Final Report

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Speech Processors for Auditory Prostheses

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I. Introduction

The main objective of this and prior projects in the "speech processors" series at the Research Triangle Institute (RTI) has been to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, such processors represent the information content of speech in a way that it can be perceived and utilized by implant patients. An additional objective of recent projects has been to record responses of the auditory nerve to a variety of electrical stimuli in studies with patients. Results from such recordings can provide important information on the physiological function of the nerve, on an electrode-by-electrode basis, and also can be used to evaluate the ability of speech processing strategies to produce desired spatial or temporal patterns of neural activity.

Work in the project just completed has included a wide range of psychophysical, electrophysiological and speech reception studies. Many of those studies are described in our progress reports for the project (see Table 1) and in recent publications. As indicated in section II of this report, results from these and prior studies provide a foundation for the further development of cochlear implant systems.

Some specific achievements and activities of the project included

- Completion of an extensive series of studies to evaluate effects of changes in stimulus rate and envelope cutoff frequency for *continuous interleaved sampling* (CIS) processors, across many combinations of the two parameters and for four subjects
- Completion of an extensive series of studies to evaluate effects of manipulations in mapping functions for CIS processors, across many choices of power-law mapping function exponents and for five subjects
- A large advancement in our knowledge about the factor or factors underlying the high variability in outcomes with implants, through comparisons among psychophysical, electrophysiological and speech reception measures in studies with each of six Ineraid subjects, and through comparisons between psychophysical and speech reception measures in studies with each of two Clarion subjects
- Completion of a series of longitudinal studies with five Ineraid subjects, to measure performance over time following substitution of a portable CIS processor for the clinical *compressed analog* (CA) processor previously used by these subjects
- Completion of an initial series of psychophysical and speech reception studies with thirteen recipients of bilateral implants, one with Cochlear Ltd. CI22 implants on both sides, four with Cochlear Ltd. CI24M implants on both sides, two with Med El COMBI 40 implants on both sides, four with COMBI 40+ implants on both sides, one with a COMBI 40 implant on one side and a COMBI 40+ implant on the other side, and one with a short-electrode version of a COMBI 40 implant on one side and standard COMBI 40+ implant on the other side (the studies included measures of sensitivities to interaural timing and amplitude differences, and evaluation of various processing strategies designed to represent cues for sound localization or to exploit the availability of bilateral electrodes in other ways, *e.g.*, to increase the number of perceptually separable channels)
- Initiation of the above studies with an additional recipient of COMBI 40+ implants on both sides
- Initial design and evaluation of "conditioner pulses" processors, in psychophysical and speech reception studies with three subjects (see Rubinstein *et al.*, 1999)

Table 1. Authors and principal topics of the quarterly progress reports (QPRs).

Report	Topic(s)	Authors
QPR 1	Pitch discrimination among electrodes for each of three subjects with bilateral cochlear implants; Measurement of interaural timing and amplitude difference cues for those same subjects	Lawson, Zerbi and Wilson
QPR 2	Measures of performance over time following substitution of CIS for CA speech processors	Lawson, Wilson and Zerbi
QPR 3	Effects of manipulations in mapping functions on the performance of CIS processors	Wilson, Lawson, Zerbi and Wolford
QPR 4	Speech reception with bilateral cochlear implants; Update on longitudinal studies	Lawson, Wilson, Zerbi and Finley
QPR 5	Comprehensive review of strategies for representing speech information with cochlear implants	Wilson, Lawson, Wolford and Brill
QPR 6	Effects of changes in stimulus rate and envelope cutoff frequency for CIS processors	Wilson, Wolford and Lawson
QPR 7	Further studies to evaluate effects of changes in stimulus rate and envelope cutoff frequency for CIS processors	Wilson, Wolford and Lawson
QPR 8	Combined electric and acoustic stimulation of the same cochlea	Lawson, Wilson, Wolford, Brill and Schatzer
QPR 9	Binaural cochlear implant findings: Summary of initial results with eleven subjects	Lawson, Brill, Wolford, Wilson and Schatzer
QPR 10	New tools, including (a) evaluation of the TIMIT Speech Database for use in studies with implant subjects, (b) processing of speech and other sounds using head-related transfer functions, and (c) an Access database of speech processor designs and study results	Cox, Wolford, Schatzer, Wilson and Lawson
QPR 11	Further studies to evaluate combined electric and acoustic stimulation	Brill, Lawson, Wolford, Wilson and Schatzer
QPR 12	Further studies regarding benefits of bilateral cochlear implants	Lawson, Wolford, Brill, Schatzer and Wilson
QPR 13	Cooperative electric and acoustic stimulation of the peripheral auditory system – Comparison of ipsilateral and contralateral implementations	Lawson, Wolford, Brill, Wilson and Schatzer
Final Report	Summary of major activities and achievements for the project; Some likely next steps in the further development of cochlear prostheses; Summary of reporting activity for the project	Wilson, Brill, Cartee, Cox, Lawson, Schatzer and Wolford

- Recordings of intracochlear evoked potentials for a variety of stimuli and with a number of subjects, including recordings of responses to trains of unmodulated and sinusoidally-amplitude-modulated pulses presented in conjunction with conditioner pulses and recordings of responses to monophasic-like pulses (using "split phase" biphasic pulses with 3 ms between the phases, and recording responses to the first phase only)
- Continuation of studies to evaluate perception of complex tones by implant subjects, using CIS processors with different numbers of channels and with various selection criteria for inclusion of complex tone partials in each bandpass channel

- Studies with the first two in a series of patients with preserved low-frequency hearing in either the implanted or contralateral cochlea, to evaluate various strategies for combined electric and acoustic stimulation of the auditory system
- Studies with a subject having exceptionally low performance with her implant (which happened to be a Clarion device, but users of other devices also fall into this unfortunate category); the studies included measures of residual hearing in the ear contralateral to the implant, evaluation of basic psychophysical abilities with the implant such as rate and electrode scaling abilities, and evaluation of various alternative processing strategies for the implant and of combined electric and acoustic stimulation
- Development of software and hardware for support of the above studies, *e.g*., development of software for processing of speech and other sounds using head-related transfer functions, in support of the studies with recipients of bilateral cochlear implants
- Development of an Access database of processor designs and study results, to bring this information together in one place and in a format that allows rapid retrieval of designs and results on the basis of shared attributes and parameter values
- Initial development of a similar database, for evoked potential studies and results
- Initial development of new processing strategies based on detailed models of normal cochlear function, *e.g.*, the models of nonlinear filtering at the basilar membrane and associated structures by Meddis and co-workers (Meddis *et al.*, 2001; Lopez-Poveda and Meddis, 2001) and the Meddis model of nonlinear and noninstantaneous processing that occurs at the synapse between inner hair cells and Type I fibers of the auditory nerve (Meddis, 1986)
- Evaluation of the TIMIT speech database (Garofolo *et al.*, 1993) as a source of difficult test material for tests with implant patients at the high end of the performance spectrum
- Visits, and in some cases multiple visits, by Thomas Lenarz and Rolf Battmer (of the Medinzinische Hochschule Hannover, in Hannover, Germany), Jim Patrick (of Cochlear Ltd.), Chris van den Honert (of Cochlear Corp.), Jan Kiefer and Thomas Pfennigdorff (of the J.W. Goethe Universität in Frankfurt, Germany), Joachim Müller and Franz Schön (of the Julius-Maximilians Universität in Würzburg, Germany), Peter Nopp (of the Med El GmbH in Innsbruck, Austria), Raymond Mederake (of the Med El subsidiary in Starnberg, Germany), Arturs Lorens (of the Institute of Physiology and Pathology of Hearing in Warsaw, Poland), Martin O'Driscol (of the Manchester Cochlear Implant Programme, Manchester, England), Sung Kim (of Seoul National University), Sig Soli (of the House Ear Institute), Jochen Tillein (of the J.W. Goethe Universität in Frankfurt, Germany), Marcel Pok (of the Vienna cochlear implant team), and Carol Gilmer (of the University of North Carolina at Chapel Hill), among others
- A *Mini Symposium on Cochlear Implants* at RTI, held in conjunction with a concurrent set of visits to RTI by Drs. Müller, Nopp and Lorens
- Identification and recruitment of three new staff members with outstanding abilities and credentials
- Ongoing analyses of data from the above and prior studies
- Ongoing preparation of manuscripts for publication

The project also included thirteen publications, a keynote speech, two lectures as a Guest of Honor, three lectures as a Distinguished Guest Speaker, 33 additional invited presentations, eight contributed presentations, two chaired sessions, and organization and presentation of a “mini symposium” on cochlear implants at RTI. A detailed listing of reporting activity for the project is presented in section III of this report.

We are pleased to note that the project benefited greatly from contributions by our consultants and from collaborative efforts with investigators affiliated with other institutions. Principal among these contributions and collaborative efforts are

- A collaboration with investigators at the Julius-Maximilians Universität in Würzburg, Germany, for studies with recipients of bilateral cochlear implants
- A collaboration with investigators at the Johann Wolfgang Goethe Universität in Frankfurt, Germany, for studies with patients having some residual hearing preserved following an implant operation in the same ear
- Collaborative studies with investigators at the University of Iowa, including studies with recipients of bilateral cochlear implants, and development and evaluation of "conditioner pulses" processors
- An especially high level of help by consultant Marian Zerbi, continuing her efforts to develop further the monitor and interface systems for the speech reception laboratory and to train new staff in areas of her prior work as a full-time member of the RTI team
- An especially high level of help by consultant Sig Soli, in visiting us twice and providing ongoing advice for studies with recipients of bilateral cochlear implants
- An especially high level of help by consultant Chris van den Honert, particularly in the further development and use of the RTI system for recording intracochlear evoked potentials
- Assistance in various studies by many visiting investigators from other institutions, as noted in the prior list above

We also are pleased to acknowledge help from the University of Innsbruck in the design of interface systems for studies with recipients of COMBI 40 and COMBI 40+ implants, help from the Med El GmbH and Med El U.S. in making travel arrangements for patients referred to us by the Würzburg and Frankfurt teams, and help from Cochlear Corp. and Cochlear Ltd. in the design of an interface system for studies with recipients of CI24M implants on both sides. Cochlear Corp. and Cochlear Ltd. also helped make the many arrangements necessary for anticipated percutaneous connector studies at RTI with recipients of the new "modiolar hugging" electrode array offered by those companies. Members of our staff also have been aided by Dorcas Kessler and others at Advanced Bionics Corp., regarding our anticipated use of a powerful new research interface to that company's new CII implant device. Needless to say, the generosity of these people and organizations has been essential to the rate of progress and breadth of studies in the project.

A highlight of the project just completed has been recognition of our work and contributions through several awards and honors, including

- Designation of Wilson as the Guest of Honor at the *5th International Cochlear Implant Workshop* and the *1st Auditory Brainstem (ABI) Workshop*, held in Würzburg, Germany, June 30 through July 4, 1999
- Many invited presentations at national and international conferences
- Designation of Lawson as a Distinguished Guest Speaker at the *4th International Surgical Workshop on Aesthetic Rhinoplasty, Middle Ear Surgery, and State of the Art Symposium*, held in Mumbai, India, November 15, 2000, and at the *International Ear Surgery Workshop and Millennium State of the Art Symposium*, held in Indore, India, November 17, 2000
- Naming of Wilson to the inaugural editorial board of *Cochlear Implants International*, the first international, peer-reviewed journal devoted to the field of cochlear implants
- Designation of Wilson as a Guest of Honor for the *Wullstein Symposium*, held in Würzburg, Germany, April 26-30, 2001. (This symposium included the *2nd Conference on Bilateral Cochlear Implantation and Signal Processing*, the *6th International Cochlear Implant Workshop*, and the *2nd Auditory Brainstem Implant (ABI) Workshop.*)

- Designation of Wilson as a keynote speaker for the *6th European Symposium on Paediatric Cochlear Implantation*, Las Palmas, Canary Islands, February 24-27, 2002
- Designation of Wilson as a keynote speaker for the *7th International Cochlear Implant Conference*, to be held in Manchester, England, September 4-6, 2002

Introduction to the remainder of this report

Section II of this report is based on a manuscript in review (Wilson *et al.*, in review), outlining some likely next steps on the further development of cochlear implant systems. The section includes summaries of results from many of the studies conducted in this project, as of the fall of 2001. Presentations of subsequent results may be found in Quarterly Progress Reports 12 and 13.

In addition to the members of the RTI team, authors for the above manuscript include Joachim M. Müller and Franz Schön of the Julius-Maximilians Universität in Würzburg, Germany; Richard S. Tyler of the University of Iowa in Iowa City, IA; and Jan Kiefer, Thomas Pfennigdorff and Wolfgang Gstöttner of the Johann Wolfgang Goethe Universität in Frankfurt, Germany (Thomas Pfennigdorff now is with a private ENT practice in Offenbach am Main, Germany). Each of these people made major contributions to the described studies. Drs. Müller, Schön and Tyler contributed to the studies involving bilateral cochlear implants, and Drs. Kiefer, Pfennigdorff and Gstöttner contributed to the studies involving combined electric and acoustic stimulation of the peripheral auditory system.

Much of the work in this project was devoted to studies with recipients of bilateral cochlear implants. Those studies are only referenced in section II. Additional information about them is presented in another manuscript in review (Lawson *et al.*, in review) and in Quarterly Progress Reports 1, 4, 9 and 12.

As noted above, section III provides a detailed listing of reporting activity for the project and Appendix 1 provides a detailed list of achievements and activities for the project. Appendix 2 provides a summary of reporting activity for the final quarter (quarter 14) of the project.

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II. Some likely next steps in the further development of cochlear prostheses

Although enormous progress has been made in the development of cochlear prostheses, much remains to be done. Patients with the best results still do not hear as well as listeners with normal hearing, especially in challenging situations such as speech presented in competition with noise or other talkers. In addition, some patients still do not enjoy much benefit from implants, even with the current speech processing strategies and electrode arrays.

Our present thinking about the most promising directions for the further development of implant systems was presented in one of the invited lectures at the recent *2001 Conference on Implantable Auditory Prostheses* (Wilson *et al.*, 2001), in the final session on "Integrative studies, insights, and speculation." In additional talks we also presented findings to date from studies at the Research Triangle Institute (RTI) with recipients of bilateral cochlear implants (Lawson *et al.*, 2001) and with a subject having a partially inserted electrode array and preserved residual low-frequency hearing (Brill and Lawson, 2001). The latter studies included evaluation of combined electric and acoustic stimulation of the same cochlea and measures of simultaneous masking with the two modes of stimulation, to assess possible interactions.

As noted in the presentation by Wilson *et al.*, we regard the following as the most promising directions:

- Combined electric and acoustic stimulation of the same cochlea for patients with preserved low-frequency hearing
- Use of bilateral cochlear implants
- Further characterization and application of new and higher levels of neural control with implants
- A closer mimicking of processing in the normal cochlea, made possible with the new levels of neural control
- Continued work to identify factors that are correlated with outcomes across patients
- Applications of new knowledge about such factors, to help close the persistently large gap between the poorest and best performances achieved with implants

In the sections below we address each of these possibilities. We also offer some concluding remarks at the end of this review.

Combined electric and acoustic stimulation

We and others have begun work to evaluate various strategies for combined electric and acoustic stimulation (EAS) of the same cochlea. Results to date from studies conducted at RTI, the J.W. Goethe Universität in Frankfurt, Germany, and the University of Iowa were reported at the *2001 Conference* (Abbas *et al.*, 2001; Brill and Lawson, 2001; Kiefer *et al.*, 2001; Tillein *et al.*, 2001; Turner and Gantz, 2001; Wilson *et al.*, 2001). Earlier reports include those by Lawson *et al.* (2000) and von Ilberg *et al.* (1999).

The situation for combined EAS is illustrated in Fig. 1. An intracochlear electrode array is only partially inserted, to minimize any threat to apical regions of surviving hair cells and corresponding residual low-frequency hearing. Electrode arrays have been inserted to a 20 mm depth in a series of patients implanted by surgeon Jan Kiefer in Frankfurt, and to a 6 or 10 mm depth in a series implanted by surgeon Bruce Gantz in Iowa City. Residual hearing was fully or

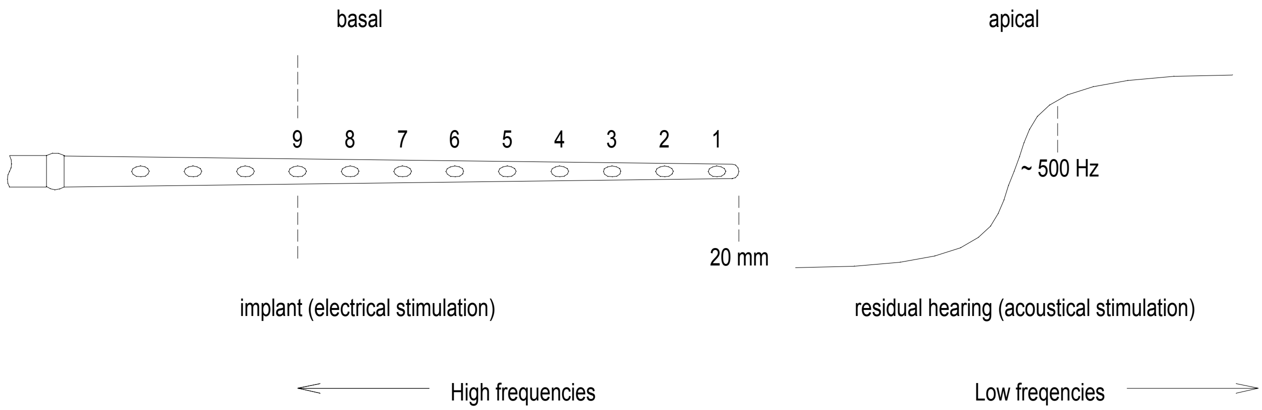

Fig. 1. Combined electric and acoustic stimulation of the same cochlea.

substantially preserved in 7 of the 9 patients implanted thus far by Dr. Kiefer and in all four of the patients implanted thus far by Dr. Gantz.

Studies with subject ME6. Our studies to date have been conducted with one of the Frankfurt patients, subject ME6. Key investigators in the studies included members of the RTI and Frankfurt teams.

Details about this subject and the initial studies with her are presented in Lawson *et al.* (2000). In broad terms, she presents a picture like that in Fig. 1. She has a Med El COMBI 40+ implant inserted to a depth of 20 mm. Her residual hearing in that ear was not affected by the operation. She has a "corner audiogram," with a 40-45 dB loss for frequencies at and below 500 Hz, and with little or no sensitivity to acoustic stimuli at higher frequencies.

Subject ME6 has returned to our laboratories since the initial studies, described in Lawson *et al.* Results from the most-recent studies are presented in Fig. 2. Two important aspects of these results are (1) a tremendous synergy of electric plus acoustic stimulation for this subject when listening to speech in noise and (2) a dramatically reduced sensitivity to the effects of increasing noise when using both modes rather than electric stimulation only.

The second aspect can be seen most clearly in the middle row of the figure, and for the CUNY sentences presented in quiet and at the speech-to-noise ratios (S/Ns) of +10 and +5 dB. Scores for recognition of the sentences in quiet approximate 100 percent correct for either electric stimulation only or for the combination of electric plus acoustic stimulation (scores are about 92 percent in both conditions). The addition of noise at the tested S/Ns produces a precipitous decrement in scores for the former, but only a shallow drop for the latter. At the relatively adverse S/N of +5 dB, the score for electric stimulation only is about 2 percent correct, whereas the score for the combination is about 58 percent correct. Such a drop in scores with electrical stimulation only is typical of findings with implant patients, while the excellent noise immunity enjoyed by this patient with combined electric and acoustic stimulation stands in sharp contrast to that pattern. (In fact, the noise immunity observed in the studies with this subject far exceed

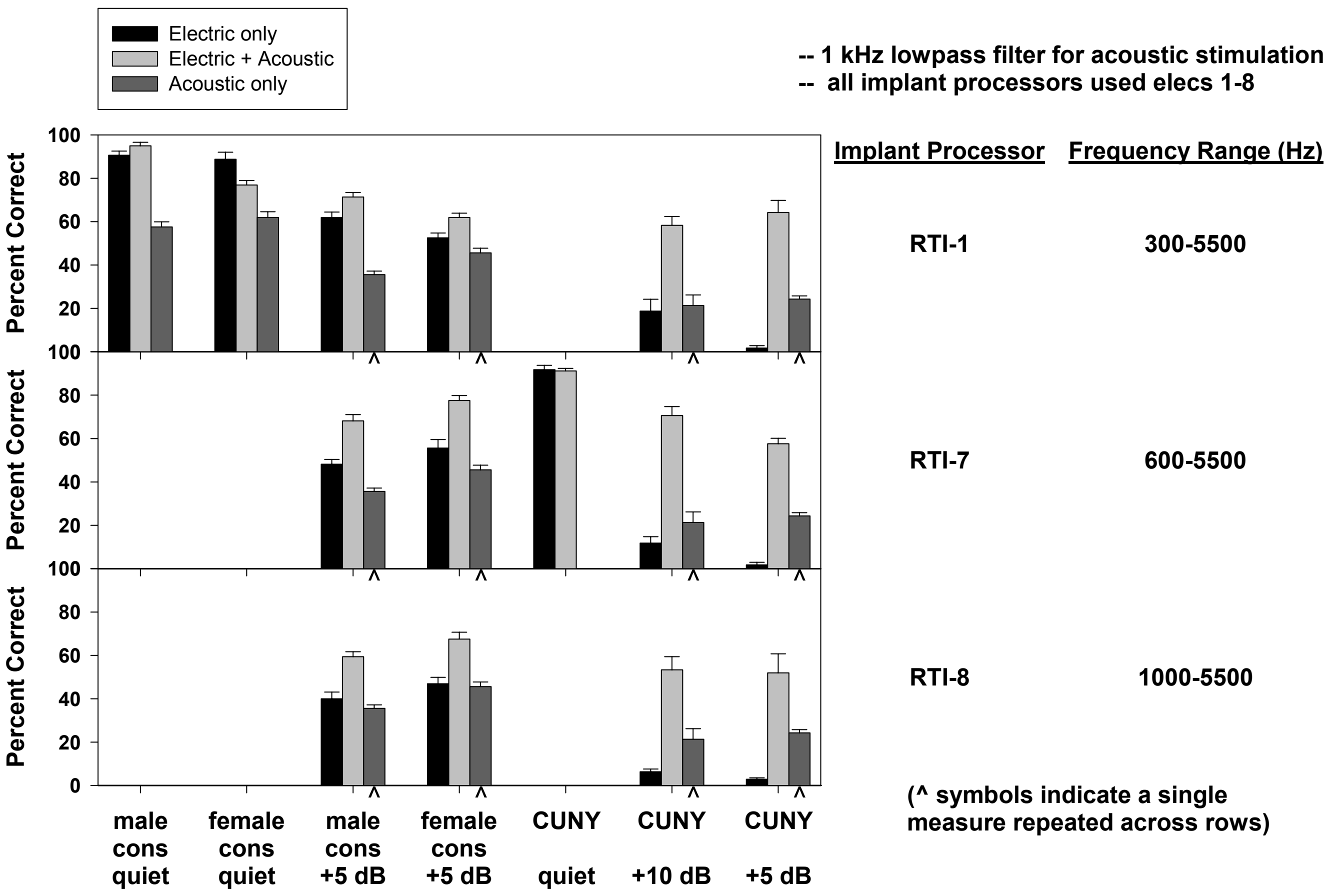

Fig. 2. Results from studies with subject ME6, who had a deliberately short insertion of a Med El COMBI 40+ electrode (to 20 mm) and preserved residual hearing at and below 500 Hz. Speech reception scores are presented for electric stimulation only (through the implant), for acoustic stimulation only (with a calibrated earphone whose input was lowpass filtered at 1 kHz), and for combined electric and acoustic stimulation. Processors used in conjunction with the implant represented different overall ranges of frequencies in the spans of their bandpass filters. A continuous interleaved sampling (CIS) strategy was used for each of these processors. The speech tests included identification of consonants in an /a/-consonant-/a/ context, for both male and female talkers (male cons and female cons, respectively). The tests also included recognition of the City University of New York (CUNY) sentences. CCITT (Consultative Committee for International Telephone and Telegraph) speech-spectrum noise was used for the conditions involving presentations of speech in competition with noise. The error bars in the figure show standard errors of the means. Performance with acoustic stimulation alone was not measured for CUNY sentences in quiet, and performance with acoustic stimulation alone was evaluated only once for each of the six remaining tests. The single measures of performance with acoustic stimulation only are repeated across rows for some of the tests to facilitate comparisons with scores for other modes of stimulation. The instances of repeated presentations of a single measure are marked in the figure by the ^ symbols. Conditions without bars were not tested.

anything we have seen for unilateral cochlear implant patients not using combined EAS, including "star" patients with fully inserted electrode arrays.)

<u>Future directions.</u> Combined electric and acoustic stimulation of the same cochlea appears to be a very promising approach for improving speech reception in noise. Future studies might include (1) additional subjects, to evaluate the generality of the initial findings, and (2) tests with a wide range of processing strategies, to optimize the ways in which the two modes of stimulation are combined to provide the best noise immunity for different patients.

Future work also might include further measures of simultaneous and forward masking for acoustic and electric stimulation, to evaluate possible (constructive or destructive) interactions between the two modes of stimulation. Results from initial studies suggest that such interactions may be relatively small (see Brill *et al.*, 2001; Brill and Lawson, 2001; Tillein *et al.*, 2001; von Ilberg *et al.*, 1999), but additional measures are needed to learn whether interactions are small for all or most subjects in a larger population of subjects, and whether interactions remain small for combinations of electric and acoustic stimuli that have not been tested to date. The findings from such future studies may well suggest combinations that will minimize deleterious interactions.

Bilateral implants

Possible advantages of bilateral implants are being investigated in a growing number of laboratories and clinics. Many recent findings were reported at the *2001 Conference*. Invited presentations included those by our RTI team (Lawson *et al.*, 2001), the Boston team (Long *et al.*, 2001), by Richard van Hoesel of the Melbourne team (van Hoesel, 2001), the Iowa City team (Tyler *et al.*, 2001), and the Würzburg team (Schön *et al.*, 2001). In general, the data collected as of this writing have been highly encouraging, with many of the studied subjects showing significant benefits of bilateral stimulation.

<u>Studies at RTI</u>. We have studied 13 subjects to date, including one with Nucleus N22 implants on both sides (subject NU4), four with Cochlear Ltd. CI24M implants on both sides (subjects NU5-8), and the remainder with various combinations of Med El COMBI 40 or COMBI 40+ implants on the two sides (subjects ME2-5 and ME7-10). Key investigators in our studies have included members of the RTI, Würzburg, and Iowa teams.

A review of these studies is presented in a companion paper, in this issue of the journal (Lawson *et al.*, 2002). As described there, the studies have included measures of sensitivities to interaural amplitude and timing differences, and also speech reception measures for processors stimulating one or both implants. In broad terms, the results from the psychophysical measures demonstrated a wide range of sensitivities to interaural timing differences (ITDs), from 25 μs to milliseconds, and generally excellent sensitivities to interaural amplitude differences. Eight of the 13 subjects exhibited ITD sensitivities of 50 μs or better, indicating intact binaural auditory pathways for these subjects. Results from the speech processor evaluations demonstrated that many of the subjects benefit from bilateral stimulation, with most of the subjects enjoying a head-shadow benefit and with some subjects enjoying binaural squelch or binaural summation benefits as well. The greatest advantages of bilateral stimulation have been observed under conditions of adverse S/Ns and with different directions of incidence for the speech and noise signals.

<u>Future directions.</u> Bilateral implants provide clear benefits for many users. Such benefits are evident in our results to date, and in results obtained in other laboratories. Future studies might usefully include investigations of (1) how closely electrodes need to be matched across the two

sides to preserve good sensitivity to ITD cues and (2) whether carrier pulses need to be synchronized in some way across the two sides for optimal sound localization and speech reception results. Many additional possibilities for future studies are presented in the companion paper.

Higher levels of neural control

Recent advances in electrode and stimulus design have increased substantially the control implants can exert over spatial and temporal patterns of responses in the auditory nerve. The advances include perimodiolar electrode arrays and use of high-rate carriers or high-rate conditioner pulses.

New electrode designs. A detailed description of the new electrode designs is presented in Wilson, 2000. Aspects of the designs are illustrated here in Fig. 3. In addition to perimodiolar arrays, a renewed development of intramodiolar implants is now underway at the University of Utah (Badi *et al.*, 2001; Maynard *et al.*, 2001), in a new project within the Neural Prosthesis Program.

As noted in the paper by Wilson referenced above, the efficacy of perimodiolar electrode arrays may be limited by (1) a maximum insertion depth into the scala tympani, (2) different anatomic courses of the scala tympani and the spiral ganglion, and (3) a relatively non-differentiated "clustering" of spiral ganglion cells at about the level of the second turn of the scala tympani (ST). The inset in Fig. 3 shows these different anatomic courses (Ketten *et al.*, 1997; also see Ariyasu *et al.*, 1989). The course of the basilar membrane (and ST) is depicted in brown and the course of Rosenthal's canal (and, within it, the spiral ganglion) is depicted in blue. The spiral ganglion has 1¾ turns whereas the ST has 2¾ turns. Closer apposition of electrodes next to the medial wall of the ST may well reduce the distance between the electrodes and target ganglion cells in the basal turn, but the distance may not be substantially reduced for higher turns. In addition, stimulation by electrodes at the second turn and higher is likely to excite the cluster of cells at the apex of the spiral ganglion (not illustrated in the inset). Thus, different stimulus sites at and beyond the second turn may not address significantly different populations of neurons.

A further possible limitation of perimodiolar electrode arrays has been suggested by Frijns and coworkers (Frijns *et al.*, 2001). Results from their modeling studies have indicated that perimodiolar electrodes beyond the first turn may stimulate axons in the modiolus at lower current levels than the nearest ganglion cells. The axons are "fibers of passage," from ganglion cells and peripheral processes that innervate higher turns of the cochlea. Exclusive stimulation of such fibers at relatively low current levels would be expected to produce unintended (and tonotopically misplaced) percepts for the patient. Stimulation of both the fibers and nearby ganglion cells at higher levels would be expected to produce complex percepts, that would correspond to excitation in multiple turns of the cochlea.

Although 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 standard electrode arrays. Perimodiolar placements can increase the spatial specificity and dynamic range of stimulation at least in the basal turn. Such placements also can reduce thresholds and increase dynamic range for most or all electrodes in the array. These changes may in turn produce improvements in the speech reception performance of implant systems.

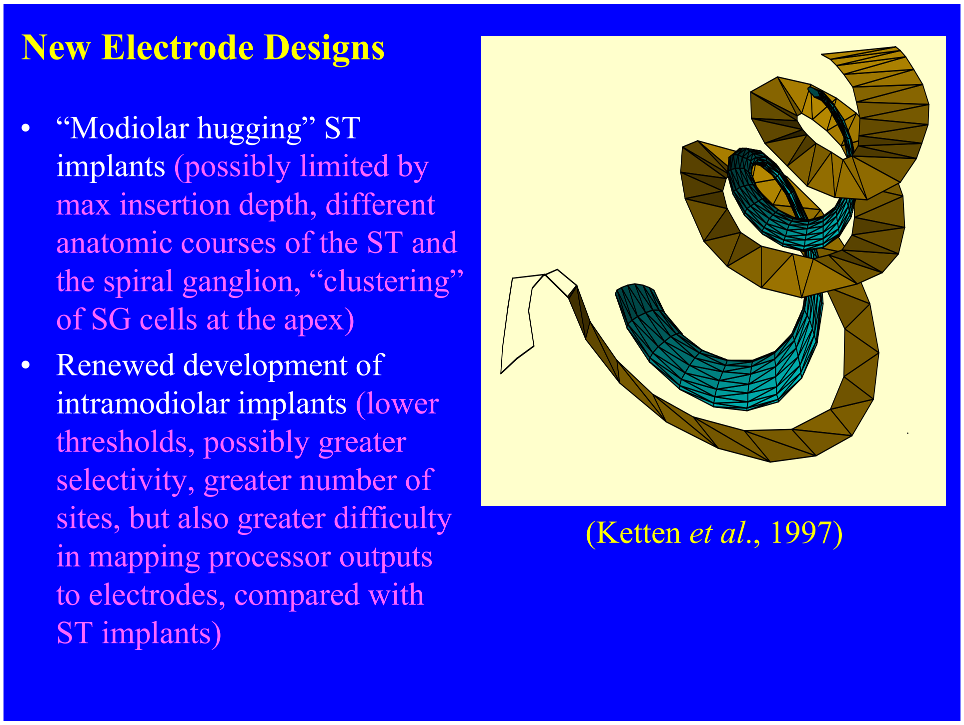

Fig. 3. New electrode designs. New designs are indicated on the left, and the anatomic courses of the basilar membrane (depicted in brown) and the spiral ganglion (depicted in blue) are indicated on the right. The diagram on the right was kindly supplied by Darlene Ketten.

An alternative approach to perimodiolar placements is to implant electrodes directly within the auditory nerve. An 8 x 10 array of pin electrodes is under development at the University of Utah, as noted above. The dimensions of the array (1.4 mm x 1.8 mm, with 200 µm spacing between adjacent pins) and graded lengths of the pins (with the longest pins at 1.5 mm) approximate the cross-sectional dimensions of the auditory nerve at the level of the basal turn, where the array is to be implanted.

An intramodiolar implant offers the likely advantages of lower currents required for threshold stimulation, greater spatial selectivity of stimulation, and a greater number of stimulus sites, compared with ST implants, including ST implants with perimodiolar placements of electrodes. On the other hand, mapping of processor channel outputs onto stimulus electrodes is likely to be far more complex with intramodiolar implants. The "roping" structure of the auditory nerve presents a complex anatomy compared with the cochleotopic organization of the spiral ganglion in Rosenthal's canal, and that complexity will without doubt complicate the fitting of speech processors used in conjunction with intramodiolar electrodes. (This problem might be addressed at least in part by placing a temporary ST implant at surgery, following placement of the intramodiolar implant. Then each electrode of the ST implant could be stimulated in sequence while recording the patterns of neural responses with all electrodes in the intramodiolar implant. The recorded activation patterns produced by stimulation with each ST electrode then could be used to construct maps of intramodiolar pin positions that correspond to the different sites of stimulation in the ST. Once the data are collected, the temporary ST implant would be withdrawn and the remainder of the surgery would be completed. The maps relating sites of stimulation in the intramodiolar implant with sites of stimulation in the temporarily-placed ST implant could greatly facilitate the fitting of a speech processor following recovery from the surgery.)

High carrier rates and high-rate conditioner pulses. In addition to greater control over the spatial patterns of neural responses provided by new electrode designs, we now have greater control over the temporal patterns as well. As discussed in detail in recent reports (Rubinstein *et al.*, 1998 and 1999b; Wilson, 2000; Wilson *et al.*, 1997a), and as illustrated here in Figs. 4 and 5, such control can be exerted either through use of high carrier rates or through use of high-rate conditioner pulses.

Effects of a change in carrier rate, from 1016 pulses/s to 4065 pulses/s, are shown in Fig. 4. Use of the higher carrier rate increases substantially the correspondence between the modulation waveform (shown in blue) and the temporal pattern of neural responses to the stimulus (shown by the black open squares), as indicated by the magnitudes of intracochlear evoked potentials recorded from a human subject. The likely mechanisms underlying this effect are discussed in Wilson *et al.*, 1997a.

Similarly, use of high-rate conditioner pulses, in conjunction with low-rate carrier pulses for the "data" or envelope signal, can increase the correspondence between modulation waveforms and patterns of neural responses. An example of this is presented in Fig. 5 (for the same subject as in Fig. 4). The amplitudes of pulses produced by a single-channel speech processor are shown by the blue diamonds and the recorded responses of the auditory nerve to those pulses are shown by the black squares. The pulse rate for the speech processor was 847/s and the pulse rate for the conditioner pulses was 5081/s.

Note that without the conditioner pulses the correspondence between the pattern of stimulation and the pattern of responses is low (top panel of Fig. 5). The pattern of responses reflects the gross periodicity of the stimulus but not the fine structure within periods. In contrast, addition of conditioner pulses at the level of 300 μA and above produces an almost perfect correlation between the modulation waveform and the pattern of neural responses (third and fourth panels of Fig. 5).

Although use of both high-rate carriers and high-rate conditioner pulses can increase the correspondence between modulation waveforms and patterns of neural responses, the detailed statistics of the responses within and among neurons are likely to be different between the two. We do not know at this time whether such differences are important for perception. Data and discussions on the statistics of neural responses to, and as modified by, conditioner-pulses stimuli may be found in Rubinstein *et al.* (1998 and 1999b) and in Litvak *et al.* (2001).

Future directions. The new and higher levels of neural control may produce improvements in the performance of conventional processing strategies for cochlear implants. For example, use of high carrier rates or high-rate conditioner pulses may improve representations of envelope information with continuous interleaved sampling (CIS) processors. Perception of that more-accurately presented information could in turn support improvements in the speech reception abilities of implant patients.

We at RTI have evaluated the use of high-rate carriers in conjunction with CIS processors, in an extensive series of studies with recipients of the Ineraid electrode array and its percutaneous connector (the initial studies in the series are described in Wilson *et al.*, 2000). In broad terms the results show that some subjects enjoy large improvements in speech reception scores with

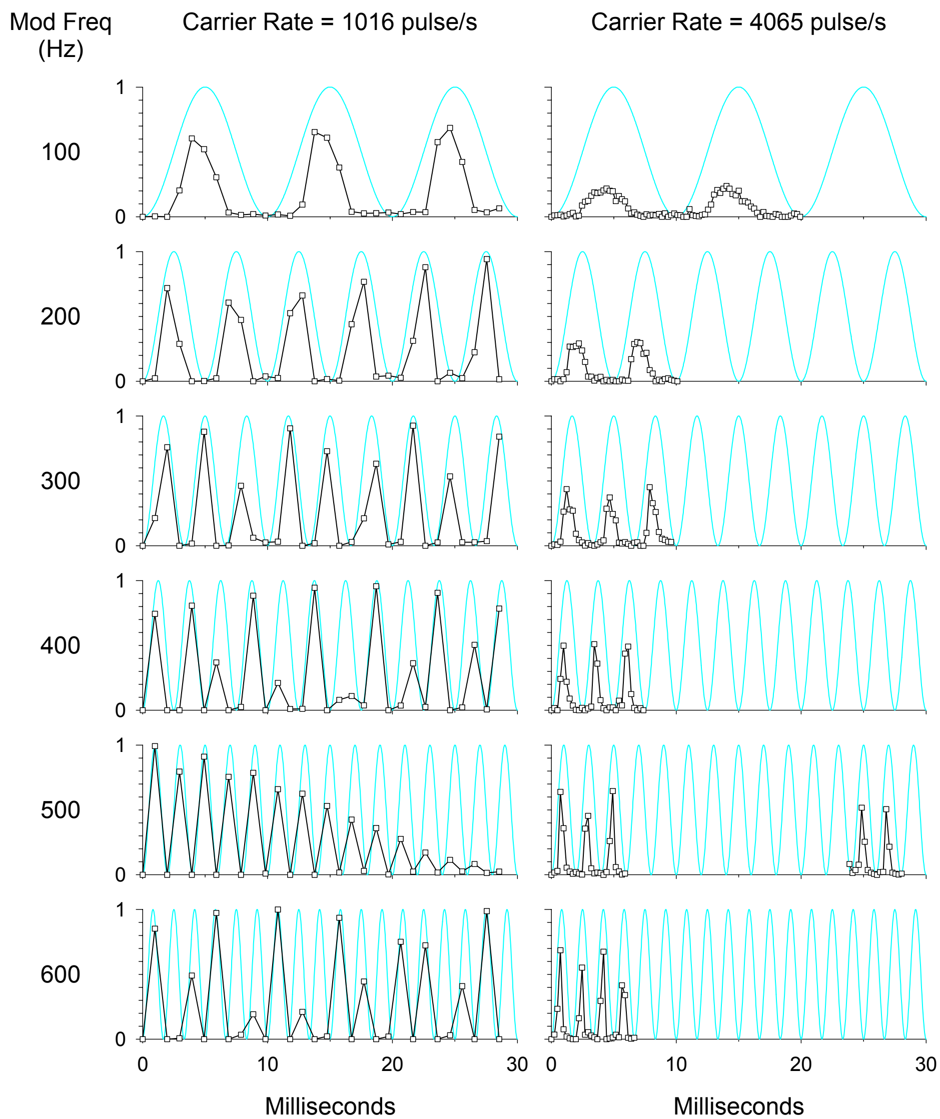

Fig. 4. Magnitudes of intracochlear evoked potentials (EPs) for sinusoidally-amplitude-modulated pulse trains, with carrier rates of 1016 and 4065 pulses/s, and with modulation frequencies ranging from 100 to 600 Hz. The EP magnitudes are normalized to the maximum value across all conditions. The modulation waveforms for the stimulus pulses are shown by the blue lines. Evoked potentials for the higher carrier rate were derived using the subtraction technique described by Wilson *et al.* (1997a). The first 30 ms of 200 ms records are shown. Data are from studies with Ineraid subject SR2. The carrier level for all conditions was 375 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.

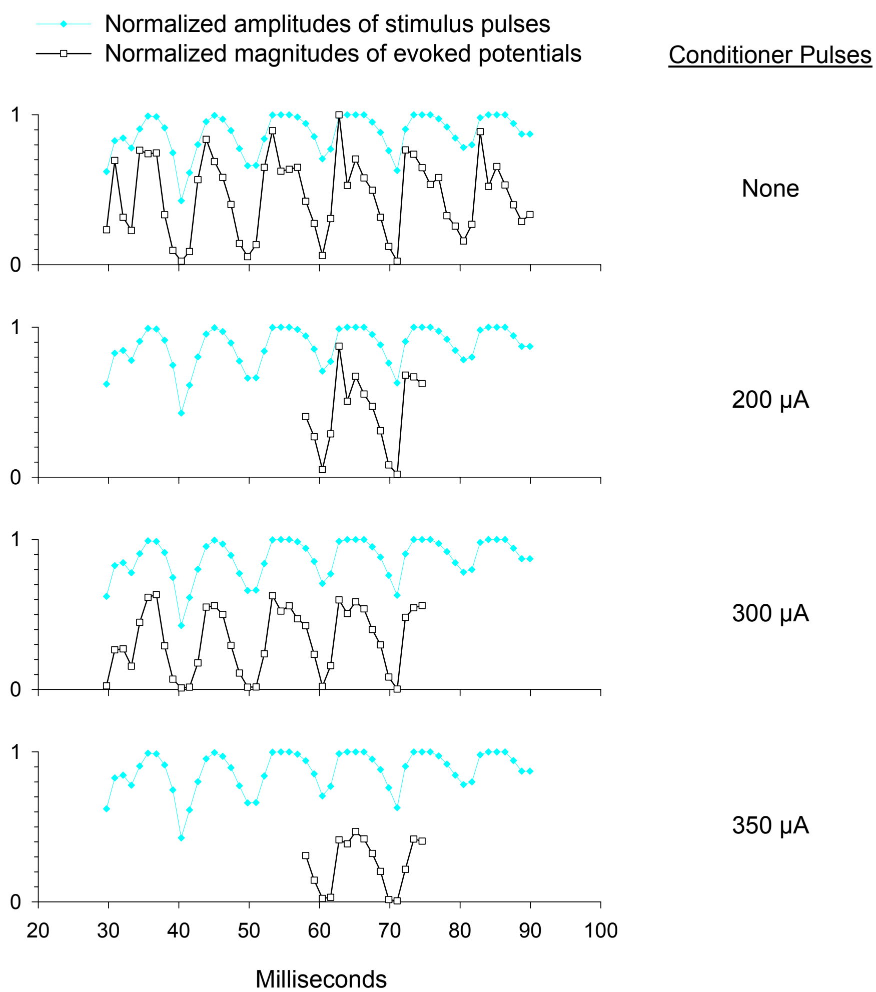

Fig. 5. Pulse amplitudes (filled blue diamonds) and evoked potential (EP) magnitudes (open black squares) for a processed speech token. Normalized values are shown, with pulse amplitudes normalized to the maximum pulse amplitude in the speech stimulus and with EP magnitudes normalized to the maximum 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, pulse duration, stimulating electrode, and recording electrode are the same as those specified in the caption to Fig. 4. The stimulus conditions of the present figure elicited comfortably loud percepts for the subject.

increases in carrier rates up to and beyond about 3000 pulses/s/channel. Other subjects show large improvements up to carrier rates of about 500 pulses/s/channel, but do not show further improvements with further increases in rate. These results, including the improvements at high carrier rates, are consistent with the findings of others, as reviewed in Wilson *et al.*, 2000 (see Figs. 17-24 and the accompanying discussion).

We also have begun studies to evaluate the use of high-rate conditioner pulses, again with users of the Ineraid device. The number of subjects studied to date is too small to make definitive statements about the efficacy of conditioner pulses. Thus far, addition of conditioner pulses has not degraded performance and in some cases has improved it. Each of the subjects has reported that processors with moderate levels of conditioner pulses sound more natural and intelligible than control CIS processors without conditioner pulses. (Higher levels of conditioner pulses are annoying.) Additional subjects and conditions are being testing in ongoing studies.

Our plans for the near future include studies with subjects using experimental implant systems, with perimodiolar electrode arrays and with percutaneous connectors, for direct electrical access to the implanted electrodes. The studies will be conducted at RTI and at Duke University Medical Center and will include

- Recordings of intracochlear evoked potentials (EPs) in the operating room, immediately before and after final placement of the electrode array by the surgeon (results from these measures will show whether the spatial specificity of neural excitation is improved with closer apposition of the array next to the medial wall and, if so, over what regions of the array and implanted cochlea)
- Recordings of intracochlear EPs following recovery from surgery to evaluate possible changes in spatial mapping over time, *e.g.*, as a result of fibrosis or changes in the electrochemistry of the electrodes after long periods of stimulation
- Evaluation of processing strategies designed to exploit the close positioning of the electrode array, *e.g.*, strategies whose optimal performance may depend strongly on independence among channels
- Evaluation of high carrier rates and of high-rate conditioner pulses in conjunction with perimodiolar implants
- Evaluation of channel-number effects with perimodiolar implants (speech reception performance may asymptote at a higher number of channels with perimodiolar implants than with standard placements, if electrode interactions are indeed reduced with the former)

Work also is underway at other centers to evaluate the use of high-rate carriers (*e.g.*, Kock and Osberger, 2001; Segel *et al.*, 2001), high-rate conditioner pulses (*e.g.*, Litvak *et al.*, 2001; Rubinstein *et al.*, 1999a), and perimodiolar electrode designs (*e.g.*, Cohen *et al.*, 2001; Gstöttner *et al.*, 2001; Jolly *et al.*, 2000; Lenarz, 2001; Lenarz *et al.*, 2001; Segel *et al.*, 2001; Tykocinski *et al.*, 2001). We should know much more within the next several years about the efficacy of each of these approaches and whether combinations of the approaches might be beneficial.

Closer mimicking of processing in the normal cochlea

Encouraging results have been reported for applications of new electrodes and/or high carrier rates in conjunction with conventional processing strategies (see above and also many of the presentations at the *2001 Conference*, *e.g.*, Lenarz *et al.*, 2001, and Segel *et al.*, 2001). A question for the future is whether the recent increases in neural control – produced with new electrodes, high carrier rates, or high-rate conditioner pulses – might be exploited to a greater extent with new types of processing strategies.

One possibility is to use the higher levels of neural control to support a closer mimicking of processing in the normal cochlea.

Aspects of normal hearing. The target for such an approach is illustrated in Fig. 6, which shows a simplified block diagram of the normal auditory periphery. The system includes highly nonlinear filtering of the input by the basilar membrane and associated structures. The nonlinearity is produced by an active feedback loop involving electromotile contractions of the outer hair cells (*e.g.*, Dallos, 1992). It is absent in many cases of sensorineural hearing loss, as a consequence of damage to or destruction of the outer hair cells.

Movements of the basilar membrane are sensed by the inner hair cells (IHCs), which excite adjacent Type I fibers of the auditory nerve through release of chemical transmitter substance in the synaptic cleft between an IHC and 10-20 Type I fibers. The IHC membrane response rectifies and compresses the signal from the basilar membrane movements, and the membrane response also attenuates strongly frequencies above about 1 kHz.

A further, noninstantaneous compression occurs at the synapse. The compression is strong and has at least two time constants, one on the order of 5 ms and the other on the order 40 ms or more.

Chemical transmitter substance is released randomly into the cleft, even in the absence of acoustic stimulation. This gives rise to random discharges in the adjacent fibers, called "spontaneous activity." The discharges are statistically independent between fibers (Johnson and Kiang, 1976), which may be important for the representation of stimuli in the collected discharge patterns of populations of neurons (*i.e.*, a set of statistically-independent neurons can represent more information than a set of neurons with highly-correlated discharge times; see Parnas, 1996, and Wilson *et al.*, 1994).

A neuron cannot respond to a stimulus for a certain amount of time after a response to a prior stimulus. Also, the threshold for stimulation is elevated for a period following the period in which the neuron cannot respond to any stimulus. These two periods are called the absolute and relative refractory periods, respectively. In auditory neurons the absolute refractory period is about 0.5 ms and the time constant of the relative refractory period is about 5 ms.

In normal hearing, neurons innervating each IHC have different sensitivities and dynamic ranges of response to changes in cleft contents. Some fibers have high thresholds and relatively wide dynamic ranges (and also have relatively low rates of spontaneous discharge), and other fibers have low thresholds and relatively narrow dynamic ranges (and also have high rates of spontaneous discharge).

The gates in the nodes of Ranvier in the fibers open and close randomly, giving rise to membrane noise. The effect of this noise is negligible in normal hearing, but may be important in electrically evoked hearing, as described in Rubinstein *et al.*, 1999b, and in Wilson *et al.*, 1994 and 1997a.

A simple model of processing in the peripheral auditory system is presented in Fig. 7. The block for modeling the responses of the basilar membrane at a particular point along the cochlear partition includes a feedback loop whose output controls the sharpness (Q factor) and gain of a bandpass filter. The time-varying tuning and gain approximates the time-varying (and amplitude dependent) tuning and gain of the basilar membrane.

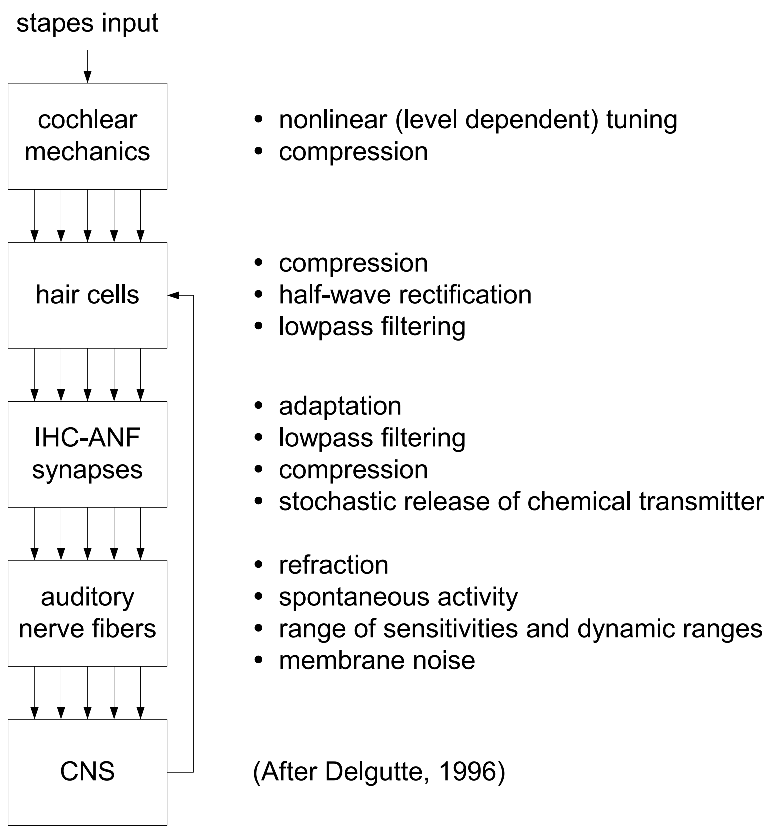

Fig. 6. Simplified block diagram of the auditory periphery. Abbreviations include “IHC-ANF” for “Inner Hair Cell – Auditory Nerve Fiber” and “CNS” for “Central Nervous System.” (Adapted from Delgutte, 1996)

The output of the time-varying bandpass filter is rectified and lowpass filtered, to reflect processing at the IHC membrane. The corner frequency of the lowpass filter is 1 kHz, matching that of the membrane response.

Signal processing at the IHC/neuron synapse is modeled with three feedback loops. The time constants of the loops approximate the time consonants of adaptation in normal hearing.

The panel to the right in Fig. 7 shows one result of the nonlinearities in the responses of the basilar membrane and associated structures – a nonlinear growth of response at the characteristic frequency (CF) or most-responsive frequency of the equivalent basilar-membrane filter for a sinusoidal input. The response at CF is approximately linear up to sound pressure levels (SPLs) of about 30 dB, but becomes highly nonlinear for SPLs between about 30 and 80 SPL.

Also shown in the panel are growth functions associated with reduced amounts of feedback and nonlinearity in the model. Those latter conditions approximate the situation in many cases of sensorineural hearing loss, in which the outer hair cells are damaged or missing. The response

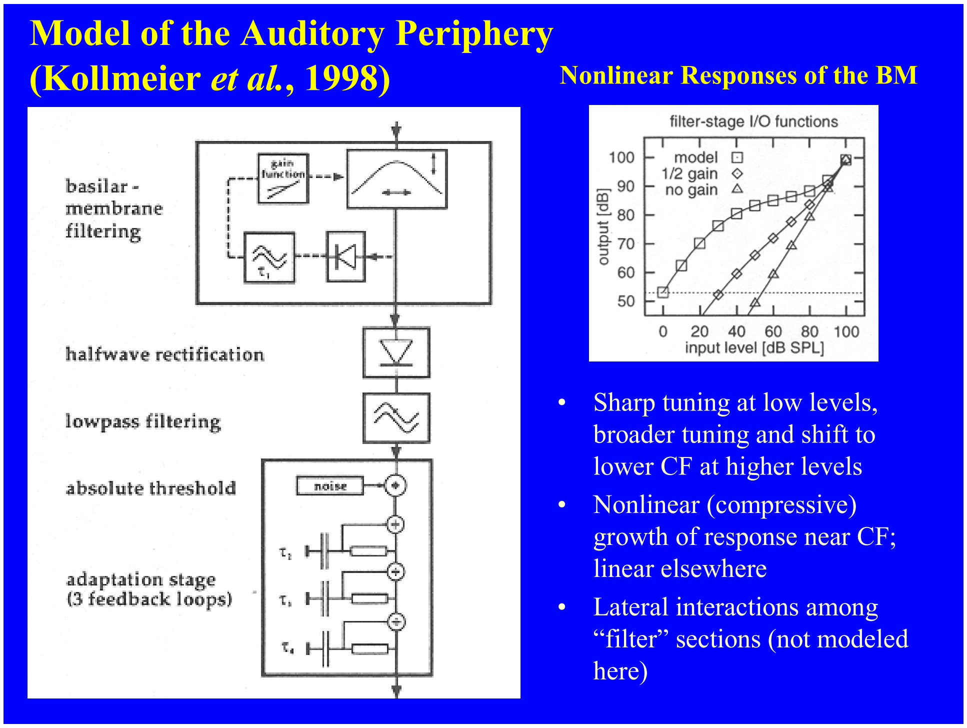

Fig. 7. Model of the "effective" signal processing in the auditory periphery. Also illustrated are aspects of nonlinear responses at the basilar membrane and associated structures. (Adapted from Kollmeier *et al.*, 1998)

with the feedback set at zero is perfectly linear, as would be expected. The higher threshold of response, along with the relatively rapid growth of response for higher input levels, is consistent with the high threshold of response and rapid growth of loudness found in cases of sensorineural hearing loss, the phenomenon of "loudness recruitment."

The nonlinear responses at the basilar membrane and associated structures produce sharp tuning at low input levels, and broader tuning and a shift in the most-responsive frequency (CF) to a lower frequency at higher input levels. The response of the membrane complex is highly nonlinear at and near the spatial position of the CF and roughly linear at other places. In normal hearing, responses at one place along the basilar membrane influence responses at other places. Such lateral or longitudinal interactions among equivalent filters are not included in the model of Fig. 7.

A major theme of current research on hearing aids is to reinstate some of the nonlinearities that are lost with the loss of outer hair cells. Deng and Geisler (1987), among others (see, *e.g.*, the review by Moore, 1998), have shown that nonlinearities in basilar membrane filtering greatly enhance the neural representation of speech sounds presented in competition with noise. Similarly, results presented by Tchorz and Kollmeier (1999), among others (*e.g.*, Delgutte, 1997; Geisler, 1998), have indicated the importance of adaptation at the IHC/neuron synapse in representing temporal events in speech, especially for speech presented in competition with noise.

Many users of hearing aids complain that, although they can hear amplified speech, they can't understand it, especially in adverse acoustic situations such as speech presented in competition with noise or other talkers. Reinstatement for them of nonlinear and noninstantaneous processing might help ameliorate this deficit.

<u>Conventional processing strategies for implants.</u> Present processing strategies for cochlear implants do not include nonlinear filtering like that at the basilar membrane and associated structures, nor do they include noninstantaneous compression that reproduces closely the adaptation effects found in normal hearing. A block diagram for one of the present strategies, the CIS strategy, is shown in Fig. 8. Only a very crude approximation to processing in the normal cochlea is provided. For example, a bank of linear bandpass filters is used instead of the nonlinear and coupled filters that would model normal auditory function. Also, a single nonlinear map is used to produce the overall compression that the normal system achieves in multiple steps. The compression in the standard CIS processor is instantaneous, whereas compression at the IHC/neuron synapse in normal hearing is noninstantaneous, with large adaptation effects.

At the time the CIS strategy was developed, we did not have nearly the control over neural response patterns that we now enjoy. In addition, knowledge about processing in the normal auditory periphery was far less advanced than present knowledge. These facts contributed to the relatively simple structure shown in Fig. 8.

<u>A new processor structure.</u> A new processor structure, designed to provide a closer mimicking of normal auditory functions, is suggested in Fig. 9. The structure incorporates the nonlinearities observed in the healthy inner ear, and it does so by utilizing models that have been developed to describe and understand the normal functions. Leading examples of such models are listed beneath the corresponding blocks in the block diagram.

Note that a compression table (or nonlinear map, as in Fig. 8) is not included in this processor design. The multiple stages of compression implemented in the auditory models should provide the overall compression needed to map the wide dynamic range of processor inputs onto stimulus levels appropriate for neural activation (some scaling may be needed, but the compression functions should be at least approximately correct). The compression achieved in this way would be much more analogous to the way it is achieved in normal hearing.

Conditioner pulses may be applied if desired, to impart spontaneous-like activity in the nerve and stochastic independence among neurons. Alternatively, high carrier rates may be used to impart these as well, but probably with different statistics of the spontaneous-like and driven activities of the nerve, as mentioned before.

We note that Geurts and Wouters (1999; also see Wouters *et al.*, 2001) and Vandali (2001) have developed variations of the CIS and spectral maxima sound processing (SMSP) strategies, respectively, that emphasize temporal variations in the representation of speech sounds. Both strategies produced immediate improvements in speech reception performance for the tested subjects. A closer approximation to the adaptation properties of the normal auditory periphery may produce further improvements. Inclusion of the nonlinear processing that normally occurs at the basilar membrane complex may push speech reception scores even higher, especially for speech presented in competition with noise, as suggested by the results of Deng and Geisler, among others.

<u>Future directions.</u> A closer mimicking of processing in the normal cochlea might be achieved with

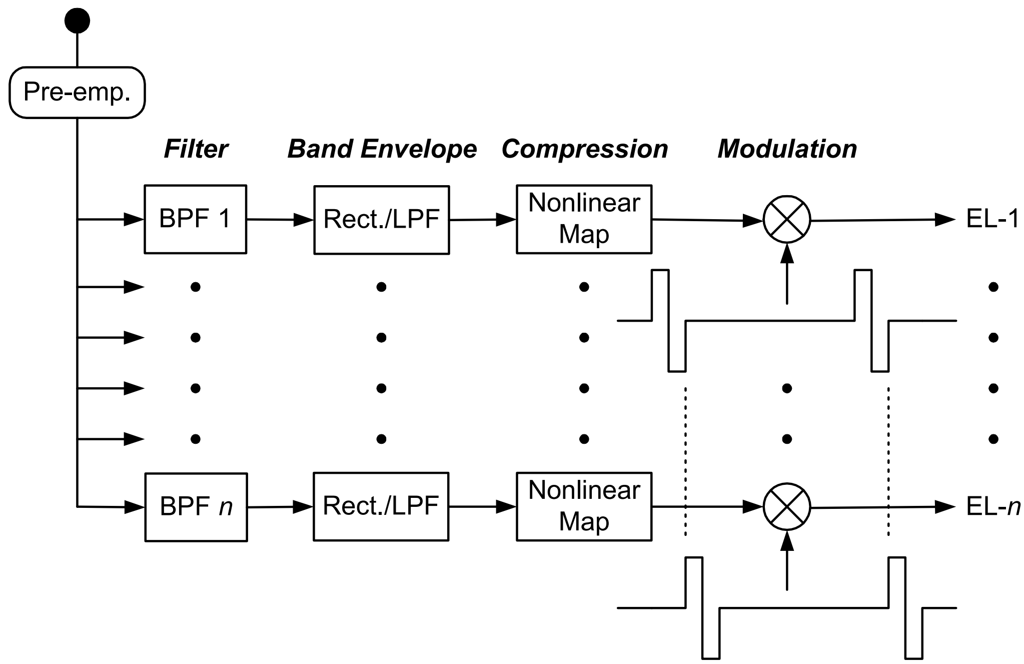

Fig. 8. Standard CIS processor. Abbreviations include "Pre-emp." for "Pre-emphasis," "BPF" for "Band Pass Filter," "Rect." for "Rectifier," "LPF" for "Low Pass Filter," and "EL" for "Electrode." (Adapted from Wilson *et al.*, 1991)

- Use of 15-19 "critical band" channels of perceptually independent stimulation, corresponding to the number channels in normal hearing that span the range of speech frequencies (with the exact number depending on the specification of endpoints for that range)
- Within-channel representations of temporal variations up to about 1 kHz, corresponding to the corner frequency of lowpass filtering at the IHC membrane
- Replication of the nonlinear responses of the basilar membrane and associated structures
- Replication of IHC/synaptic processing, including rectification, lowpass filtering, compression, and adaptation
- Reinstatement of at least some degree of spontaneous-like activity and associated stochastic independence among neurons

The first two items in this list are nearly within reach using the new and higher levels of neural control described elsewhere in this review. Fulfillment of the remaining three items may be achievable with a processor structure like the one shown in Fig. 9.

We note that some approximations to normal processing might actually be easier to achieve with implants than with hearing aids. With implants, we now have the tools and knowledge to exert a high level of control over neural response patterns. With hearing aids, the nerve responses can only be controlled indirectly, using acoustic stimuli that are affected by damaged hair cells and grossly-altered responses of the basilar membrane complex.

An additional advantage of implants is that we can measure patterns of responses at the auditory nerve in human subjects, with recordings of intracochlear evoked potentials. Such recordings

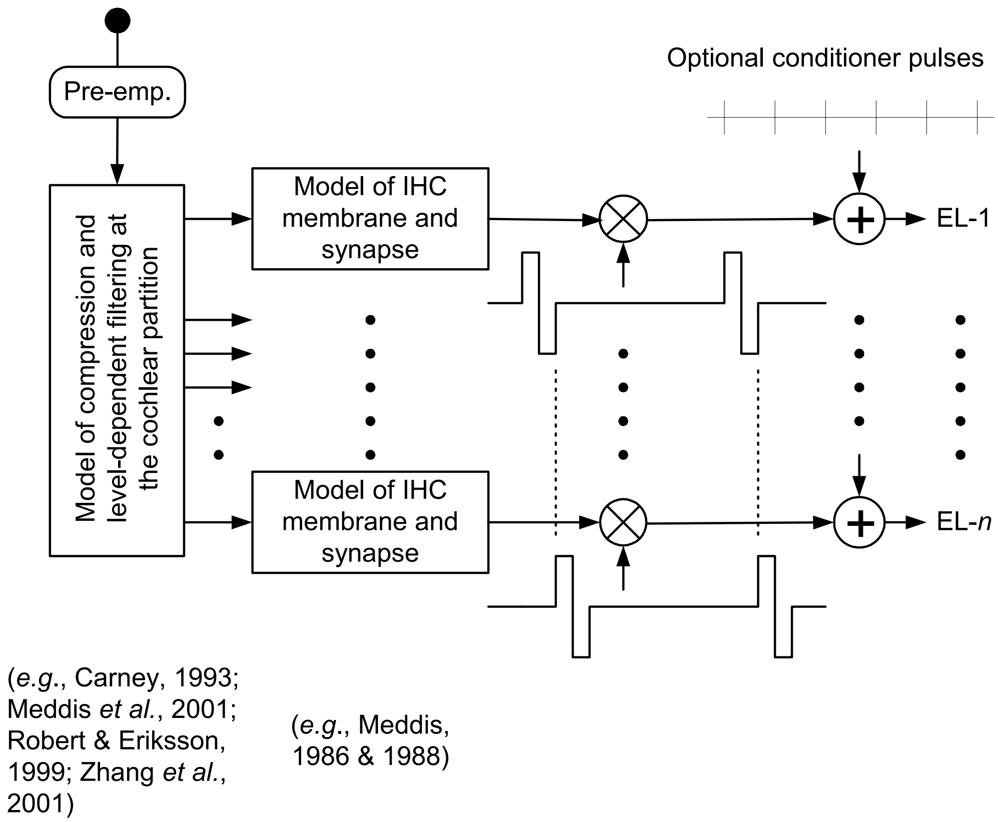

Fig. 9. Processor structure for closer mimicking of normal auditory functions. Examples of existing models that could be incorporated into a speech processor design are listed beneath the corresponding blocks in the block diagram.

will allow us to evaluate objectively whether or not a particular strategy is producing the intended patterns of neural responses. If not, revisions may be made to repair the identified defects in interim designs. The iterative and "closed loop" process made possible with the objective measures should shorten the time required for the development of new strategies for implants.

We plan to develop in the immediate future a strategy with the structure presented in Fig. 9. The Meddis model (1986, 1988) will be used in the initial implementation for the blocks labeled "Model of IHC membrane and synapse." Updated parameters for the model, published by Lopez-Poveda *et al.* (1998), will be used. The cleft contents (c(t)) signal will be used as the output of the Meddis model, rather than the spike timing signal, which is not relevant for the present application.

Various alternatives will be implemented and tested for the block labeled "Model of compression and level-dependent filtering at the cochlear partition." The selected model must run in real time and yet provide an accurate simulation of normal processing. For these reasons, the Meddis *et al.* model (2001) is our leading candidate at present, as it is especially designed for high-speed simulations of processing in the auditory periphery. An even simpler and more efficient model has been proposed by Kollmeier *et al.* (1998), as described above in connection with Fig. 7, and it may be sufficiently accurate for our purposes (Kollmeier's model was designed to simulate the "effective" processing in the auditory periphery). If the Meddis *et al.* model is selected, then we will use the parameter values suggested by Lopez-Poveda and Meddis (2001) for simulating processing in the human cochlea, as opposed to the cat cochlea, which was simulated in the work reported in Meddis *et al.*, 2001.

Other, more-complex models may be considered if the above models prove to be unsuitable for some reason. We doubt that this will be necessary, however, based on the published results for the various models described by Meddis and coworkers, and for the model described by Kollmeier *et al.*

Once developed, the new strategy will be evaluated with controlled comparisons that will include (1) a standard CIS processor, (2) an otherwise standard CIS processor but with a model of nonlinear filtering and gain at the cochlear partition substituted for the bank of linear bandpass filters, (3) an otherwise standard CIS processor but with a model of the IHC membrane and synapse substituted for the envelope detector and a portion of the compression normally provided by the mapping table, and (4) the full strategy as indicated in Fig. 9. Tests with each of these strategy options will include a minimum of (the same) six subjects and evaluations of speech reception in quiet and in noise.

We note that combined electric and acoustic stimulation of the same cochlea also might provide a closer mimicking of normal auditory functions. In particular, at least a semblance of those functions might be present in the low-frequency region of residual hearing for such patients. That region would be excited by acoustic stimuli, and the high-frequency region of the cochlea would be excited by electric stimuli, as described before in connection with Figs. 1 and 2.

The tough cases

A large gap persists between the poorest and best performances achieved with cochlear implants. Many patients enjoy great benefits from their implants. Indeed, according to the 1995 NIH Consensus Statement on Cochlear Implants in Adults and Children, "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." As noted elsewhere in this review, overall performance levels have continued to improve since 1995.

Despite this progress, however, some patients still do not receive much benefit from their implants using hearing alone, even with the new processing strategies. These are the tough cases. The people in this unfortunate category deserve our greatest attention.

Prior results. Much research has been conducted over the years to identify the mechanisms or factors underlying the wide range of outcomes with implants. Until quite recently, no identified factor, or collection of factors, could explain more than about 30 percent of the variance in outcomes (see, *e.g.*, Blamey *et al.*, 1996). Some of the previously-identified factors include patient age at the time of implantation, duration of deafness prior to the implant operation, and the depth and placement of intracochlear electrodes.

New results. These and some of the more-recent findings are summarized in Fig. 10. We reported at the *1999 Conference on Implantable Auditory Prostheses* a strong relationship between speech reception scores and the "pitch saturation limit" (*i.e.*, the rate or modulation frequency beyond which further increases do not produce further increases in perceived pitch) for implant patients (Wilson *et al.*, 1999; also see Wilson *et al.*, 1997b). The data presented at the

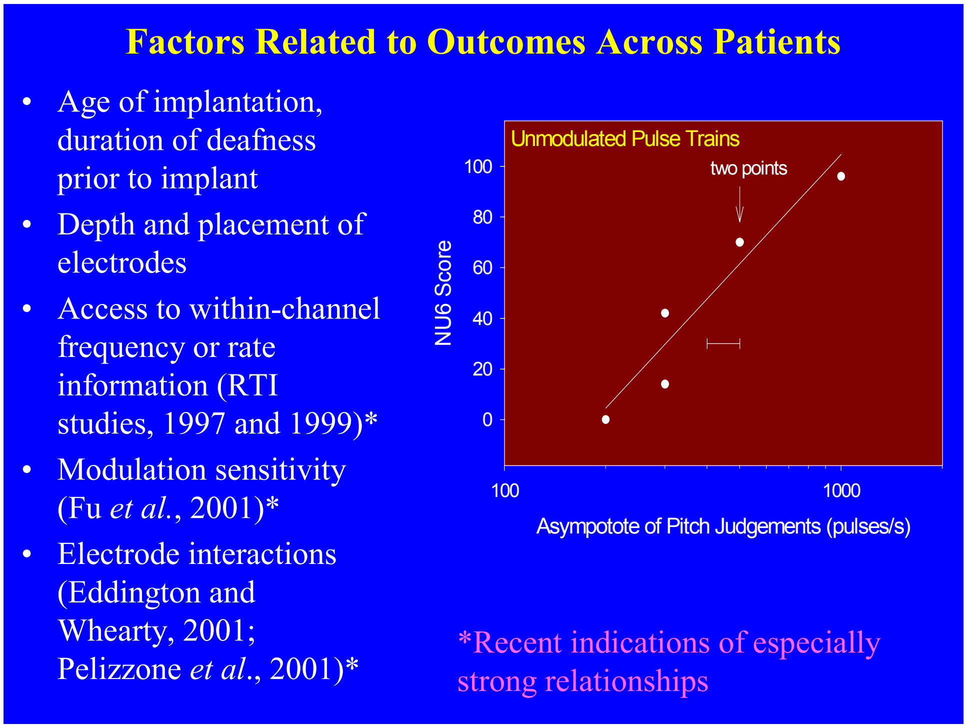

Fig. 10. Factors related to outcomes across patients. Examples of factors that are correlated with outcomes are listed to the left. High correlations, exceeding 0.9, have been demonstrated in recent studies by Wilson *et al.* (1997b and 1999), Fu *et al.* (2001), Eddington and Whearty (2001), and Pelizzone *et al.* (2001). A result from the studies by Wilson *et al.* is presented in the graph on the right.

conference are shown in the inset in Fig. 10. Since that time measures have been collected for three additional subjects and the relationship remains strong.

At the *2001 Conference* there were three new reports of significant progress in this area. Qian-Jie Fu and coworkers reported a stunningly strong relationship between modulation sensitivity and consonant identification (Fu *et al.*, 2001). Marco Pelizzone and coworkers reported a strong relationship between measures of electrode interactions and consonant identification (Pelizzone *et al.*, 2001), and Don Eddington and Margaret Whearty reported a strong relationship between electrode interactions and recognition of monosyllabic words, for nine of their eleven tested subjects (Eddington and Whearty, 2001). We now have several such relationships with correlation coefficients that exceed 0.9, whereas the prior correlations for single factors were in the range of 0.3 to 0.5.

<u>*Applications of new findings.*</u> Such strong correlations suggest possibilities for helping patients presently at the low end of the performance spectrum. Two examples of ways in which the new knowledge might be applied were presented at the *2001 Conference*. Qian-Jie Fu suggested that training might improve performance on a factor that is highly correlated with outcomes, and that the improvement produced by the training might transfer or generalize to better performance with the implant. Marco Pelizzone suggested that removal of electrodes that produce high levels of

interactions also might improve performance, based on the high correlation between interactions and outcomes observed by his group. Both speakers presented data supporting these ideas. Fu and coworkers provided training for their subjects, in an effort to improve their performance on another identified factor, electrode discrimination (electrode discrimination also was highly correlated with outcomes, but not as highly correlated as modulation sensitivity). Over the course of the training period, performance improved on the discrimination task and performance improved on a phoneme identification task. The correlation between the two measures was significant. Pelizzone and coworkers identified the single electrode that produced the greatest interactions (when paired with other electrodes) for each of their subjects and removed that electrode from those stimulated by the speech processor. This change in electrode assignments (reducing the total number of stimulating electrodes) produced significant improvements in performance for subjects who previously had relatively low speech reception scores with their implants.

<u>Future directions.</u> These exciting results and possibilities should be pursued. We at RTI plan to measure pitch saturation limits, modulation sensitivities, and electrode interactions in tests with at least six subjects. This will allow comparisons among the measures, and assessments of their predictive power, using within-subject controls. We also will repeat the experiment described by Pelizzone *et al.*, in tests with these same subjects. The speech reception measures collected for all subjects will include identification of consonants in an /a/-consonant-/a/ context and recognition of CNC (Consonant-Nucleus-Consonant) monosyllabic words.

We also plan to develop a training procedure designed to extend pitch saturation limits. The efficacy of the training procedure will be evaluated with periodic tests to measure psychophysical (pitch saturation limits) and speech reception (consonant identification) performances. Increases in both measures over time, and a significant correlation between the two, would indicate effectiveness of the training procedure.

The recent findings of highly-significant correlations between psychophysical factors and speech reception scores offer new hope for patients with poor or modest outcomes. Applications of such findings may be the single greatest opportunity at present to improve the design and performance of implant systems.

Concluding remarks

This is an exciting time in the history of cochlear prostheses. We now enjoy unprecedented levels of control over response patterns in the auditory nerve, which in turn offers the prospect of a much closer mimicking of normal auditory processing than was heretofore possible. Stimulation with bilateral implants has provided important advantages for many of the patients studied to date, including head shadow benefits for the most of the patients and binaural summation or binaural squelch or both for some of the patients. Results from future studies may indicate better ways to utilize bilateral implants. Recent experience has demonstrated that preservation of residual low-frequency hearing is possible with careful surgery and short insertions of electrode arrays into the scala tympani. Speech reception results with combined electric and acoustic stimulation of the same cochlea have been encouraging. Results from future studies may establish the generality of such findings, and they may point the way to more optimal combinations for the two modes of stimulation. An especially encouraging set of quite recent findings are the demonstrations of high correlations between certain psychophysical measures – including pitch saturation limits, modulation sensitivity, and electrode interactions – and speech reception scores with implants. These correlations suggest some promising possibilities for improving outcomes for patients presently at the low end of the performance spectrum. Among the possibilities are (1) training to increase scores for selected psychophysical tasks such as pitch saturation limits or modulation sensitivity, that are correlated with speech reception scores, and (2) eliminating electrodes that produce the highest interactions for a given patient.

Some likely next steps in the further development and application of cochlear prostheses include the following:

- Bilateral implants will be widely applied if arrangements can be made for third-party coverage of their additional cost
- Combined electric and acoustic stimulation of the same cochlea will become commonplace if a substantial fraction of the initially-implanted patients retain their residual hearing for many years
- The new and higher levels of neural control will be exploited to support a closer mimicking of signal processing in the normal cochlea
- Progress will be made in treating the "tough cases," with applications of new and increasing knowledge about factors that are correlated strongly with implant outcomes

We expect that the pace of improvements in cochlear implant design and performance, especially for speech reception in noise and especially for patients having disappointing outcomes with present systems, will increase sharply over the next five years. In the not-too-distant future we also may see applications of intramodiolar implants, with the attendant likely advantages of reduced stimulus levels (and power consumption), increased spatial specificity of neural excitation, and a larger number of stimulus sites. Problems need to be solved before such applications can become practical, but the problems do not appear at this time to be insurmountable.

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We are especially pleased to acknowledge the generous and enthusiastic participation of our subjects and to thank them for their interest, time and diligent effort. Technical assistance in developing interface systems for simultaneous and synchronized laboratory control of bilateral Med El implants was kindly provided by Med El GmbH and the University of Innsbruck.

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III. Record of reporting activity for NIH Project N01-DC-8-2105

Reporting activity for this project, covering the period from September 30, 1998 through March 31, 2002, included 13 quarterly progress reports, this final report, 13 publications (three of which are in press), a book (with J. K. Niparko, K. I. Kirk, N. K. Mellon, A. M. Robbins, and D. L. Tucci), a keynote speech, two lectures as a Guest of Honor, three lectures as a Distinguished Guest Speaker, 33 additional invited presentations, eight contributed presentations, two chaired sessions, and organization and presentation of a "mini symposium" at RTI on cochlear implants. Travel and all other expenses were covered by the conference organizers for the great majority of the invited presentations, allowing us to present results from the project at a greatly reduced cost to the project. We also have maintained a web site for ready access to the progress reports and other information about the Center for Auditory Prosthesis Research. A detailed record of reporting activity for the project is presented in the subsections below.

Publications

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Wilson BS: Cochlear implant technology. In *Cochlear Implants: Principles & Practices*, edited by JK Niparko, KI Kirk, NK Mellon, AM Robbins, DL Tucci and BS Wilson, Lippincott Williams & Wilkins, Philadelphia, PA, 2000, pp. 109-119.

Wilson BS: Strategies for representing speech information with cochlear implants. In *Cochlear Implants: Principles & Practices*, edited by JK Niparko, KI Kirk, NK Mellon, AM Robbins, DL Tucci and BS Wilson, Lippincott Williams & Wilkins, Philadelphia, PA, 2000, pp. 129-170.

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Loeb GE, Wilson BS: Prosthetics: Sensory systems. In *Handbook of Brain Theory and Neural Networks*, edited by MA Arbib, MIT Press, 2nd edition, in press.

Tyler RS, Preece JP, Wilson BS, Rubinstein JT, Parkinson AJ, Wolaver AA, Gantz BJ: Distance, localization and speech perception pilot studies with bilateral cochlear implants. Adv Oto-Rhino-Laryngol, in press.

Book

Niparko JK, Kirk KI, Mellon NK, Robbins AM, Tucci DL, Wilson BS (Eds.), *Cochlear Implants: Principles & Practices*, Lippincott Williams & Wilkins, Philadelphia, PA, 2000.

Manuscripts in review

Wilson BS, Brill SM, Cartee LA, Cox JH, Lawson DT, Schatzer R, Wolford RD, Müller JM, Schön F, Tyler RS, Kiefer J, Pfennigdorff T, Gstöttner W: From the 2001 Conference on Implantable Auditory Prostheses: Some likely next steps in the further development of cochlear implants. Ear Hear (submitted March 5, 2002).

Lawson DT, Wolford RD, Brill SM, Schatzer R, Wilson BS, Müller JM, Schön F, Tyler RS: Initial studies at the Research Triangle Institute with recipients of bilateral cochlear implants. Ear Hear (submitted March 5, 2002).

Invited chapters in preparation

Wilson BS: Engineering design of cochlear implant systems. In *Auditory Prostheses*, edited by F-G Zeng, AN Popper and RR Fay, Springer-Verlag, to be published in late 2002. (This book will be part of the series of books in the highly acclaimed *Springer Handbook of Auditory Research.*)

Wilson BS: Neural prostheses. In *CRC Handbook of Biomedical Technology and Devices*, edited by G Zouridakis, CRC Press.

Keynote speech

Wilson BS: Some likely next steps in the further development of cochlear implants. *6th European Symposium on Paediatric Cochlear Implantation*, Las Palmas, Canary Islands, February 24-27, 2002.

Lectures as a Guest of Honor

Wilson BS: The future of cochlear implants. *5th Int. Cochlear Implant Workshop* and *1st Auditory Brainstem (ABI) Workshop*, Würzburg, Germany, June 30 through July 4, 1999.

Wilson BS, Brill SM, Lawson DT, Schatzer R, Wolford RD, Zerbi M, Müller J, Schön F, Tyler R: Psychophysical and speech reception results from studies with recipients of bilateral cochlear implants. *Wullstein Symposium*, Würzburg, Germany, April 26-30, 2001. (The *Wullstein Symposium* includes the *2nd Conference on Bilateral Cochlear Implantation and Signal Processing*, the *6th International Cochlear Implant Workshop*, and the *2nd Auditory Brainstem Implant (ABI) Workshop.*)

Lectures as a Distinguished Guest Speaker

Lawson DT, Wilson BS, Wolford RD, Brill S, and Schatzer R: Initial work to restore binaural hearing with bilateral cochlear implants. *4th International Surgical Workshop on Aesthetic Rhinoplasty, Middle Ear Surgery, and State of Art Symposium*, Mumbai, India, November 14, 2000.

Lawson DT, Wilson BS, Wolford RD, Brill S, and Schatzer R: Next steps in the further development of cochlear implants. *4th International Surgical Workshop on Aesthetic Rhinoplasty, Middle Ear Surgery, and State of Art Symposium*, Mumbai, India, November 15, 2000.

Lawson DT, Wilson BS, Wolford RD, Brill S, and Schatzer R: Next Steps in the Continuing Development of Cochlear Prostheses: Bilateral Implants and Combined Electrical and Acoustic Stimulation. *International Ear Surgery Workshop and The Millennium State of Art Symposium*, Indore, India, November 17, 2000.

Additional invited presentations

Wilson BS: Speech processors for auditory prostheses. *29th Annual Neural Prosthesis Workshop*, Bethesda, MD, October 28-20, 1998.

Wilson BS: Speech coding strategies. *5th Int. Cochlear Implant Workshop* and *1st Auditory Brainstem (ABI) Workshop*, Würzburg, Germany, June 30 through July 4, 1999.

Lawson DT, Wilson BS: Experiments in bilateral implanted patients using the CIS strategy. *5th Int. Cochlear Implant Workshop* and *1st Auditory Brainstem (ABI) Workshop*, Würzburg, Germany, June 30 through July 4, 1999. (Lecture presented by Wilson).

Finley CC, van den Honert C, Wilson BS, Miller RL, Cartee LA, Smith DW, Niparko JK: Factors contributing to the size, shape, latency, and distribution of intracochlear evoked potentials. *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999.

Wilson BS, Zerbi M, Finley CC, Lawson DT, van den Honert C: Relationships among electrophysiological, psychophysical and speech reception measures for implant patients. *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999.

Lawson DT, Wilson BS, Zerbi M, Finley CC: Future directions in speech processing for cochlear implants. *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999. (Wilson presented the talk for Lawson, who could not attend the conference due to illness.)

Wilson BS: Speech processors for auditory prostheses. *30th Annual Neural Prosthesis Workshop*, Bethesda, MD, October 12-14, 1999.

Wilson BS: Psychophysical measures and speech understanding in bilaterally implanted patients. *Bilateral Research Meeting*, Frankfurt, Germany, December 3, 1999. (This meeting was sponsored by the Med El GmbH.)

Wilson BS: New directions in cochlear implants. *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000.

Brill S: Electrode discrimination along the cochlea based on pitch perception. Meeting of the Duke/RTI Cochlear Implant Team, Duke University Medical Center, Durham, NC, May 28, 2000.

Wilson BS, Lawson DT, Brill S, Wolford RD and Schatzer R: Binaural cochlear implants. *Conference on Binaural Hearing, Hearing Loss, Hearing Aids, & Cochlear Implants*, Iowa City, IA, June 22-24, 2000.

Tyler R, Parkinson A, Gantz B, Rubinstein J, Wilson B, Witt S, Wolaver A, Lowder M: Independent binaural cochlear implants. *Conference on Binaural Hearing, Hearing Loss, Hearing Aids, & Cochlear Implants*, Iowa City, IA, June 22-24, 2000.

Wilson BS, Lawson DT, Brill S, Wolford RD, and Schatzer R: Speech Processors for Auditory Prostheses. *31st Annual Neural Prosthesis Workshop*, Bethesda, MD, October 26, 2000.

Brill SM: Interaurale Zeitunterschiedswahrnehmung bei der bilateralen Cochlea-Implantat Versorgung. Fortbildungsveranstaltung HNO-Klinik, Würzburg, Germany, November 27, 2000.

Brill SM: Lateralization with Bilateral Cochlear Implants. *First Investigators' Meeting on Bilateral Cochlear Implantation*, Stans, Austria, November 29, 2000.

Wilson BS, Lawson DT, Wolford R, Brill S, Schatzer R, Müller J, Schön F, Tyler RS, Zerbi M: Bilateral cochlear implants. *First Investigators' Meeting on Bilateral Cochlear Implantation*, Stans, Austria, November 29, 2000.

Brill SM: ITD lateralization with bilateral nonsynchronous pulse carrier CIS. *Wullstein Symposium*, Würzburg, Germany, April 26-30, 2001. (The *Wullstein Symposium* includes the *2nd Conference on Bilateral Cochlear Implantation and Signal Processing*, the *6th International Cochlear Implant Workshop*, and the *2nd Auditory Brainstem Implant (ABI) Workshop.*)

Helms J (moderator), Baumgatner W-D, Fitzgerald D, Heusler R, Hildmann H, Hockman M, van Hoesel R, Müller J, Vischer M, Wilson B: Round table discussion on bilateral cochlear implantation. *Wullstein Symposium*, Würzburg, Germany, April 26-30, 2001. (The *Wullstein Symposium* includes the *2nd Conference on Bilateral Cochlear Implantation and Signal Processing*, the *6th International Cochlear Implant Workshop*, and the *2nd Auditory Brainstem Implant (ABI) Workshop.*)

Brill SM: Combined electric and acoustic stimulation of the same cochlea – Psychoacoustic measurements. *EAS Focus Group Meeting*, Frankfurt, Germany, June 28-29, 2001. (This meeting was sponsored by Med El GmbH.)

Brill SM, Lawson DT: Psychophysics of simultaneous electric and acoustic stimulation. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 34 in the book of Abstracts)

Lawson DT, Brill SM, Wolford RD, Schatzer R, Wilson BS: Speech processors for binaural stimulation. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 24 in the book of Abstracts)

Tyler RS, Preece JP, van Hoesel R, Parkinson AJ, Rubinstein JT, Gantz BJ, Wolaver AP, Wilson BS: Preliminary speech perception and localization experiments involving binaural cochlear implants. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 22 in the book of Abstracts; Wilson's participation in this work was supported jointly by the present project and by the Program Project Grant on Cochlear Implants at the University of Iowa)

Wilson BS, Brill SM, Cartee LA, Lawson DT, Schatzer R, Wolford RD: Some likely next steps in the further development of cochlear prostheses. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 47 in the book of Abstracts)

Brill SM: Binaural psychophysics. *Med-El US Investigator's Meeting*, Quebec City, Canada, July 20-21, 2001.

Lawson DT: Improving CIS processor fittings. *Med-El US Investigator's Meeting*, Quebec City, Canada, July 20-21, 2001.

Wilson BS, Lawson DT *et al.*: Speech processors for auditory prostheses. *32nd Annual Neural Prosthesis Workshop*, Bethesda, MD, October, 2001.

Brill SM: Psychophysical studies with recipients of bilateral cochlear implants. *Meeting of the Duke/RTI Cochlear Implant Team*, Duke University Medical Center, Durham, NC, November 26, 2001.
Lawson DT: Overview of current studies on cochlear implants at the Research Triangle Institute. *Clinical Research Meeting, Med El Corporation*, Dallas, TX, February 1-3, 2002.
Wolford RD: Bilateral cochlear implants/RTI results. *Clinical Research Meeting, Med El Corporation*, Dallas, TX, February 1-3, 2002.
Wolford RD: Research ideas for cochlear implants. *Clinical Research Meeting, Med El Corporation*, Dallas, TX, February 1-3, 2002.
Wilson BS, Lawson DT, Brill SM, Wolford RD, Schatzer R (RTI); Kiefer J, Pfennigdorff T, Tillein J, Gstöttner W (J. W. Goethe Universität, Frankfurt): Pillsbury H, Gilmer C (UNC Chapel Hill): Combined electric and acoustic stimulation (EAS) studies at the Research Triangle Institute. *2nd Focus Meeting on Electric-Acoustic Stimulation (EAS)*, Las Palmas, Canary Islands, February 24, 2002. (This workshop was sponsored by Med El GmbH.)
Brill SM, Lawson DT: Psychophysics of combined electric and acoustic stimulation of the same cochlea. *2nd Focus Meeting on Electric-Acoustic Stimulation (EAS)*, Las Palmas, Canary Islands, February 24, 2002. (This workshop was sponsored by Med El GmbH.)
Wolford RD: Combined electric/acoustic stimulation: Results and thoughts for future directions. Meeting of the Duke/RTI Cochlear Implant Team, Duke University Medical Center, Durham, NC, March 25, 2002.

Contributed presentations

Rubinstein JT, Miller CA, Abbas PJ, Wilson BS: Emulating physiologic firing patterns of auditory neurons with electrical stimulation. *1999 Midwinter Meeting of the Association for Research in Otolaryngology*, St. Petersburg Beach, FL, February 13-17, 1999. (Abstract 31)
van den Honert C, Finley CC, Wilson BS: Measurement of intracochlear evoked potentials. *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999. (This was a poster presentation.)
van den Honert C, Finley CC, Wilson BS: Measurement of intracochlear evoked potentials. *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000.
Brill S, Kerber M: Electrode discrimination along the cochlea based on pitch perception. *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000. (This presentation reported results previously collected by the authors in Innsbruck; preparation of the talk, and participation in the conference, was supported by the current "speech processors" project at RTI.)
Tyler RS, Parkinson A, Wilson BS, Witt S, Gantz B, Rubinstein J, Wolaver A, Lowder M: Binaural cochlear implants and hearing aids and cochlear implant: Speech perception and localization. *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000. (Wilson's participation in this effort was jointly supported by the Program Project Grant on Cochlear Implants at the University of Iowa and by the current "speech processors" project at RTI.)
Brill SM, Lawson DT: Lateralization with Bilateral Cochlear Implants. *Binaural Bash 2000*, Boston University, October 5-8, 2000.
Tyler RS, Gantz BJ, Rubinstein JT, Preece JP, Wilson BS, Parkinson AJ, Wolaver A: Distance, localization and speech perception pilot studies with bilateral cochlear implants. *3rd Congress of Asia Pacific Symposium on Cochlear Implant and Related Sciences*, Osaka, Japan, April 5-7, 2001. (Wilson's participation in this effort was supported jointly by the present project and by the Program Project Grant on Cochlear Implants at the University of Iowa.)
Cartee LA, Finley CC, Wilson BS: A model of the intracochlear evoked potential. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p.

82 in the book of Abstracts; this work was supported jointly by the present project and Dr. Cartee's separate NIH project, on "Development of a Cochlear Neuron Electrophysiology Model")

Chaired sessions

Finley CC: Chair of the session on otology and cochlear implants. *1999 Midwinter Meeting of the Association for Research in Otolaryngology*, St. Petersburg Beach, FL, February 13-17, 1999.

Brill SM: Moderator. Session on Signal Processing for Implants II. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001.

Keynote speech scheduled for a future conference

Wilson BS: Future directions for cochlear implants. To be presented at the *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.

Mini symposium on cochlear implants

A Mini Symposium on Cochlear Implants was held at RTI on February 7, 2000, following the *6th International Cochlear Implant Conference* held in Miami Beach, FL, the week before. The Mini Symposium allowed much longer talks and greater discussion on selected topics, compared with the conference in Miami. Wilson served as the Chair for the Symposium. The talks included those listed below. (Dr. Cartee is a member of the RTI team; Dr. Müller is the Director of the Cochlear Implant Program and an Otologic surgeon at the University of Würzburg, in Würzburg, Germany; Dr. Nopp is Director of Research at Med El GmbH, in Innsbruck, Austria; and Mr. Lorens is a Research Scientist at the Institute of Physiology and Pathology of Hearing, in Warsaw, Poland.)

Cartee L: Comparison of scala tympani and intrameatal electrical stimulation responses of cochlear neurons.

Müller J: Bilateral Cochlear Implantation.

Nopp P: Overview of Research in Innsbruck.

Lorens A: Psychophysical Measurements for Cochlear Implant Fitting.

Web site

Our progress reports are posted on our web site, http://www.rti.org/capr/caprqprs.html. They also are posted on the web site for the Neural Prosthesis Program, http://npp.ninds.nih.gov.

Appendix 1: Detailed List of Achievements and Activities for NIH project N01-DC-8-2105

Except for quarter 14, the list below was extracted from the introductions to the Quarterly Progress Reports for the project. Achievements and activities for that final quarter were compiled separately for inclusion in this final report.

Quarter 1

- Studies with Ineraid subject SR10, from September 28 through October 9. The studies included (a) measures of forward masking across electrode positions, using the procedure of Lim *et al.*, to map excitation patterns for maskers at each of the six electrodes in the Ineraid implant; (b) longitudinal measures of speech reception performance with chronic use of a portable CIS processor; (c) measures of electrode interactions using recordings of intracochlear evoked potentials; (d) measures of consonant identification and sentence recognition for 15 conditions combining different rates of stimulation and cutoff frequency of the lowpass filters in the envelope detectors for CIS processors; (e) psychophysical scaling of pulse rate for unmodulated pulse trains, for each of the six electrodes; (f) psychophysical scaling of modulation frequencies for SAM pulse trains, for one of the electrodes and various depths of modulation; (g) psychophysical scaling of electrodes, for unmodulated pulse trains delivered to each of the electrodes and for SAM pulse trains delivered to each of the electrodes; (h) measures of forward masking across electrode positions, but now using recordings of intracochlear evoked potentials instead of the psychophysical procedure above; (i) recordings of the electrically evoked auditory brainstem response, using some of the same stimuli used for this subject in prior recordings of intracochlear evoked potentials; (j) evaluation of processors suggested by results of various psychophysical scaling studies above, *e.g.*, evaluation of processors using fewer than 6 channels to increase perceptual differences among channels; (k) comparisons of CIS processors using different update orders in each cycle of stimulation across electrodes; and (l) a comparison between 3-channel CIS processors, each with a cycle rate of 500/s, but with one presenting pulses at the beginning of each cycle with no time delay between pulses, and the other presenting pulses spaced evenly in time across the cycle. The scaling experiments extended greatly the range of conditions included in initial studies with this and other subjects, as reported in QPR 8 for the prior project in this series (NIH project N01-DC-5-2103).
- Studies with Ineraid subject SR15, from November 18 through November 21. The studies included some of those conducted for SR10 above, including studies (a), (b), and (e). Additional scaling studies included scaling of modulation frequencies for SAM pulse trains and 3 electrodes, for various depths of modulation, and scaling of modulation frequencies for all electrodes with 100 percent modulation. Studies with SR15 also included evaluation of various 2, 3 and 4 channel CIS processors, as suggested by results from the psychophysical scaling experiments and other considerations.
- Ongoing studies with Ineraid subject SR2, seven half days during the present reporting period. The studies included forward masking and psychophysical scaling studies like those conducted with subjects SR10 and SR15 above; initial evaluation of "conditioner pulses" processors (see Rubinstein *et al.*, 1998, and the Final Report for the prior project in this series); measures of auditory thresholds with and without conditioner pulses; and measures of electrode interactions using recordings of intracochlear evoked potentials.
- Presentation of project results at the annual Neural Prosthesis Workshop (October 28-30).
- Development of DSP (Digital Signal Processor) code to implement conditioner-pulses processors

- Further development of other hardware and software for the speech reception and evoked potential laboratories, including among many other developments (a) refinement of software for support of psychophysical scaling studies and (b) development of hardware and software for recording of intracochlear evoked potentials, along the lines indicated in QPR 9 for the prior project in this series.
- Continued analysis of psychophysical, speech reception, and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication, including in this quarter two chapters for the book *Cochlear Implants: Principles, Practice and Pitfalls*, edited by John Niparko.

Quarter 2

- Studies with Clarion subject MI-4, from January 11 through January 15. The studies included measures of (a) scalp potentials produced with different commanded levels of stimulation to characterize the current sources in the Clarion device; (b) speech reception in quiet and in noise with this subject's SAS and CIS processing options; and (c) rate scaling for trains of unmodulated pulses delivered separately to several monopolar electrodes in the implant and separately to bipolar electrodes at corresponding positions in the electrode array.
- Studies with Ineraid subject SR16, from January 25 through January 29. The studies included (a) longitudinal measures of performance with this subject's portable CIS processor, (b) psychophysical scaling of pulse rate for unmodulated pulse trains, for each of the six electrodes in the Ineraid implant; (c) psychophysical scaling of modulation frequencies for SAM pulse trains, for one of the electrodes and various depths of modulation; (d) psychophysical scaling of electrodes, for unmodulated pulse trains (at either of two fixed rates) delivered to each of the electrodes; and (e) measures of forward masking across electrode positions, to assess the spatial profile of stimulation with each of the monopolar electrodes in SR16's implant. The scaling experiments extended greatly the range of conditions included in initial studies with this and other subjects, as reported in QPR 8 for the prior project in this series (NIH project N01-DC-5-2103).
- Studies with Clarion subject MI-5, March 8. The studies included initial baseline measures of performance with three variations of CIS processors, as implemented in the subject's clinical system. Additional visits are scheduled with this subject, to include all of measures collected before with subject MI-4 above. Subject MI-5 lives in nearby Greensboro, NC, and is able to visit the laboratory in relatively frequent, one-day visits.
- Studies with subject NU-5, a recipient of bilateral CI24M implants, from March 29 through April 1. The studies included evaluation of various processing strategies designed to exploit bilateral implants. (Results from a prior visit by this subject are presented in QPR 1 for this project; those results indicate that this subject has exceptionally good sensitivity to timing differences in stimuli delivered to her two implants.)
- Ongoing studies with Ineraid subject SR2, for a morning each week in January and for two full days each week beginning in February. Studies during this quarter included (a) further scaling and forward masking experiments, as suggested by results from experiments with this subject in the prior quarter of the project; (b) continued evaluation of "conditioner pulses" processors; (c) measures of consonant identification for a large number of 4-channel CIS processors using different combinations of the cutoff frequencies for the lowpass filters in the envelope detectors and the pulse rate for each of the electrodes; and (d) measures of consonant identification for 4-channel CIS processors using a wide range of compression functions, replicating the conditions of a study recently described by Fu and Shannon ("Effects of amplitude nonlinearity on phoneme recognition by cochlear implant users and normal-hearing listeners," J. Acoust. Soc. Am. 104: 2570-2577, 1998).

- Development by Marian Zerbi of a new tool that allows real-time adjustment(s), by the subject and/or the investigator, of speech processor parameters. The tool has been applied initially in preliminary studies of "conditioner pulses" processors. The subject (SR2) adjusted the level of the conditioner pulses over a wide range, while listening to a book on tape. This allowed rapid identification of different perceptual regions across the range of manipulations, and also indicated the likely sensitivity to changes in the parameter value. Such "screening" of parametric spaces allows identification of "sweet spots" or "dead zones" that easily could be missed in traditional testing, usually with fixed step sizes within a selected range of parameter values. The screening also can save time by identifying ranges of values that do not seem to make any difference in perception. We plan to use the tool in further studies, involving different parameters with this and other subjects (*e.g*., real-time manipulations in number of channels, rate of stimulation, mapping functions, etc.). The tool can greatly improve the efficiency of subsequent formal testing, by identifying choices of parameter values that are likely to affect the outcome measure.
- Discussions with Thomas Lenarz, M.D., Ph.D., and Rolf Battmer, Ph.D., of the Medizinische Hochschule Hannover, during a visit to RTI by them on February 12.
- Presentation of project results at the annual midwinter meeting of the Association for Research in Otolaryngology, February 13-17.
- Participation by Zerbi in a course on C++ object programming, March 16-19.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication, including in this quarter completion of two chapters by Wilson for the book *Cochlear Implants: Principles, Practice and Pitfalls*, edited by John Niparko.

Quarter 3

- Studies with Clarion subject MI-5 (April 13). The main purpose of these studies was to characterize the current sources in the Clarion implant with recordings of scalp potentials produced with different commanded levels of pulse amplitude. Speech reception with alternative choices of parameter values for CIS processors also was measured.
- Ongoing studies with Ineraid subject SR2, who now is working with us for one or two days each week. Studies in this quarter included continuation of two extensive series of measures, including (a) measures of consonant identification for CIS processors using different combinations of cutoff frequencies for the lowpass filters in the envelope detectors and the pulse rate for each of the electrodes, and (b) measures of consonant and vowel identification for CIS processors using a wide range of mapping functions. The consonants and vowels for these measures were presented in quiet and at the speech-to-noise ratios of +15 and +10 dB. Studies in the quarter also included measures of consonant identification for CIS processors using different resolutions of output mapping, to determine the minimum number of discrete output levels required for asymptotic performance (this study was inspired by recent results obtained with the SPEAK strategy, reported by Zeng and Galvin, "Amplitude mapping and phoneme recognition in cochlear implant listeners," Ear and Hearing 20: 60-74, 1999).
- Completion of current studies with subject NU-5, a recipient of bilateral CI24M implants (March 29 to April 1). These studies included evaluation of various processing strategies designed to exploit bilateral implants.
- Discussions with Paul Carter from Cochlear Corporation, during a visit by him to RTI on June 23.
- Development of an Access database of processor designs and studies, to bring this information together in one place for fast access and in a structure that will provide responses to queries about prior designs and studies.

- Participation by Finley in a workshop on the new interface system designed by Advanced Bionics and the House Ear Institute, for laboratory control of the implanted receiver in the Clarion device (April 9-11).
- A visit by Oguz Poroy, of the University of Arkansas at Little Rock, for evaluation by Finley of a laboratory processor system developed by Oguz under the supervision of Philip Loizou, for future studies with implant patients at the University of Arkansas (May 5-7).
- Participation by Wilson, as the Guest of Honor, in the *5th International Cochlear Implant Workshop* and *1st Auditory Brainstem Implant (ABI) Workshop*, Würzburg, Germany (June 30 to July 4).
- Presentation of project results in three invited lectures at the Würzburg Workshops.
- Preparation for studies with patients having bilateral COMBI 40+ implants, from the University Hospital in Würzburg. This preparation included interviews with prospective subjects during and after the Würzburg Workshops, and screening tests with several prospective subjects during the week after the Workshops. The screening tests included measures of electrode ranking (according to pitch percepts) within and across the two sides. These tests were conducted by Stefan Brill, in anticipation of his future work as a full-time member of our team (see Announcements section of this report).
- Preparation for Marian Zerbi's departure as a full-time member of the team. This preparation included seminars to transfer knowledge about processor specifications, real-time software for implementing processor designs, and software for various psychophysical tests to Finley, Lawson and Wilson. (Zerbi will continue as a consultant for the project after she leaves RTI.)
- Interviews with candidates to replace Zerbi and to fill an Audiologist position on the team.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 4

- Ongoing studies with Ineraid subject SR2, who now is working with us for one or two days each week. Studies in this quarter included continuation of an extensive series of measures to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors. The measures have included consonant identification in quiet and at the speech-to-noise ratios of +15 and +10 dB.
- Studies with Ineraid subject SR9, for the weeks beginning August 2 and August 9. The studies included an extensive series of measures to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors, as with SR2 above. The measures for SR9 included consonant identification and recognition of CUNY sentences in quiet. The studies with SR9 also included measures of consonant identification for CIS processors using a wide range of compression functions. Tests of speech presented in conjunction with noise were not conducted with SR9, as even small amounts of noise greatly depress her scores and often produce floor effects in the data.
- Discussions with Chris van den Honert from Cochlear Corporation, during a visit by him to RTI on July 12.
- Continued development of an Access database of processor designs and study results, to bring this information together in one place for fast access and in a structure that will allow retrieval of prior designs and results on the basis of shared attributes and parameter values.
- Initial development of additional databases, for psychophysical and evoked potential studies.
- Interviews with candidates to fill a DSP/Electrical Engineer position on the team.

- Presentation of project results in three invited lectures and one poster at the *1999 Conference on Implantable Auditory Prostheses*, held in Pacific Grove, CA, August 29 through September 3.
- Preparation for studies in the next quarter with patients having bilateral COMBI 40+ implants or bilateral CI24M implants. The preparation included visits by consultant Marian Zerbi to work with Finley in completing an interface system for simultaneous laboratory control of two CI24M implants. Zerbi is continuing ongoing work to implement new processing strategies that are designed to preserve sound localization cues through coordinated stimulation of the two sides.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 5

- Ongoing studies with Ineraid subject SR2. Studies in this quarter included (1) completion of an extensive series of measures to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors and (2) evaluation of the TIMIT speech data base as a source of difficult sentences for sensitive measures of speech reception by a high-performance subject.
- Studies with Ineraid subject SR10, for the week beginning August 2 and August 9. The studies included (1) longitudinal measures with his portable CIS (CIS-Link) processor, (2) extension of prior studies conducted with this subject to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors, and (3) measures of consonant identification for CIS processors using a wide range of compression functions.
- Continued development of an Access database of processor designs and study results, to bring this information together in one place for fast access and in a structure that will allow retrieval of prior designs and results on the basis of shared attributes and parameter values.
- Participation by Blake Wilson and Stefan Brill in a workshop in Frankfurt, Germany, on bilateral implants and binaural processing, at the invitation of the Med El company. (Invited speakers for the Workshop included J. Müller, F. Schön, and H. Kühn-Inacker of the Julius-Maximilians Universität in Würzburg, G. Smoorenburg of the University of Utrecht, B. Wilson of RTI, and J. Tillein of the J.W. Goethe Universität in Frankfurt. Approximately 30 people attended the workshop.)
- A visit by Wilson to the J.W. Goethe Universität in Frankfurt, at the invitation of Professor Dr. von Ilberg. Results from studies at the university to evaluate combined electric and acoustic stimulation of the same cochlea were discussed in detail, as were possibilities for future joint studies between the university and RTI to evaluate additional conditions for combined stimulation.
- A visit by Wilson to the Julius-Maximilians Universität in Würzburg, in part for further development of plans for cooperative studies between the university and RTI with recipients of bilateral COMBI 40+ implants.
- Presentation of project results in invited lectures at the *Bilateral Research Meeting* in Frankfurt and at the *30th Neural Prosthesis Workshop.*
- Continued preparation for studies with patients having bilateral COMBI 40+ implants or bilateral CI24M implants, principally by Stefan Brill, Charles Finley and consultant Marian Zerbi.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 6

- Ongoing studies with Ineraid subject SR2. Studies in this quarter included (1) evaluation of the TIMIT speech database as a source of difficult sentences for sensitive measures of speech reception by a high-performance subject; (2) application of the database in further measures of effects of changes in several parameters of CIS processors, including the exponent for the mapping function, rate of stimulation, and cutoff frequency for the lowpass filters in the envelope detectors; (3) further evaluation of effects of changes in the exponent for the mapping function, using CUNY sentences presented in quiet and in noise; and (4) recordings of intracochlear evoked potentials for single polarities of stimulation, with biphasic pulses and with "split phase" biphasic pulses with 3 ms between the first and second phases. (The TIMIT database proved to be both difficult and reliable. We anticipate extensive use of the database as a source of test material in future studies.)
- Studies with Ineraid subject SR15 during the week beginning on February 7. The studies included (a) longitudinal measures with her portable CIS (CIS-Link) processor, (b) measures of consonant identification for CIS processors using a wide range of compression functions, and (c) evaluation of combinations of low stimulus rates and low cutoff frequencies for the lowpass filters in the envelope detectors in CIS processors, as suggested by the results from prior psychophysical scaling experiments with this subject. (The prior scaling results, some of which are presented in Quarterly Progress Report 8 for NIH project N01-DC-5-2103, indicated especially poor access to within-channel rate and frequency information for this subject.)
- Continued development of a new strategy, designed to mimic closely the nonlinear processing in the peripheral auditory system, including the strong and nearly instantaneous compression at the basilar membrane for sound pressure levels above 35-40 dB and the strong and noninstantaneous (with multiple time constants) compression that occurs at the synapse between inner hair cells and type I fibers of the auditory nerve.
- A visit by Jan Kiefer and Thomas Pfennigdorff, of the J.W. Goethe Universität in Frankfurt, on February 1 and 2, for further discussions on combined electric and acoustic stimulation of the same cochlea and for further development of plans for cooperative studies between the university and RTI. (This visit follows one by Blake Wilson to Frankfurt; see Quarterly Progress Report 5 for this project.)
- Continued preparation for studies with recipients of CI24M implants on both sides, and with recipients of COMBI 40+ implants on both sides (principally by Stefan Brill and Marian Zerbi, with contributions by other members of the team).
- A visit by Marian Zerbi to assist in the above preparation (February 7-9).
- A separate visit by Zerbi on March 11-16, principally to transfer knowledge about use and programming of the laboratory systems to Reinhold Schatzer, a new member of the project team who began work at RTI on March 1 (see Announcements section of this report).
- Presentation of project results in an invited lecture at the *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000.
- Visits by Joachim Müller of the Julius-Maximilians Universität in Würzburg, Peter Nopp of the Med El company in Innsbruck, and Arturs Lorens of the Institute of Physiology and Pathology of Hearing in Warsaw, for between two days (Müller) and one week (Nopp and Lorens) following the Miami conference.
- A *Mini Symposium on Cochlear Implants* at RTI, held in conjunction with, and in honor of, the above visitors (February 7). (The agenda for the symposium is presented in Appendix 2 to this report.)
- Detailed discussions with Dr. Müller during his visit, on the scheduling of his patients for cooperative studies at RTI.

- A visit by Jim Patrick on March 2, in part to discuss upcoming studies at RTI of an experimental version of the Nucleus device, with the new "modiolar hugging" electrode array developed by Cochlear Pty. Ltd. in conjunction with a percutaneous connector. (We expect to study 4-6 such subjects.)
- Continued development of an Access database of processor designs and study results, to bring this information together in one place for fast access and in a structure that will allow retrieval of prior designs and results on the basis of shared attributes and parameter values. (Work in this quarter included development of "front end translators," written in Visual Basic, for automated reading of previously-recorded specification files for processors into the Access database.)
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 7

- Studies with Ineraid subject SR3 during the periods from April 3 to April 14 and from May 9 to May 12. The studies included (1) measures of consonant identification and sentence recognition for CIS processors using a wide range of compression functions, (2) measures of consonant identification for processors using various combinations of pulse rate and envelope cutoff frequency, (3) measures of consonant identification, sentence recognition, and monosyllabic word recognition for CIS processors using various pulse rates and a fixed envelope cutoff frequency, and (4) evaluation of processors with high rate "conditioner" pulses in addition to the pulses conveying information.
- Studies with subject ME3, a recipient of Med El COMBI 40+ implants on both sides, during the two weeks beginning on May 22. The studies included measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies designed to represent cues for sound localization or to exploit the availability bilateral electrodes in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants). This subject was referred to us by colleagues at the Julius-Maximilians Universität in Würzburg, and the studies with her were a cooperative effort between our two institutions. The subject was accompanied by Raymond Mederake of the Med El company in Starnberg, Germany, who also contributed to the studies.
- Studies with Ineraid subject SR1 during the two weeks beginning on June 5. The studies included measures of consonant identification and sentence recognition for CIS processors using a wide range of compression functions, (2) evaluation of processors with high rate "conditioner" pulses in addition to the pulses conveying information, (3) measures of consonant identification and monosyllabic word recognition for CIS processors using various rates of stimulation, and (4) measures of intracochlear evoked potentials for single pulses and for trains of unmodulated pulses, with pulse rates ranging from 100 to 2000/s.
- Studies with Ineraid subject SR8 during the week beginning on June 26. The studies included measures of complex tone perception, using CIS processors with different numbers of channels and with various selection criteria for complex tone partials within each channel. SR8 has a special ability to describe her percepts for complex tones, as she was a music major in college and continues to play and teach piano using hearing provided through her implant. The studies with her also included an initial evaluation of conditioner-pulses processors.
- A meeting among Bill Heetderks, Terry Hambrecht and Blake Wilson at NIH on May 4, to discuss progress and plans for the project.

- A visit by Marian Zerbi to RTI from May 6 to May 9, to assist with the development of software for simultaneous control of bilateral CI24M implants using the Cochlear Corporation's embedded protocol for those devices and to continue transferring her knowledge about the DSP and laboratory systems at RTI to Reinhold Schatzer.
- Presentation of project results in an invited talk by Wilson at the conference on *Binaural Hearing, Hearing Loss, and Hearing Aids*, held at the University of Iowa, June 22-24.
- Participation by Stefan Brill in the above conference.
- Completion of an Access database of processor designs and study results.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 8

- Studies with two recipients of bilateral COMBI 40+ implants, referred to us by our colleagues at the Julius-Maximilians Universität in Würzburg, Germany. Studies with subject ME4 were conducted during the two weeks beginning July 17, and those with subject ME5 during the three weeks beginning July 31. Joachim Müller, M.D., of the Würzburg group participated in the studies with subject ME5. The studies with both subjects included measures of sensitivities to interaural timing and amplitude differences, and evaluation of various processing strategies designed to represent cues for sound localization or to exploit the availability of bilateral electrodes in other ways. (See Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants.)
- Studies with a recipient of a relatively short array of electrodes (a Med-El COMBI 40+ implant intentionally inserted only 20 mm into the cochlea) whose low frequency residual hearing in the same ear also is preserved, for the two weeks beginning August 28. This subject, ME6, was referred to us by our colleagues at the J. W. Goethe Universität in Frankfurt, Germany. Thomas Pfenningdorff, M.D., of the Frankfurt group participated in the studies, which included evaluation of various strategies for combined electric and acoustic stimulation of the same cochlea.
- Studies with a recipient of bilateral CI24M implants, referred to us by our colleagues at the University of Iowa. Studies with this subject, NU6, were conducted during the two weeks beginning September 18 and included measures of sensitivities to interaural timing and and amplitude differences and evaluation of various processing strategies designed to represent cues for sound localization or to exploit the availability of bilateral electrodes in other ways. (See Quarter Progress Report 4 for this project for a detailed discussion of processing options for bilateral implants.)
- A visit by Reinhold Schatzer to Fishkill, NY, to work with Marian Zerbi in the further development of software for simultaneous control of bilateral CI24M implants using the Cochlear Corporation's embedded protocol for those devices (July 5-7).
- A visit to our laboratories by Sung June Kim, Ph.D., Director of the Nano Bioelectrics and Systems Research Center, Seoul National University, Seoul, Korea, for discussions on the possible development of an inexpensive but effective cochlear implant system for use in countries with highly limited health budgets (August 8).
- A visit by Marian Zerbi to RTI, for further development of software for studies with bilaterally implanted subjects, and for further transfer of knowledge to Reinhold Schatzer about RTI laboratory tools developed by Ms. Zerbi.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 9

- Studies with two recipients of bilateral CI24M implants, referred to us by our colleagues at the University of Iowa. Studies with subject NU7 were conducted during two weeks in October, and studies with subject NU8 during two weeks in November. Studies with both subjects included measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies designed to convey cues for sound localization or to exploit the availability of bilateral electrodes in other ways (see Quarterly Progress Report 4 for this project for a detailed discussion of processing options for bilateral implants).
- Studies with a recipient of bilateral COMBI40+ implants, referred to us by our colleagues at the Julius-Maximilians Universität in Würzburg, Germany. Studies with this subject, ME7, took place over one week in late October and early November. Joachim Müller and Franz Schön of the Würzburg group participated as co-investigators in these studies, which included a subset of the studies conducted with other recipients of bilateral implants (see above), inasmuch as the subject was available for only one week.
- Participation in the annual "Binaural Bash" at Boston University by Dewey Lawson and Stefan Brill, October 5 - 8. Brill presented results from our studies with recipients of bilateral implants.
- Participation in the annual *Neural Prosthesis Workshop,* October 25-27.
- Presentation of project results by Dewey Lawson as an invited Guest Speaker at *International Ear Surgery Workshops* and *Millennium State of the Art Symposia* in Mumbai, India, November 12-15 and Indore, India, November 16-18.
- Presentation of project results by Blake Wilson and Stefan Brill as invited speakers at Med-El's *First Investigators' Meeting on Bilateral Cochlear Implantation,* in Stans, Austria, November 28 and 29.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 10

- Studies with subject ME8 during the three-week period beginning on January 8. This subject was referred to us by our colleagues in Manchester, England, and is a recipient of a COMBI 40S implant on one side and a COMBI 40+ implant on the contralateral side (the 40S implant is designed for a short insertion and includes 8 rather than 12 electrodes). The studies included measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies either to represent cues for sound localization or to exploit the availability of bilateral implants in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants).
- A visit by Martin O'Driscol of the Manchester Cochlear Implant Team, in conjunction with the visit by subject ME8. (Mr. O'Driscol visited us during the period from January 22 to 28 and participated in the studies with ME8.)
- Studies with subject ME9 during the two-week period beginning on March 5. This subject was referred to us by our colleagues in Würzburg, Germany, and is a recipient of COMBI 40+ implants on both sides. Studies with him were similar to those outlined above for subject ME8.
- A visit by consultant Marian Zerbi, to work with Reinhold Schatzer in the further development of the speech reception laboratory, especially monitor programs for the specification of speech processor designs in studies with recipients of bilateral cochlear implants (Jan 9-12).

- Participation by Lianne Cartee in a workshop sponsored by the Advanced Bionics Corporation, on a new interface system the company has developed for support of research studies with their CII implant device (January 26-29, in Los Angeles).
- Visits by three members of an Engineering Research Center on "Wireless Integrated Microsystems" at the University of Michigan (February 23). One of two demonstration projects for the Center is development of a fully-implanted cochlear prosthesis, and the group from the Center visited us to learn more about the design and implementation details for CIS processors. The visit was hosted by Reinhold Schatzer.
- Participation by Reinhold Schatzer in the *8th Symposium on Cochlear Implants in Children*, held in Los Angles, February 27 to March 3.
- Further development of tools for support of our studies, including the tools listed in the first paragraph below.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 11

- Studies with subject MI6 during the week beginning on April 16. This subject is a recipient of the Clarion (version 1) device, with quite low levels of performance. She no longer uses the implant and instead relies on minimal residual hearing in the ear contralateral to the implant. Studies with her included (1) measures of hearing in the ear contralateral to the implant, (2) evaluation of basic psychophysical abilities with the implant such as rate and electrode scaling abilities, and (3) evaluation of various alternative processing strategies for the implant and of strategies for combined stimulation using both the implant and acoustic stimulation of the contralateral ear. The strategies tested for the implant were designed to provide relatively sparse representations of speech signals, tailored to MI6's limited psychophysical abilities.
- Presentation of project results in invited lectures by Stefan Brill and by Blake Wilson at the *Wullstein Symposium*, held in Würzburg, Germany, April 26-30. (The *Wullstein Symposium* included the *2nd Conference on Bilateral Cochlear Implantation and Signal Processing*, the *6th International Cochlear Implant Workshop*, and the *2nd Auditory Brainstem Implant (ABI) Workshop*; Blake Wilson was a Guest of Honor for the Symposium.)
- Studies with subject ME6, in a return visit by her during the two weeks beginning on June 4. ME6 has a deliberately short insertion of a COMBI 40+ implant with preserved residual (low frequency) hearing in the implanted cochlea (see QPR 8 for details about her case). Studies with ME6 during this visit included measures of simultaneous masking between electric and acoustic stimuli presented to the implanted cochlea, further evaluation of processing strategies to optimize the combination of acoustic and electric stimulation of the same cochlea, and additional tests of speech reception abilities with relatively adverse speech-to-noise ratios.
- A trip by Reinhold Schatzer to New Fairfield, CT, to work with consultant Marian Zerbi in the further development of monitor programs for specification and control of psychophysical studies with recipients of bilateral implants (June 7-9).
- A visit by Jochen Tillein, of the J.W. Goethe Universität in Frankfurt, Germany, from June 11 through June 14, to participate in the studies with subject ME6.
- Participation by Reinhold Schatzer in a MATLAB seminar, held in the Research Triangle Park on June 14.
- Studies with Ineraid subject SR3, in a return visit by her during the two weeks beginning on June 18. The studies during this visit included (1) completion of prior studies to evaluate effects of changes in carrier rate and envelope cutoff frequency in CIS processors, using tests of consonant identification; (2) completion of prior studies to evaluate rate effects while

holding the cutoff frequency constant at 200 Hz, using word and sentence tests in addition to the consonant tests; (3) evaluation of "conditioner pulses" processors (see Rubinstein *et al.*, Hearing Research 127: 108-118, 1999); (4) further tests, with TIMIT sentences, to evaluate effects of changes in the mapping functions used with CIS and other processors (see QPR 3 for initial results with two other subjects); (5) scaling of pulse rates, for unmodulated pulse trains presented in conjunction with conditioner pulses, for various levels (including zero) of the conditioners; (6) measures of intracochlear evoked potentials (EPs) for unmodulated trains of pulses with various pulse rates; (7) measures of intracochlear EPs for unmodulated pulses at 1000 pulses/s presented in conjunction with conditioner pulses at 5000 pulses/s and at various amplitudes; (8) measures of intracochlear EPs for single polarities of biphasic and monophasic-like pulses using a template subtraction procedure (the monophasic-like pulses were "split phase" pulses, with equal charges in the two phases and with a 3 ms inter-phase gap); and (9) measures of artifact (electric field) potentials at unstimulated electrodes for subthreshold pulses presented separately to each of the intracochlear electrodes.

- A visit by consultant Chris van den Honert, who helped us in the evoked potential studies with SR3 and also provided advice on the further development of the evoked potentials laboratory (June 25-28).
- Presentation of project results by Stefan Brill in an invited lecture at the *EAS Focus Group Meeting*, held in Frankfurt, Germany, June 28-29. (This meeting was sponsored by the Med El GmbH.)
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

Quarter 12

- Studies with subject ME10 during the three-week period beginning on July 16. This subject was referred to us by our colleagues in Vienna, Austria, and is a recipient of a COMBI 40 implant on one side and a COMBI 40+ implant on the contralateral side. The studies included measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies either to represent cues for sound localization or to exploit the availability of bilateral implants in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants).
- A visit by Marcel Pok of the Vienna Cochlear Implant Team, in conjunction with the visit by subject ME10.
- Continued studies with local subject NU4, during the mornings of August 7-9. (NU4 is a recipient of Nucleus 22 devices on both sides; see QPR 4.) The studies with her included fitting of new ear-level processors and evaluation of various processing alternatives.
- Continued studies with Ineraid subject SR10, during the week beginning on August 13. The studies included (1) completion of prior studies to evaluate effects of changes in carrier rate and envelope cutoff frequency in CIS processors, using tests of consonant identification; (2) further tests, with TIMIT sentences, to evaluate effects of changes in the mapping functions used with CIS and other processors (see QPR 3 for initial results with two other subjects); (3) scaling of pulse rates, for unmodulated pulse trains presented in conjunction with conditioner pulses, for various levels (including zero) of the conditioners; (4) measures of intracochlear evoked potentials for single polarities of biphasic and monophasic-like pulses using a template subtraction procedure (the monophasic-like pulses were "split phase" pulses, with a 3 ms inter-phase gap and with equal charges for the two phases); and (5) measures of artifact (electric field) potentials at unstimulated electrodes for subthreshold pulses presented separately to each of the intracochlear electrodes.

- Continued studies with Ineraid subject SR9, during the week beginning on August 27. The studies included (1) completion of prior studies to evaluate effects of changes in carrier rate in CIS processors while holding the envelope cutoff frequency constant at 200 Hz, using a wide range of speech reception measures; (2) further tests, with CUNY sentences, to evaluate effects of changes in the mapping functions used with CIS and other processors; and (3) scaling of pulse rates, for unmodulated pulse trains presented in conjunction with conditioner pulses, for various levels of the conditioners.
- Continued studies with subject ME7 during the two-week period beginning on September 4. This subject was initially referred to us by our colleagues in Würzburg, Germany, and is a recipient of COMBI 40+ implants on both sides. The studies with her included many of the measures listed above for subject ME10. (Initial studies with ME7 were for one week only, and thus included only a limited set of speech reception measures and no measures of sensitivities to the interaural difference cues.)
- Presentations of project results in several invited talks at the *2001 Conference on Implantable Auditory Prostheses*, held in Pacific Grove, CA, August 19-24
- Presentation of project results in (1) two other invited talks at the *Med-El US Investigators Meeting*, held in Quebec City, Canada, July 20-21, and (2) a contributed poster at the *2001 Conference on Implantable Auditory Prostheses*.
- Participation by Lianne Cartee in an "update" workshop sponsored by the Advanced Bionics Corporation, on a new interface system the company has developed for support of research studies with their CII implant device (August 23, during one of the open afternoons at the *2001 Conference on Implantable Auditory Prostheses*).
- Further development of tools for support of our studies, including (1) the Access database of speech processor designs and study results, initially described in QPR 10, and (2) monitor programs for implementing psychophysical test procedures for studies with recipients of bilateral CI24M implants.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication, including invited contributions to the upcoming volume 4 of the *Annual Review of Biomedical Engineering* and to the upcoming book titled Auditory Prostheses, which will be a new addition in the ongoing series of books in the *Springer Handbook of Auditory Research*.

Quarter 13

- Preparation for, and participation by the entire project staff in, the *32nd Annual Neural Prosthesis Workshop* in Bethesda, MD, October 17-19.
- Further development of new processing strategies designed to provide a closer mimicking of normal auditory functions, especially implementation of dual-resonance non-linear (drnl) filters to simulate non-linear processing at the basilar membrane and outer hair cell complex [see Meddis *et al.*, J. Acoust Soc Am 109: 2852-2861, 2001].
- Initial development of Access databases for psychophysical and evoked potential studies (these databases will be similar in design to the database already developed for speech processor studies).
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.
- Studies throughout the quarter with subjects NU4 and ME12, local recipients of bilateral cochlear implants. (Studies with additional bilateral subjects had been scheduled, but were cancelled because of travel concerns following the tragedy of September 11)

- A visit by consultant Marian Zerbi, October 13 - 15, to assist in the further development of software for the speech reception laboratory.
- A visit by consultant Sig Soli on October 22, to discuss tools and techniques for the analysis of speech reception in the presence of noise from various directions.
- An initial visit by a new local subject, ME13, on November 12.
- A visit by Carol Gilmer of the University of North Carolina at Chapel Hill, in conjunction with the visit by subject ME13.
- Participation in a Symposium on Pediatric Cochlear Implants on November 16, sponsored by the Division of Otolaryngology, Head and Neck Surgery at Duke University Medical Center.
- Studies December 10 - 14 with ME14, a subject with full insertion of a C40P electrode array on one side and substantial residual hearing with the other ear
- Completion of Stefan Brill's postdoctoral appointment with the Center for Auditory Prosthesis Research.

Quarter 14

- Continued studies with subject NU7, a recipient of Nucleus CI24M implants on both sides, during the weeks of February 25 and March 4. Studies in this visit included evaluation of various processing strategies for bilateral cochlear implants and measures of sensitivities to interaural time delays for a fixed (standard) electrode on one side, paired separately with a number of electrodes on the contralateral side.
- Continued studies with subject ME14, a recipient of Med El COMBI 40+ implants on both sides, March 25-27. Studies in this visit included measures of sensitivities to interaural time delays for selected stimuli and pairings of electrodes.
- Presentation of project results in (1) invited talks by Dewey Lawson and Robert Wolford, in the Clinical Research Meeting sponsored by Med El Corporation, Dallas, TX, January 31 through February 2; (2) a keynote speech by Blake Wilson, at 6th European Symposium on Paediatric Cochlear Implantation, Las Palmas, Canary Islands, February 24-27; (3) invited talks by Blake Wilson and Stefan Brill at the 2nd Focus Meeting on Electric-Acoustic Stimulation (EAS), Las Palmas, Canary Islands, February 24 (this last meeting was sponsored by Med El GmbH); and (4) an invited talk by Robert Wolford at a meeting of the Duke/RTI cochlear implant team, Duke University Medical Center, March 25.
- A meeting between Enrique Lopez-Poveda and Blake Wilson in Madrid on February 28, to discuss possible applications of Dr. Lopez-Poveda's work, on nonlinear filtering in the normal human cochlea, in a new processing strategy for cochlear implants (see Lopez-Poveda and Meddis, J. Acoust. Soc. Am. 110: 3107-3118, 2001).
- Further development by Reinhold Schatzer of the above processing strategy, designed to provide a closer mimicking of normal auditory functions.
- Participation by Reinhold Schatzer in an advanced course on C++ programming, January 15-18.
- A visit by consultant Marian Zerbi, February 24-26, to assist in the further development of software for the speech reception laboratory.
- A trip by Blake Wilson to the University of Michigan on March 18-19, to provide advice on a project there to develop a fully implantable auditory prosthesis (Wilson is a member of the outreach faculty for the Engineering Research Center at the university, on "Wireless Integrated Microsystems," and one of two demonstration projects for the Center is the development of a fully implantable auditory prosthesis.)
- Continued analyses of psychophysical, speech reception, and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication.

Appendix 2: Summary of reporting activity for this quarter

Reporting activity for the final quarter of project N01-DC-8-2105, from January 1 through March 30, 2002, included the following publications and presentations:

Publications

Tyler RS, Gantz BJ, Rubinstein JT, Wilson BS, Parkinson AJ, Wolaver AA, Preece JP, Witt S, Lowder MW: Three-month results with bilateral cochlear implants. Ear Hear 23: 80S-89S, 2002.

Tyler RS, Parkinson AJ, Wilson BS, Witt S, Preece JP, Noble W: Patients utilizing a hearing aid and a cochlear implant: Speech perception and localization. Ear Hear 23: 98-105, 2002.

Papers in press

Loeb GE, Wilson BS: Cochlear prosthesis. In *Encyclopedia of Neuroscience*, Elsevier, 2nd edition, in press.

Loeb GE, Wilson BS: Prosthetics: Sensory systems. In *Handbook of Brain Theory and Neural Networks*, edited by MA Arbib, MIT Press, 2nd edition, in press.

Tyler RS, Preece JP, Wilson BS, Rubinstein JT, Parkinson AJ, Wolaver AA, Gantz BJ: Distance, localization and speech perception pilot studies with bilateral cochlear implants. Adv Oto-Rhino-Laryngol, in press.

Keynote speech

Wilson BS: Some likely next steps in the further development of cochlear implants. *6th European Symposium on Paediatric Cochlear Implantation*, Las Palmas, Canary Islands, February 24-27, 2002.

Additional invited talks

Lawson DT: Overview of current studies on cochlear implants at the Research Triangle Institute. *Clinical Research Meeting, Med El Corporation*, Dallas, TX, February 1-3, 2002.

Wolford RD: Bilateral cochlear implants/RTI results. *Clinical Research Meeting, Med El Corporation*, Dallas, TX, February 1-3, 2002.

Wolford RD: Research ideas for cochlear implants. *Clinical Research Meeting, Med El Corporation*, Dallas, TX, February 1-3, 2002.

Wilson BS, Lawson DT, Brill SM, Wolford RD, Schatzer R (RTI); Kiefer J, Pfennigdorff T, Tillein J, Gstöttner W (J. W. Goethe Universität, Frankfurt): Pillsbury H, Gilmer C (UNC Chapel Hill): Combined electric and acoustic stimulation (EAS) studies at the Research Triangle Institute. *2nd Focus Meeting on Electric-Acoustic Stimulation (EAS)*, Las Palmas, Canary Islands, February 24, 2002. (This workshop was sponsored by Med El GmbH.)

Brill SM, Lawson DT: Psychophysics of combined electric and acoustic stimulation of the same cochlea. *2nd Focus Meeting on Electric-Acoustic Stimulation (EAS)*, Las Palmas, Canary Islands, February 24, 2002. (This workshop was sponsored by Med El GmbH.)

Wolford RD: Combined electric/acoustic stimulation: Results and thoughts for future directions. Meeting of the Duke/RTI Cochlear Implant Team, Duke University Medical Center, Durham, NC, March 25, 2002.