributions by Cochlear Ltd. in the development of the interface system for simultaneous laboratory control of bilateral CI24M implants.
- A collaborative effort with investigators at the University of Iowa, principally Richard Tyler and Paul Abbas, in studies with subjects implanted at the University of Iowa with CI24M devices on both sides (studies conducted both at the University of Iowa and at the RTI).

We also have enjoyed, and benefited from, visits by Deborah Ballantyne of the Universita Degli Studi di Roma "La Sapienza," Van Harrison of Advanced Bionics Corporation, Jim Heller of Cochlear Corporation (several visits), Ingeborg Hochmair of Med El GmbH, Albert Maltan formerly with Med El Corporation in the United States and now with Advanced Bionics Corporation (multiple visits as a representative of Med El and two subsequent visits as a representative of Advanced Bionics), Darcy Ochs and others associated with Med El Corporation in the United States (multiple visits), Jim Patrick of Cochlear Ltd. (multiple visits), Russ Snyder of the University of California at San Francisco, Ron West of Cochlear Corporation, and Martin Zimmerling of the University of Innsbruck.

This and prior projects in the "speech processor" series have been part of a larger cochlear implant program founded by the Duke University Medical Center and RTI in 1985. The program has grown substantially over the years, and the interaction between and among researchers and clinicians has benefited everyone involved.

The oversight and insightful suggestions provided by Terry Hambrecht and Bill Heetderks have been of inestimable value to this and the prior projects. The quality and importance of our work have been greatly enhanced by their advice.

Many people and institutions have contributed time and other resources to the successful outcome of the project. We are both honored by and grateful for these contributions.

Appendix 1. Summary of Reporting Activity for this Quarter

The last quarter of this project included a two-month extension. Reporting activity for the extended quarter, covering the period of May 1 through September 29, 1998, included the following presentations:

Keynote speech

Wilson BS: New directions in implant design. *4th European Symposium on Paediatric Cochlear Implantation*, ‘s-Hertogenbosch, The Netherlands, June 14-17.

Invited presentations

Wilson BS: Possibilities for improving the performance of cochlear prostheses. University of Innsbruck, Innsbruck, Austria, June 18, 1998.

Lawson DT: Future trends in cochlear implant processing strategies. *Annual Meeting of the British Cochlear Implant Group*, Manchester, England, September 3-4, 1998.

Poster

Rubinstein JT, Wilson BS, Abbas PJ: Restoration of acoustic-like patterns of auditory nerve activity with electrical stimulation. *4th European Symposium on Paediatric Cochlear Implantation*, ‘s-Hertogenbosch, The Netherlands, June 14-17.