Thirteenth Quarterly Progress Report

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Speech Processors for Auditory Prostheses

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I. Introduction

The main objective of this project is to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, such processors will represent the information content of speech in a way that can be perceived and utilized by implant patients. An additional objective is 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 and activities in this quarter included:

- 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.

In this report we describe the recent studies with subject ME14 and relate them to previously reported results obtained with subject ME6. Other work accomplished during this quarter will be described in more detail in subsequent quarterly reports.

II. Cooperative electric and acoustic stimulation of the auditory periphery: comparison of ipsilateral and contralateral implementations

Background

In recent years, we and others have been investigating two new areas of cochlear implant application. One area has involved bilaterally implanted electrodes, and the other combined electric and acoustic stimulation of the same cochlea.

We have studied a total of 14 bilaterally implanted subjects thus far, some of whom had received Nucleus 22 or 24 devices at the University of Iowa and others C40 or C40P devices at clinics in North Carolina, the UK, Germany, and Austria.

In some cases recently, surgeons have limited the depth of insertion of an intracochlear electrode array, in order to preserve low frequency residual hearing in the implanted ear. In a study at the University of Iowa, the insertion depth has been restricted to 6 or 10 mm beyond the round window in such cases, while at the J. W. Goethe Universität in Frankfurt insertion to a depth of 20 mm has been the standard practice. We have studied one of the latter group of subjects (ME6) in some detail, spread over two visits to our laboratory totalling four weeks. Some surgeons have raised concern about immediate damage to residual hearing as a function of insertion depth, and/or long term damage for any insertion depth (some immediate loss has been observed in a few cases at Frankfurt.) Other surgeons favor full insertion to obtain optimal cochlear implant performance, regardless of the impact on any (perhaps temporary) residual hearing.

In our work with binaural implants (see QPRs 4, 9, and 12 for the current contract) the potential benefits of separate processing for stereophonic inputs were, of course, a major emphasis. Also studied, however, were potential benefits of having electrodes available in both ears for stimulation by the output channels of a monophonic speech processor. In the latter studies we observed that information from different parts of the frequency spectrum could be distributed between the two ears in a variety of arbitrary ways without degrading speech reception performance.

In our work with combined electric and acoustic stimulation of a single cochlea (see QPRs 8 and 11 for the current contract) we found that speech reception with the combined modes was much less sensitive to noise interference than when relying on either mode alone.

Considered together, those findings led us to undertake a systematic comparison of ipsilateral and contralateral implementations of combined electrical and acoustical stimulation of the auditory periphery. Recently we completed an initial one week of studies with subject ME14, whose residual hearing is comparable to that of ME6 but in the ear contralateral to the cochlear implant. Among our principal questions were (1) *Can similar advantages in noise be demonstrated for contralaterally as well as ipsilaterally combined electric and acoustic stimulation?* and, if so, (2) *Are the potential benefits great enough to warrant consideration in the context of such clinical decisions as which ear to implant or whether to implant a second ear?* We noted that a decision to reserve the "better ear" to receive complementary acoustic stimulation for use with a contralateral cochlear implant would render moot some of the surgical concerns currently surrounding combined electrical and acoustic stimulation. We set out to repeat with ME14, as exactly as possible, a subset of the studies previously conducted with ME6.

Subjects

Our ipsilateral subject, ME6, was a member of the group implanted at Frankfurt. Our studies with her were reported in QPRs 8 and 11 for the current contract. The subject was born in 1959. Her sudden hearing loss occurred in 1978 during treatment of a severe infection using an ototoxic drug. A right ear hearing aid was employed beginning in 1990. In 1999 Dr. Jan Kiefer inserted a standard Med-El C40P electrode array 20 mm into her right cochlea, placing 8 of the device's 12 electrodes within scala tympani. Pre- and post-implantation clinical audiograms were within 5-10 dB of each other over the frequency range of 125-500 Hz.

The subject related a history of tinnitus from about the time of her sudden hearing loss, periodically requiring drug therapy. Her tinnitus was especially severe immediately post surgery and seems to have remained louder than generally experienced before the cochlear implant, though perhaps softening somewhat recently. The subject also has a pre- and post-implant history of episodic vertigo, for which she continues to receive medication.

Clinically, ME6 uses an 8-channel CIS strategy running on a Tempo+ BTE cochlear implant processor, along with a Resound ITE hearing aid. She reports that her speech understanding is better with the cochlear implant alone than with the hearing aid alone, and best with simultaneous use of both devices.

Our contralateral subject is ME14. She was born in 1933, and began to experience hearing loss -- for which there is a strong familial progressive history -- in 1978. The right ear was aided beginning in 1984, with binaural aids in use by 1987. In early 2001 her right ear was implanted with a standard Med-El C40P electrode array by Dr. Harold Pillsbury at the University of North Carolina in Chapel Hill.

Clinically, ME14 uses a 12-channel CIS strategy running on a Tempo+ BTE cochlear implant whose input microphone is located in a contralateral (left) earhook, an arrangement she says was chosen to facilitate communication when she is a passenger in the right front seat of an automobile. The programming of her left ear Widex Senso ITE aid -- set to boost high frequencies as much as possible -- had not been changed since her implant, and she was no longer using it as of her visit to our laboratory. The subject volunteered, however, that having both her cochlear implant microphone and her (unaided) residual hearing at the left ear facilitated use of the telephone.

Prior to implant surgery ME14 experienced constant tinnitus, which has become less severe and more episodic since. She denies any history of vertigo other than very briefly following surgery.

As we had done earlier with ME6, we assessed ME14's residual hearing by determining relative pure tone thresholds for frequencies of 100 Hz to 1 kHz, at 100 Hz intervals. Results for the two subjects are compared in Figure 1.

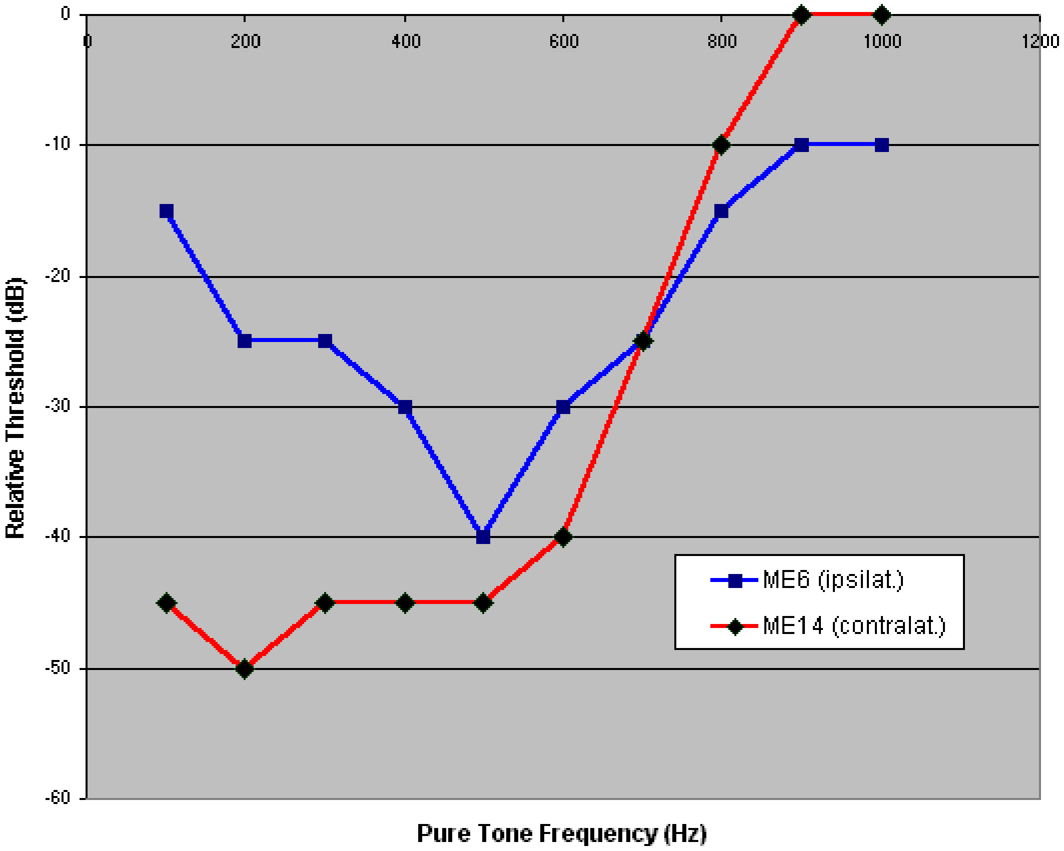

Figure 1. High resolution audiograms. Relative pure tone thresholds obtained under headphones at 100 Hz frequency intervals for the ear ipsilateral to the cochlear implant of subject ME6 (squares connected by blue line) and the ear contralateral to the cochlear implant of subject ME14 (diamonds connected by red line).

The upper frequency limits of significant residual hearing for the two subjects are about the same, approximately 800 Hz, and the variations in threshold as a function of frequency are quite similar down to about 500 Hz. Below 500 Hz, ME14's residual hearing is considerably more sensitive than ME6's, with the difference growing to 30 dB at 100 Hz.

ME6 had pitch ranked all eight of her usable electrodes in normal tonotopic order. ME14 ranked her electrode 3 as lowest in pitch, and was unable to discriminate reliably between electrodes 2 and 4 on the basis of pitch. Ascending pitch order for her electrodes in terms of electrode number was 3, 1, 2/4, 5, 6, 7, 8, 9, 10, 11. Increasing the current amplitude to electrode 12 beyond about one quarter of its threshold-to-MCL dynamic range resulted in a tactile sensation localized at the distal corner of ME14's right eye. Both subjects were able reliably to rank pure tone acoustic stimuli at 100 Hz intervals on the basis of pitch, using their residual hearing, up to about 700 Hz.

Comparison of ipsilateral and contralateral implementations

To compare speech reception performance across the two subjects as a function of stimulation modes and levels of competing speech spectrum noise, we repeated with ME14 a considerable battery of tests designed to be identical with some administered earlier to ME6.

As noted above, ME6 had been tested with eight channel CIS processors utilizing all eight of her available electrodes. In the case of ME14, the indiscriminability of electrodes 2 and 4 and the tactile percepts associated with electrode 12 led us to reduce the number of channels from the 12 she was using clinically. We tested her with an eight-channel laboratory CIS processor using electrodes 3, 1, 5, 6, 7, 8, 10, and 11 in observed pitch order and observed no decrease in performance. Thus the two subjects were compared with very similar signal processing for the electrical mode stimuli. In both cases the processors delivered 26.7 µs/phase pulses at a rate of 2272 p/s/channel in a staggered order of presentation. A first-order 1.2 kHz high-pass filter provided preemphasis. The bandpass filters defining the eight channels were 6th order and divided the overall frequency range logarithmically. Full wave rectification was used in the envelope detectors, along with 4th-order 200 Hz low-pass smoothing filters.

The speech tests included identification of medial consonants in quiet and at +5 dB with respect to CCITT speech-spectrum noise, and identification of words in CUNY sentences at speech-to-noise levels of +10 dB and +5 dB. ME14's high overall performance level led us to use a set of 24 English consonants to obtain sensitivity in quiet, whereas a set of 16 German consonants had been used for the corresponding tests with ME6. The excellent English language abilities of ME6, on the other hand, had allowed use of the CUNY sentence materials, and those tests were repeated exactly with ME14. In each tested condition, there were 10 presentations of each medial consonant token and 4 lists of CUNY sentences containing a total of 408 words.

16-bit, 44.1 ks/s digital recordings were prepared in advance for each speech test condition. Both speech and CCITT noise were processed for incidence from the front using a head related transfer function (HRTF) with pinna and ear canal effects removed. Speech and noise were combined at the specified S/N ratio. One channel of the stereo recording contained that signal for presentation to the cochlear implant speech processor input, while the other channel received the same signal, low pass filtered to exclude components above 1 kHz for presentation via earphone to the ipsilateral or contralateral ear, as appropriate.

Both subjects were tested with three distinct electric signal processing designs. In all three cases the upper limit of frequencies analyzed by the cochlear implant processor was 5.5 kHz. The cases differed in the lower frequency limit of sounds analyzed for representation via electrical stimuli: 300 Hz, 600 Hz, and 1 kHz, respectively.

For each of these three processing conditions and each of the four combinations of speech test material and speech-to-noise ratio, data were obtained for three different modes of stimulation: electric alone, combined electric and acoustic, and amplified acoustic alone. Speech most comfortable loudness (MCL) levels were determined separately for the amplified acoustic signal and each of the three cochlear implant speech processor designs.

All these speech test data for both subjects are summarized in Figure 2.

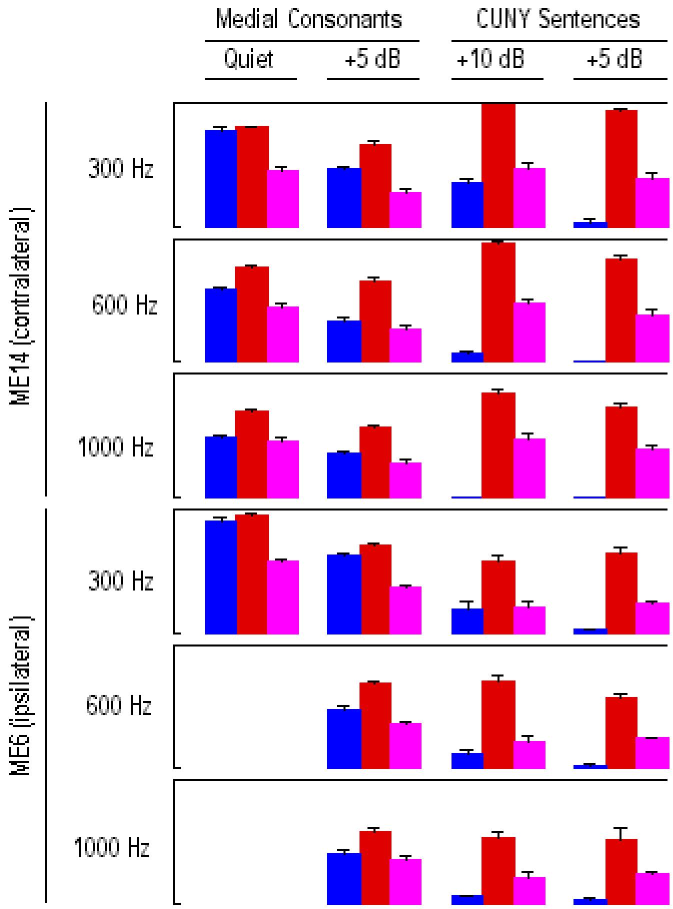

Figure 2. Speech reception data for subjects ME14 (top three rows) and ME6 (bottom three rows). A horizontal line marks the 100% upper scale limit for the bar charts in each row. For each group of three bars, the leftmost (blue) bar is for electric stimulation alone, the center (red) bar is for combined electric and acoustic stimulation, and the rightmost bar (magenta) is for amplified acoustic stimulation alone. The left two columns display percent correct data for medial consonant identification (24 consonants for ME14 and 16 consonants for ME6), with the first column corresponding to speech in quiet and the second to speech at +5 dB with respect to CCITT speech spectrum noise. Error indications on consonant test bars show the standard deviation of the mean, ranging from 1 to 3%. The right two columns display percent correct identification of words in CUNY sentences, at speech-to-CCITT-noise ratios of +10 and +5 dB respectively. The three rows of data for each subject correspond to three different lower bounds on the overall sound spectrum analyzed for electrical stimulation in each case, 300 Hz, 600 Hz, and 1 kHz as indicated. The upper limit of the analyzed spectrum was 5.5 kHz in every case. Performance with acoustic stimulation alone was evaluated only once for each of the four tests; those results are repeated in multiple rows to facilitate comparisons. No testing was done in conditions for which no bars are displayed.

For both subjects, as one would expect, the best performance with electric stimulation alone (leftmost bars, blue in the HTML version) occurs in quiet (first column) and for a speech processor that represents the full 300 Hz to 5.5 kHz frequency range (first and fourth rows). In those two cases, consonant identification performance is not significantly improved by adding the aided acoustic mode. For ME14 we obtained consonant identification data in quiet for all three cochlear implant processing configurations, and the electric-only scores show the decreases one would expect as the overall frequency range represented is reduced by increasing the lower frequency limit from 300 Hz to 600 Hz and then to 1 kHz (leftmost bars, first column, first three rows). Performance in quiet with combined electric and acoustic modes, however, is less sensitive to those manipulations (center bars, first column, first three rows). The acoustic-only scores, of course, are independent of cochlear implant processor configuration. .

In every one of the 18 test conditions for both subjects involving noise (second, third, and fourth columns), combined electric and acoustic stimulation (center bars) supported speech reception results superior to either mode alone (leftmost and rightmost bars).

In quiet, a cochlear implant alone (leftmost bars) supports better consonant identification scores than aided acoustic stimulation alone (rightmost bars, magenta in the HTML version). That difference is reduced for consonant identification at +5 dB with respect to CCITT noise (second column). For identification of words in CUNY sentences at both +10 and +5 dB with respect to such noise, however, amplified acoustic stimulation alone supports better performance than a cochlear implant alone (third and fourth columns).

The negative impact on speech test scores of adding speech spectrum noise is most profound for electrical stimulation alone. Both acoustic stimulation alone and combined electric and acoustic stimulation are much less sensitive to the addition of noise.

Scores for the sentences presented in noise (third and fourth columns) show enormous benefits for combined electric and acoustic stimulation, whether ipsilateral (ME6, last three rows) or contralateral (ME14, first three rows). In many cases, the performance scores for the combined modes far exceed the sum of scores achieved with each mode alone.

Comparing performance in the combined electric and acoustic mode across the three different choices of frequency range conveyed by the cochlear implant, the 1000 Hz case is consistently inferior to the 300 Hz and 600 Hz cases for both subjects. For ME6, the 600 Hz processor configuration supports better sentence performance at +10 dB than the 300 Hz configuration, while the 300 Hz configuration supports equivalent or slightly better performance than the 600 Hz for ME6 at +5 dB and at both noise ratios for ME14. The 1000 Hz setting probably corresponds to an effective gap between the frequency bands represented by acoustic and electric modes, while the 300 Hz setting results in a region of overlapping bands represented in both modes. The 600 Hz setting may come closest to a no gap, no overlap condition among the frequency bands. These results suggest that a modest frequency gap may have a stronger negative effect on performance than a modest frequency overlap.

We note that, on the basis of the data in Figure 1, one might anticipate that inclusion of the lowest frequencies in the cochlear implant representation (300 to 600 Hz) would be more likely to benefit ME6 than would be the case for ME14. At least for +10 dB, however, ME6's combined mode performance with a 600 Hz low frequency limit was decidedly better than with a 300 Hz limit.

Comparison to Earlier Results from the Melbourne Group

Consider the third and fourth columns of Figure 2, for identification of words in CUNY sentences. In the third column -- for +10 dB S/N -- adding acoustic stimulation to electric stimulation improves scores by 39% to 89%, with a median improvement of 62%. Adding electric stimulation to acoustic stimulation at that S/N ratio improves scores by 32% to 53%, with a median improvement of 43%. In the fourth column -- for +5 dB S/N -- adding acoustic stimulation to electric stimulation improves scores by 49% to 90%, with a median of 68%. Adding electric stimulation to acoustic stimulation at that S/N ratio improves scores by 28% to 55%, with a median of 38%.

Armstrong *et al.* of the Melbourne group [M Armstrong, P Pegg, C James, and P Blamey, *Am J Otol* **18**: S140-S141 (1997)] have reported similar data for CUNY sentences mixed with four-talker babble presented in free field at 70 dB(A). Three sentence lists were presented in each condition. Their studies included two groups of subjects, one American and the other Australian. The Americans achieved higher levels of performance as a group. The five American subjects had a mean pure tone average hearing loss of 100 dB (75 - 112 dB HL). All were chronic users of both electric and (contralateral) acoustic stimulation, four with SPECTRA processors and one with a MSP processor. The individual clinical hearing aids were not identified, and there was no indication of any attempt to alter either electric or acoustic stimulation processing to make the two complementary. The American group was tested at both +10 dB and +5 dB, but the data were combined for analysis when no significant difference was observed between scores for the two S/N ratios. No scores were reported for acoustic stimulation alone. Adding use of a hearing aid to use of a cochlear implant improved the group's average score by 22%, (36% cochlear implant only to 58% cochlear implant plus hearing aid).

Pure tone average audiograms, obtained clinically in free field, were 90 dB HL for both our subjects ME6 and ME14.

Since the purpose of the Melbourne paper's comparisons was to assess the advantage of using a hearing aid in addition to a cochlear implant, there was no reason in their studies to employ any means beyond turning off or removing the hearing aids in their free field comparisons of performance. Our experience indicates that residual hearing may well have enhanced performance on their tests of speech reception in noise, even with the hearing aids turned off or removed. If so, ear plugs or other measures to ensure an "electric only" condition might have obtained results comparable to the larger differences observed in our studies.

Comparison to Performance with Bilateral Cochlear Implants in Noise

Consider the second column of Figure 2, where electric stimulation alone supports better performance than acoustic stimulation alone for consonant identification in noise. Adding acoustic stimulation to electric stimulation improves scores by 9% to 33%, with a median improvement of 20% across the 6 conditions.

Recent studies in our lab allow us to compare such improved speech understanding in noise with that achieved by implanting a second ear. In Figure 3 we display Percent identification of 16 or 24 medial consonants in the presence of CCITT speech spectrum noise at S/N values of 0, +5, or +10 dB, for 8 subjects with bilateral cochlear implants.

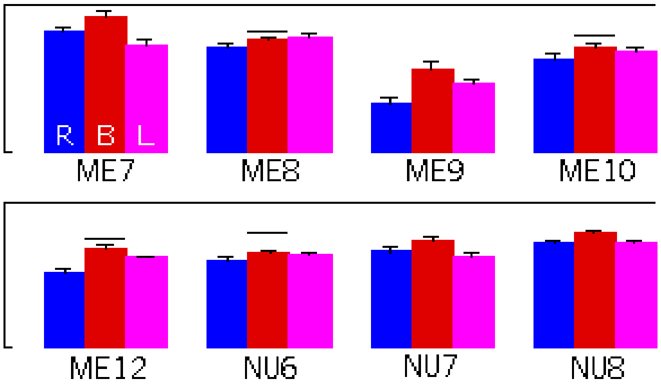

Figure 3. Medial consonant identification in noise by eight subjects with bilateral cochlear implants. Bar heights indicate percent correct scores for both noise and speech coming from the front. A horizontal line marks the 100% upper scale limit for the bar charts in each row. For each group of three bars, the leftmost (blue) bar is for electric stimulation of the right ear alone, the center (red) bar is for electric stimulation of both ears, and the rightmost bar (magenta) is for electric stimulation of the left ear alone. Error indications on the bars show the standard deviation of the mean. For subjects achieving better performance with the same processor configuration for directionally distinct noise, the best recorded score is indicated by a horizontal line above the respective center bar. Depending on the subject, as shown in Table 1 below, the scores are for identification of 16 or 24 English consonants or of 16 German consonants, with speech to CCITT noise ratios of 0, +5, or +10 dB. All scores for each subject were obtained using the same speech test, the same processor configuration, and the same S/N level. Subjects with ME codes use bilateral Med-El implant systems, while codes beginning with NU indicate use of bilateral Nucleus implants.

By comparing the bars in Figure 3 we can obtain percent differences in scores for processor configurations producing the best performances for each subject with both speech and noise coming from the front. The improvements in scores for the use of both ears over the scores achieved with the poorer ear alone ranged from 5% to 23% with a median value of about 10%. The improvements obtained with the use of both ears rather than the better ear alone ranged from -2% to 10% with a median value of about 6%.

The cases represented by bars in Figure 3 were limited to those for which both speech and noise came from the front, to provide the closest comparison to the electric-acoustic data of Figure 2. One might expect additional benefits to be available to the user of binaural implants when speech and noise come from distinct directions. For 4 of the 8 subjects represented in Figure 3 this was true. Those subjects' overall best performance scores with the same processor configurations -- including directionally distinct noise and optimization of better ear orientation with respect to that noise -- are indicated by horizontal lines. Percent differences between those best-condition scores and the corresponding scores using the better ear only with noise from the front ranged from 3% to 18%, with a median difference of about 10%. (Often, of course, it it may not be convenient or even possible to optimize better ear orientation with respect to directionally distinct noise.)

Table 1. Consonant test type, language, and speech-to-noise ratios for subjects included in Figure 3.

Subject	Consonants		Language		S/N (dB)		
	16	24	Eng	Gm	+0	+5	+10
ME7	*			*			*
ME8		*	*			*	
ME9	*			*		*	
ME10	*			*	*		
ME12		*	*			*	
NU6		*	*		*		
NU7	*		*				*
NU8	*		*				*

One should be cautious in comparing such differences in scores between electric-acoustic and bilateral electric stimulation data. Because of generally higher absolute scores for the bilateral electric subjects, for instance, there is insufficient range available on scores for the same tests to accommodate improvements as large as some of those observed in electric-acoustic studies. While alternative metrics could be proposed (*e.g.* fraction of remaining range for each given test and subject) none that we know of would completely avoid the inherent limitations of the present situation.

While we have substantial quantities of data regarding identification of words in sentences by our bilaterally implanted subjects, and have generally found it easier with sentence material than with medial consonant tokens to demonstrate binaural advantage in such subjects, we have been concentrating on benefits associated with directionally distinct noise and as yet have relatively few results for the noise front conditions emphasized in this report. Figure 4 shows one set of such data for one of our subjects, and two sets obtained in free field conditions for another subject studied by Joachim Müller, Franz Schön, and colleagues in Würzburg.

As has been our experience with binaural cochlear implant studies in general, these sentence materials are more sensitive than medial consonant tokens to differences between unilateral and bilateral performance. The results for the Würzburg subject in particular at +5 dB S/N show bilateral improvements that resemble those we have observed for both ipsilateral and contralateral combinations of electric and acoustic stimulation.

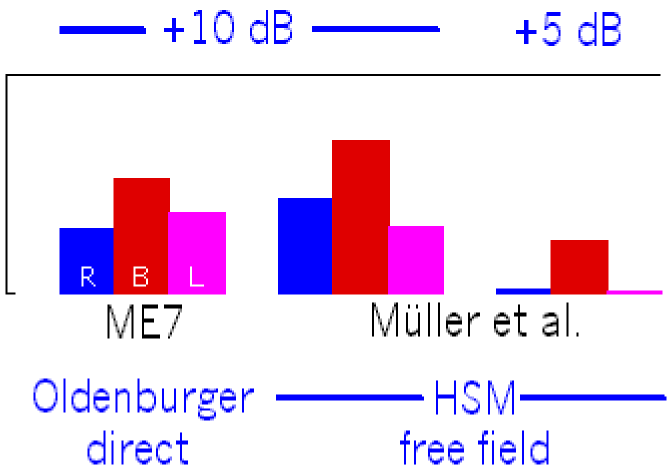

Figure 4. Identification of words in sentences by subjects with electrical stimulation from bilateral cochlear implants, and with both speech and noise presented from the front. In each case the left (blue in the HTML version) bar represents performance with the right ear alone, the right bar (magenta) performance with the left ear alone, and the center (red) bar performance with both at once. A horizontal line indicates 100% performance on the word identification tasks. The left group of bars represents performance by our subject ME7 with a S/N ratio of +10dB for the Oldenburger sentences with respect to CCITT noise. As for other studies in our laboratory, combined speech and noise signals were injected directly into the processor inputs. [The Oldenburger test materials are formulaic German sentences, with each word chosen randomly from a closed set appropriate to a particular location within the sentence. While such materials have obvious differences from open set sentences, they do support extensive comparisons among processor conditions using connected speech. Our experience with these German sentences encourages us to produce similar formulaic connected speech materials in English.] The remaining two groups of bars represent identification of words in the standard German HSM sentences (Hochmair, Schultz, and Moser) by a subject studied by our colleagues in Würzburg. The S/N ratio with respect to CCITT noise was +10 dB in the case of the center group, and +5 dB for the group on the right. Sound was presented in free field conditions and detected by the subject's earhook microphones for cochlear implant processing.

Combined electric and acoustic stimulation and Automatic Gain Controls

Automatic gain controls (AGCs) typically are used clinically in both hearing aids and cochlear implant systems. When two such devices are used together in combined electric and acoustic stimulation, their AGCs will act independently and, typically, differently in response to changes in ambient noise. While our ipsilateral subject ME6 uses combined clinical devices to good effect in the presence of noise, one can imagine circumstances in which the action of one or both AGCs might substantially reduce or even negate the benefits of combined electric and acoustic stimulation that we have observed in laboratory conditions.

Comparison to performance with cochlear implants that also represent lower frequencies

The large benefits we have demonstrated of adding low frequency acoustic stimulation to the electric representation of higher frequency information via cochlear implant raises the question of whether equivalent benefits could be achieved by adding representation of that low frequency information via electric stimulation. Inclusion of information from lower frequency spectral regions was studied in detail some years ago in our laboratory and elsewhere. Those studies, which did not indicate any advantage to including still lower frequencies, also did not evaluate identification of speech in competing speech spectrum noise. We note that our present studies of combined electric and acoustic stimulation also do not show any significant benefit in the absence of noise. We plan to evaluate the addition of lower frequency information to cochlear implant speech processing strategies in tests with competing CCITT speech spectrum noise.

Evolving role of the "better ear" in planning cochlear implantation

The concept of the "better ear" has played a role in decisions regarding implant surgery from the beginning. Generally, the term has referred to the ear with the greater spectral extent and/or sensitivity of residual hearing or, in the absence of any significant difference in those regards, the more recently deafened ear.

In the early years of cochlear implantation, when typical speech reception outcomes were not nearly so good as is the case today, many surgeons preferred not to implant the better ear. This served to minimize any residual hearing destroyed by implantation and made it less likely that the benefits of a cochlear implant would fail to at least compensate for that sacrifice. Reference also was made at that time to preserving the better ear as a future implant site, perhaps to take advantage of technological progress. It was widely suspected that later reimplantation of the same ear would damage its potential as a site for electrical stimulation.

Patients whose better ear was being aided at the time of cochlear implantation on the other side often were counseled to forego use of the aid in the interest of learning to rely on the implant. We know that some patients did try using both devices together, and some of them found the combination advantageous and continued the practice. We do not know of any systematic effort to alter the programming of aids or implant speech processors to make them function in a more complementary way.

As typical cochlear implant speech reception results improved over the years there was an increasing tendency to implant the better ear, in the expectation that results might benefit further from better neural survival on the implanted side. Various upgrade procedures and failures of implanted devices led to a growing surgical experience with explantation of electrode arrays after various periods *in situ* and substitution of new arrays, sometimes of a different design. It was observed that speech reception performance after revision surgery frequently matched or even exceeded that with the original implant.

At the same time the improvement in typical results led to an expansion of the candidate population, to include people with more and more residual hearing. So some of the "better ears" being more frequently implanted also were better and better in absolute terms, with more and more residual hearing being sacrificed at implantation.

Summary

Both our principal questions have been answered affirmatively in the course of the studies described in this report. Contralateral subject ME14 enjoys even greater benefits from combined electric and acoustic stimulation in the presence of competing speech-spectrum noise than we reported earlier for ipsilateral subject ME6. The magnitude of the potential advantage we have documented does seem to merit its consideration at present in decisions about whether to implant the "better ear" even if it retains significant residual hearing, and decisions as to whether to implant a second ear that provides significant residual hearing (and as to the timing of such second implantations in cases of progressing hearing loss). We have observed quite large improvements in situations combining three elements: the presence of competing speech spectrum noise, the representation of higher frequency bands via electrical stimulation of cochlear implant electrodes, and the representation of lower frequencies via an amplified acoustical signal. Data for situations that combine only the first two of these elements are quite discouraging. Data for situations in which low frequency information was conveyed electrically in the absence of competing noise showed no evidence of similar improvements. We plan further studies designed to determine whether there is some unique benefit attached to acoustic representation of lower frequency sounds or, whether similar benefits can be obtained in noise with electrical representation of that additional spectral region. Further research also is needed to determine how best to design automatic gain control(s) for use with combined electric and acoustic stimulation in the presence of noise.

III. Plans for the next quarter

- Resumed schedule of binaural studies with subjects from Europe and the Iowa clinic, beginning with a visit by Iowa subject NU7 February 25 through March 8.
- Beginning of a study in cooperation with Cochlear Corporation and Duke University Medical Center, involving implantation of an experimental perimodiolar electrode array.
- Further development of new processing strategies designed to provide a closer mimicking of normal auditory functions.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.
- Continuing studies throughout the quarter with subjects NU4 and ME12, local recipients of bilateral cochlear implants.
- Presentation of invited talks by Wolford and Lawson at Med-El Corporation's Clinical Research Meeting in Dallas, TX, February 1 - 3, 2002.
- Presentation of a keynote speech by Wilson at the *6th European Symposium on Paediatric Cochlear Implantation*, to be held in Las Palmas, Canary Islands, February 24 - 27, 2002.
- Presentation of invited talks by Wilson and Brill at the *2nd Focus Meeting on Electric-Acoustic Stimulation*, to be held in Las Palmas, Canary Islands, February 24, 2002.

IV. Acknowledgments

We thank volunteer research subjects ME6 and ME14 for their generosity and good humor, and their surgeons and audiological caregivers in Frankfurt and in Chapel Hill, respectively.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of October 1 through December 30, 2001, included the following:

> A presentation by Wilson and Lawson at the *32nd Annual Neural Prosthesis Workshop* in Bethesda, MD, October 18, 2001.
>
> A presentation by Brill on binaural psychophysical studies at a meeting of the Cochlear Implant Group at Duke University Medical Center, November 26, 2001.