Final Report

April 1, 2002 through March 31, 2006
NIH Project N01-DC-2-1002

Speech Processors for Auditory Prostheses

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CONTENTS

I. Human Subjects

The work accomplished under this contract required extensive use of volunteer research subjects with a variety of implanted devices. There were a total of 57 subject visits to our laboratories by a total of 24 different subjects. In duration, those visits ranged from two days to three weeks, for a total of 335 subject days, excluding weekends and holidays. We again express our gratitude to these inspiring people who cheerfully contributed so much of their time in support of improving cochlear implant performance in the future. As has been the case with prior NIH contracts, most of our studies emphasized within-subject comparisons of large numbers of different processor configurations and processing strategies. We also undertook one longitudinal study, of local subjects early in their experience with bilateral cochlear implants.

Subjects were invited to participate in our research on the basis of recommendations from their clinical caregivers, in response to requests from us for suggestions of subjects meeting specific criteria for planned studies. While some subjects were appropriate for multiple study topics, others participated only in one.

Twelve research subjects had bilateral Med-El or Nucleus cochlear implants – some with identical devices in both ears and others with different devices and/or depths of insertion. These subjects participated in a variety of studies designed to assess various potential advantages of bilateral electrical stimulation. Results from those studies were combined with data from additional bilaterally implanted subjects seen during a prior NIH contract.

Six research subjects had percutaneous devices with no implanted electronics, making possible direct electrical connection of laboratory apparatus to their implanted electrodes. Two of those subjects had the six-ball electrode arrays of the Ineraid device. The other four offered temporary percutaneous access to all 24 electrodes of an array currently being used transcutaneously in Cochlear Ltd. products. These percutaneous subjects made possible studies involving stimulation patterns impossible with the intervening implanted electronics of current clinical transcutaneous devices, and direct recordings of intracochlear potentials evoked by electrical stimulation.

Some of the stimulation patterns evaluated in those percutaneous studies were, near the end of the contract, also applied successfully in two transcutaneous subjects, utilizing special features of a new Med-El clinical device, the PULSAR.

Four of the studied subjects had significant residual acoustic hearing – all with a unilateral Med-El device. These subjects participated in studies of combined electric and acoustic stimulation (EAS), extending investigations initiated with two additional Med-El subjects, and one additional Ineraid subject, under a prior NIH contract.

II. Major Areas of Research under this Contract

Bilateral Cochlear Implants

We have considered a wide range of ways in which bilateral intracochlear electrode arrays could be employed to improve speech reception or to support studies to inform the design of better processing for unilateral implants. Our studies have ranged from independent bilateral processors and implanted electrodes, to a single stereo processor with binaural inputs controlling stimulation of both implants, to utilization of electrodes on both sides for stimulation by a single monophonic processor.

We assembled a group of research subjects that provided opportunities to explore the potential benefits of a large number of bilateral electrode pairs with matched pitch percepts, and opportunities to explore the potential benefits of a large number of distinct pitch percepts across the two sides (QPR 1). We completed a survey of detailed pitch ranking data for a total of 22 bilaterally implanted subjects, including some subjects from the prior NIH "speech processors" contract to RTI (QPR 10 of the present contract).

Studies of speech reception in the presence of speech-spectrum noise from the same or distinct directions were analyzed to assess the relative importance of a variety of mechanisms that in similar situations contribute to the performance of listeners with normal hearing. In such studies reported in QPR1, neither variations in stimulation synchronicity between the ears, nor analysis band overlap or offset between the ears, or pitch-distinct assignments of electrodes to channels had any significant effect on performance in noise. In the same report we confirmed and documented the advantages in noise reported by one subject when using a custom in-the-canal microphone system of his own design.

We conducted a longitudinal study with two of our subjects, of improvements in speech reception performance over the first 7 months of their experience with bilateral implants (QPRs 2 and 4). Over that period three trends were observed: (1) relatively slow improvements in overall consonant recognition scores, (2) more rapid improvements in performance when noise came from the same direction as speech, and (3) reduced differences in performance across noise direction differences.

We conducted a study of interaural timing difference (ITD) sensitivity across 7 bilaterally implanted subjects (QPR 4). Among the findings were (1) high sensitivities to ITDs are exhibited by some subjects, as high as 25 µsec or better under some conditions; (2) sensitivities tended to be highest at the apical and middle sections of the electrode arrays, for "pitch matched" pairs of electrodes across the two sides; (3) the minimum ITD that can be detected for a given position in one implant may or may not be sensitive to such matching across the two sides; (4) a relatively sharp dependence on matching across the two sides was found for two subjects at basal sites of stimulation (where sensitivity to ITDs also was lower than at other sites); (5) a much shallower dependence was found at other sites for these and other subjects; and (6) for unmodulated pulse trains, ITD sensitivity decreases as pulse rate is increased from 100 pulses/s to about 1500 pulses/s (the highest rate tested). The sharpest dependence of ITD sensitivity on across-ear matching observed in these implant subjects was not nearly as sharp as the dependence found in normal hearing.

Combined Electric and Acoustic Stimulation

In this case as well, the characteristics of the research subjects we were able to assemble made possible a complete and systematic exploration of the potential benefits of simultaneous cochlear electric and amplified acoustic stimulation (EAS) for speech reception. Across 7 subjects, we had 9 ears with sufficient residual acoustic sensitivity for the purposes of our studies. Thus we were able to compare electric only, acoustic only, and combined EAS for all subjects, with all stimuli delivered to the same side. For three of the subjects, we also were able to compare results for deliveries of the acoustic stimulus on the same side as the implant, to the contralateral ear, or to both ears. All of these cases provided highly sensitive within-subject controls for the comparisons.

Clinical audiograms taken just prior to our studies were available for each subject and for both ears in cases of bilateral acoustic sensitivity. Detailed audiograms also were obtained by us for each ear with residual acoustic sensitivity, to allow custom designs of both the frequency bands for association with each channel of electrical stimulation and the frequency range to be amplified for simultaneous acoustic stimulation (QPR 3).

We found that (1) for some subjects, speech reception scores in noise for combined EAS stimulation exceed the sum of their scores with electric stimulation alone and acoustic stimulation alone; (2) even an extremely limited range of residual hearing can support some improvement in speech reception in the presence of speech spectrum noise; (3) comparable ranges and degrees of residual hearing, however, do not assure comparable benefits from combined EAS stimulation; (4) there was no indication of any difference – within subjects or across subjects – in the EAS benefits to speech reception in speech spectrum noise depending on whether ipsilateral or contralateral residual hearing is used in conjunction with electrical stimulation; (5) EAS is associated with a decreased sensitivity to the negative effects of increasing speech spectrum noise; and (6) in some cases speech reception performance is improved by raising the low frequency boundary of the overall band analyzed by the cochlear implant speech processor, reducing overlap with the range of frequencies conveyed via acoustic stimulation.

Direct Measurements of Intracochlear Potentials Evoked by Electrical Stimulation

With research subjects having direct percutaneous access to their implanted electrodes, we continued to use and refine our apparatus and techniques for recording intracochlear potentials arising in response to electrical stimulation. In QPR 9 we reported on a series of studies using phase-separated balanced biphasic pulses as stimuli.

Development of New Research Tools in Support of Studies with Complex Strategies

An extensive set of new software tools was developed under this contract to allow the rapid realization and testing of new speech processing algorithms too complex for immediate implementation in real-time. A streaming mode was developed, in which stimulation sequences for specific new processor designs and specific test materials were produced as files using computer code written in MATLAB. The stimulation sequence files then serve as input to a program that delivers the appropriate stimuli via the laboratory master processor hardware and interfaces to percutaneous electrodes or various clinical transcutaneous systems, both unilateral and bilateral. Also developed were new programs to supervise and record the results of a variety of psychophysical and speech reception tests, for any combination of unilateral or bilateral processor(s) and real-time or streaming mode realizations (QPR 5).

Noting the high degree of flexibility and control over stimulus patterns, including waveforms, sequencing, and rates inherent in the PULSAR implant system introduced by Med-El in Europe, our laboratory worked closely with colleagues from the University of Innsbruck to develop an interface to give our master processor hardware access to the capabilities of the new transcutaneous implant. The result, described in detail in QPR 11, made possible for the first time transcutaneous realization of some of the new processing strategies that we previously could study only with percutaneous access.

Development of New Speech Processing Strategies

A major thrust during this contract has been the development of speech processing strategies that more closely mimic certain normal auditory functions. Among the principal aspects of such designs have been modeling of compression and level-dependent filtering at the cochlear partition, modeling of inner hair cell membrane and synapse characteristics, the use of conditioner pulses to achieve some stochastic independence among stimulated neurons, the use of fine structure or fine frequency analysis, and the use of virtual stimulation channels obtained by allocation of stimulus currents across more than one physical electrode. As reported in QPRs 6, 7, 8, and 15, we have explored the use of dual-resonance nonlinear filters as a replacement for a bank of linear bandpass filters, and substitution of an inner hair-cell model for the envelope detector and compression table used in traditional CIS designs.

Relationships among the number of physical electrodes available and the utilization of such physical electrodes in combinations to achieve additional (virtual) patterns of stimulation have been studied extensively. A crucial element in such studies was the availability of subjects with percutaneous access to a modern electrode array containing more than the relatively small number of electrodes available in chronic users of the Ineraid implant.

Studies with Percutaneous Access to the Nucleus Contour Electrode Array

With the cooperation of Cochlear Americas and Duke University Medical Center, we were able to study a group of 4 research subjects implanted temporarily with a research version of the Nucleus device, which includes a percutaneous connector in conjunction with the Contour electrode array. The studies selected for these subjects emphasized processors likely to benefit from the closer proximity to target neural tissue expected for this electrode array, and processors likely to benefit from a large number of implanted electrodes but requiring percutaneous access for implementation (QPR 13).

Based on those criteria and on preliminary results with the new approaches to speech processing described above, a set of 100 processor designs was chosen for speech reception studies across the 4 subjects. Fundamental processor types included standard CIS (with various pulse waveforms, numbers of channels, analysis frequency ranges, rates and durations, and smoothing filter characteristics), conditioner pulse processors, processors utilizing DRNL filters, processors utilizing fine structure analysis, processors utilizing both fine structure analysis and DRNL filters, processors with simultaneous stimulation of all channels, and a processor with 3 stimulus channels controlled by a peak-picking analysis (QPR 14).

Unforeseen medical and personal circumstances reduced the time available with 3 of these 4 subjects. Full evaluation across all 4 subjects was achieved with only 11 processors from the intended set. Another 28 were evaluated with 3 of the 4 subjects (QPR 15). A variety of design features included in the processors described in that report are capable of significantly altering speech reception performance under certain combinations of subject and listening conditions. The inclusion of fine structure analysis in general, the exploration of various combinations of the number of analysis channels and the number of stimulus options associated with each channel, and consideration of alternative ways of allocating stimulus options among channels all have demonstrated potential for improving individual performance.

A large number of within-subject binary comparisons of processors differing only in a single respect are included in the data from our Nucleus percutaneous studies, as indicated and briefly described in QPR 15. Full analyses and publication of these data are planned.

Studies Exploiting Special Features of the Med-El PULSAR System

Extension of some of our new speech processing strategies – initially possible only with percutaneous access to implanted electrodes – to transcutaneous subjects as well became possible late in this contract with the availability of our custom interface to the Med-El PULSAR cochlear implant system (see above). Early studies making use of these new capabilities were reported in QPR 12.

A considerable number of the 100 processor designs chosen for evaluation in the Nucleus percutaneous study can be implemented or approximated for transcutaneous testing using this interface. Preliminary studies with PULSAR subjects already have resulted in a 12th processor from the list being evaluated across 4 subjects and 3 additional processors from the list being evaluated across 3 subjects each. While the PULSAR subjects have a different electrode array – one with fewer physical electrodes – it too is an array in current clinical use and we expect future data to contribute to meaningful patterns of performance across the two platforms

III. Suggested Future Directions

Suggested future directions, stemming directly from work in this contract, are presented in the following recent publications:

Wilson BS, Lawson DT, Müller JM, Tyler RS, Kiefer J, et al.: Cochlear implants: Some likely next steps. Annu Rev Biomed Eng 5: 207-249, 2003.

Wilson BS, Sun X, Schatzer R, Wolford RD: Representation of fine-structure or fine-frequency information with cochlear implants. Int Cong Ser 1273: 3-6, 2004.

Dorman MF, Wilson BS: The design and function of cochlear implants. Am Scientist 92: 436-445, 2004.

Wilson BS: Speech processing strategies. In *Cochlear Implants: A Practical Guide, 2nd Edition*, edited by HR Cooper and LC Craddock, Whurr, London and Philadelphia, 2006, pp. 21-69. Wilson BS, Schatzer R, Lopez-Poveda EA: Possibilities for a closer mimicking of normal auditory functions with cochlear implants. In *Cochlear Implants, 2nd Edition*, edited by SB Waltzman and JT Roland, Jr, Thieme Medical Publishers, New York, 2006, pp. 48-56.

Wilson BS, Schatzer R, Lopez-Poveda EA, Sun X, Lawson DT, Wolford RD: Two new directions in speech processor design for cochlear implants. Ear Hear 26: 73S-81S, 2005.

These and six other papers resulting from the project are attached to this report. Additionally, the article by Dorman and Wilson is available online for free at http://www.americanscientist.org/template/AssetDetail/assetid/35121.

IV. Reporting of Results from Work Done under this Contract

Results of our studies under this contract have been extensively reported to colleagues, through 12 publications (copies of which are appended to this report), 15 Quarterly Progress Reports (made available to the public both on the NIH Web site and on our own), 5 guest of honor and one special guest addresses, 2 keynote speeches, 25 additional invited presentations and 7 further presentations at scientific meetings. Blake Wilson chaired 4 conferences during this contract on topics related to its studies, and chaired 9 scientific sessions at scientific meetings. He also was the recipient of a large number of awards and honors associated with the work of this contract. Each of those categories is detailed in the lists below.

Publications

1. 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.
2. 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.
3. Loeb GE, Wilson BS: Cochlear prosthesis. In Adelman G, Smith BH (eds.), *Encyclopedia of Neuroscience*, 3rd edition. Amsterdam: Elsevier, 2004. (The *Encyclopedia* is available both in book and CD-ROM formats.)
4. Loeb GE, Wilson BS: Prosthetics, Sensory systems. In *Handbook of Brain Theory and Neural Networks*, 2nd edition, edited by MA Arbib, MIT Press, Cambridge, MA, 2003, pp. 926-929.
5. 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. In *Cochlear Implants – An Update*, edited by T Kubo, Y Takahashi and T Iwaki, Kugler Publications, The Hague, The Netherlands, 2002, pp. 517-521.
6. Wilson BS, Lawson DT, Müller JM, Tyler RS, Kiefer J, et al.: Cochlear implants: Some likely next steps. Annu Rev Biomed Eng 5: 207-249, 2003.
7. Wilson BS: Engineering design of cochlear implants. In *Cochlear Implants: Auditory Prostheses and Electric Hearing*, edited by F-G Zeng, AN Popper and RR Fay, Springer-Verlag, New York, 2004, pp. 14-52. (This book is Volume 20 in the *Springer Handbook of Auditory Research*, and also may be cited as Wilson BS, *SHAR* 20: 14-52.)
8. Wilson BS, Sun X, Schatzer R, Wolford RD: Representation of fine-structure or fine-frequency information with cochlear implants. Int Cong Ser 1273: 3-6, 2004.
9. Dorman MF, Wilson BS: The design and function of cochlear implants. Am Scientist 92: 436-445, 2004.
10. Wilson BS: Speech processing strategies. In *Cochlear Implants: A Practical Guide, 2nd Edition*, edited by HR Cooper and LC Craddock, Whurr, London and Philadelphia, 2006, pp. 21-69. (Whurr Publishers Ltd. is a subsidiary of John Wiley & Sons Ltd.)
11. Wilson BS, Schatzer R, Lopez-Poveda EA: Possibilities for a closer mimicking of normal auditory functions with cochlear implants. In *Cochlear Implants, 2nd Edition*, edited by SB Waltzman and JT Roland, Jr, Thieme Medical Publishers, New York, 2006, pp. 48-56.
12. Wilson BS, Schatzer R, Lopez-Poveda EA, Sun X, Lawson DT, Wolford RD: Two new directions in speech processor design for cochlear implants. Ear Hear 26: 73S-81S, 2005.

Principal Topics of the Quarterly Progress Reports

QPR	Topic(s)
1	Pitch matched and pitch distinct electrode pairs in binaural processors
2	Longitudinal studies of early progress with binaural cochlear implants
3	New perspectives on combined electric and acoustic stimulation
4	ITD studies with unmodulated pulse trains [and update on longitudinal binaural studies]
5	Recent enhancements of the speech laboratory system [including streaming mode]
6	Strategies for closer mimicking of normal auditory functions – DRNL filter bank
7	Combined use of DRNL filters and virtual channels
8	Representation of fine structure or fine frequency information with cochlear implants.
9	Intracochlear potentials evoked by electrical stimulation with phase-separated balanced biphasic pulses
10	Pitch ranking of electrodes for 22 subjects with bilateral implants
11	Laboratory interface for the new Med-El PULSAR implant
12	Initial studies with a recipient of the PULSAR implant system
13	Progress in the Nucleus percutaneous studies
14	Further progress in the Nucleus percutaneous studies
15	Results from the Nucleus percutaneous studies

Lectures as a Guest of Honor

1. Wilson BS: The RTI's perspective on bilateral cochlear implantation. *Wullstein Symposium 2002*, Würzburg, Germany, December 12-17, 2002. (This second *Wullstein Symposium* included the *3rd Conference on Bilateral Cochlear Implantation and Bilateral Signal Processing*, the *7th International Cochlear Implant Workshop*, and the *1st Workshop on Binaural Rehabilitation.*)
2. Wilson BS: Evaluation of combined EAS in studies at the Research Triangle Institute. *Hearing Preservation Workshop II*, Frankfurt, Germany, October 17-18, 2003.
3. Wilson BS, Wolford RD, Brill S, Lawson DT, Schatzer R: Speech coding for bilateral cochlear implants. *Fifth Wullstein Symposium on Bilateral Cochlear Implants and Binaural Signal Processing*, Würzburg, Germany, December 2-5, 2004.
4. Wilson BS, et al.: EAS and possible mechanisms underlying benefits. *Hearing Preservation Workshop IV*, Warsaw-Kajetany, Poland, October 14-15, 2005.
5. Wilson BS: Cochlear implants: A remarkable past and a brilliant future. *Ninth International Cochlear Implant Conference*, Vienna, Austria, June 14-17, 2006.

Special Guest Address

1. Wilson BS, Schatzer R, Wolford RD, Sun X: Two new directions in implant design. *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004.

Keynote Speeches

1. Wilson BS: Future directions for cochlear implants. *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.
2. Wilson BS: Where are we and where can we go with cochlear implants? *Annual Meeting of the British Cochlear Implant Group: Pushing the Boundaries of Cochlear Implantation*, Birmingham, UK, April 18-19, 2005.

Additional Invited Presentations

1. Lawson DT, Wilson BS, Brill SM, Wolford RD, Schatzer R, Kiefer J, Pfennigdorff T, Tillein J, Gstöttner W., Pillsbury H, Gilmer C: Some Likely Next Steps in the Further Development of Cochlear Prostheses, *Prentice Bloedel Day Lectures*, University of Washington, Seattle, WA, May 20, 2002.
2. Cooper H, Tyler RS (moderators), Graham J, Wilson BS, Plant G, Saeed S (panelists): Panel on the future for adults. *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.
3. Wilson BS: Speech processors for auditory prostheses. *33rd Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, October 16-18, 2002.
4. Lawson DT: Recent progress and current areas of emphasis in cochlear implant research. *Annual Meeting, North Carolina Chapter of the Acoustical Society of America*, Raleigh NC, November 8, 2002.
5. Wilson BS: Evaluation of combined EAS in studies at the Research Triangle Institute. *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, November 8-10, 2002.
6. Brill SM, Wilson BS: Speech coding strategies for binaural cochlear implants. *6th Annual Conference of the German Audiological Society (DGA)*, Würzburg, Germany, March 26-29, 2003.
7. Wilson BS, Brill SM, Cartee LA, Cox JH, Lawson DT, Schatzer R, Sun X, Wolford RD: Recent progress and likely next steps in the development of cochlear implants. *VII International Conference on Cochlear Implants and Related Audiological Sciences*, Warsaw – Kajetany, Poland, May 22-25, 2003.
8. Wilson BS, Lawson DT, Brill SM, Wolford RD, Schatzer R, Kiefer J, Pfennigdorff T, Pok M, Tillein J, Gstöttner W, Baumgartner W-D, Gilmer C. Pillsbury HC: Results from speech reception studies. Satellite Symposium on "Partial deafness cochlear implantation," *VII International Conference on Cochlear Implants and Related Audiological Sciences*, Warsaw – Kajetany, Poland, May 22-25, 2003.
9. Wilson BS, Brill SM, Cartee LA, Cox JH, Lawson DT, Schatzer R, Sun X, Wolford RD: Recent and future cochlear implant stimulation strategies. Conference celebrating *25 Years of Cochlear Implants in Vienna*, Vienna, Austria, June 19, 2003.
10. Wilson BS, Wolford RD, Lawson DT, Schatzer R, Brill SM: Evaluation of combined EAS in studies at the Research Triangle Institute. *2003 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-22, 2003.
11. Tyler R, Witt S, Dunn C, Kane D, Kenworthy M, Wilson B, Rubinstein J, Gantz B, Preece J, Parkinson A: A framework for cochlear implantation guidelines in the case of monaural and binaural fittings. *2003 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-22, 2003.
12. Wilson BS, Lawson DT, Cartee LA, Wolford RD, Schatzer R, Sun X, Cox JH, Lopez-Poveda E, Zerbi M: Speech processors for auditory prostheses. *34th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, October 21-3, 2003. (Presented by Dewey Lawson and Reinhold Schatzer)
13. Wilson BS, Cartee LA, Cox JH, Lawson DT, Lopez-Poveda E, Schatzer R., Sun X, Wolford RD: Future developments of CI. *II Meeting Consensus on Auditory Implants*, Valencia, Spain, February 19-21, 2004.
14. Wilson BS: Recent progress and some possible next steps with cochlear implants. Symposium in honor of Franz Schön, Ph.D., on the occasion of his retirement, Würzburg, Germany, March 20, 2004.

15. Wilson BS, Wolford RD, Lawson DT, Schatzer R, Brill S, *et al.*: Combined electric-acoustic stimulation (EAS) of the auditory system. *Med-El Satellite Meeting, Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004. (Honorary Speaker presentation)
16. Wilson BS, Wolford RD, Lawson DT, Schatzer R, Brill S, *et al.*: Combined electric-acoustic stimulation (EAS) of the auditory system. *Med-El Satellite Meeting, Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004. (Surgeon's Workshop presentation)
17. Wilson BS, Wolford RD, Lawson DT, Schatzer R, Sun X: Update on EAS studies at the Research Triangle Institute. *Hearing Preservation Workshop III*, Dallas, TX, October 15-16, 2004.
18. Wilson BS, Cartee LA, Cox JH, Lawson DT, Schatzer R, Sun X, Wolford RD: The auditory prosthesis as a paradigm for successful neural interfaces. *Neural Interfaces Workshop*, National Institutes of Health, Bethesda, MD, November 15-17, 2004.
19. Wilson BS: Where are we and where are we headed with cochlear implants? Nalli Family Lecture, The Hospital for Sick Children, University of Toronto, Toronto, Canada, February 17, 2005.
20. Wilson BS: Advances in cochlear implant research. Grand Rounds presentation, Department of Otolaryngology, University of Toronto, Toronto, Canada, February 18, 2005.
21. Wilson BS, Lorens A, et al.: Evaluation of combined electric and acoustic stimulation of the auditory system in studies at the Research Triangle Institute. *8th International Conference on Advances in Diagnosis and Treatment of Auditory Disorders*, Kajetany, Poland, May 19-21, 2005. (Presented by Artur Lorens)
22. Wilson BS: Moderator's overview and introduction, session on Signal Processing and Speech in Noise. *2005 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, July 30 to August 4, 2005.
23. Wilson BS, Müller JM, Wolford RD, Lawson DT: Signal processing for binaural devices. *International Binaural Symposium 2005*, Manchester, UK, October 29-31, 2005.
24. Wilson BS: The auditory prosthesis as a paradigm for successful neural interfaces. *Ninth Annual Meeting of the North American Neuromodulation Society*, Washington, D.C., November 10-12, 2005.
25. Gstöttner W (Moderator), Wilson B, Skarzynski H, Kiefer J, Gantz B, Fraysse B, Baumgartner W-D: Roundtable on Electric Acoustic Stimulation. *Ninth International Cochlear Implant Conference*, Vienna, Austria, June 14-17, 2006.

Additional Presentations

1. Wolford RD: Bilateral cochlear implants = Binaural advantage? *Annual Meeting of the American Academy of Audiology,* Philadelphia PA, April 18-20, 2002.
2. Tyler RS, Gantz BJ, Rubinstein JT, Witt S, Bryant D, Wilson BS: What we have learned about binaural hearing? *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.
3. Schatzer R, Wilson BS, Lopez-Poveda EA, Zerbi M, Wolford RD, Lawson DT: A novel CI speech processing structure for closer mimicking of normal auditory functions. *2003 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 17-22, 2003. (poster presentation)
4. Skarzynski H, Wilson BS, Lorens A, Piotrowska A: Electroacoustic stimulation in patients with partial deafness. *XXXI Congress of the European Society for Artificial Organs*, Warsaw, Poland, September 8-11, 2004.

5. Adunka A, Unkelbach M, Radeloff A, Wilson BS, Gstoettner W: Outcomes of hearing preservation and cochlear vulnerability in cochlear implant recipients. *10th Symposium on Cochlear Implants in Children*, Dallas, TX, March 15-19, 2005.
6. Lorens A, Wilson BS, Piotrowska A, Skarzynski H: Electric and acoustic pitch perception after Partial Deafness Cochlear Implantation (PDCI). *8th International Conference on Advances in Diagnosis and Treatment of Auditory Disorders*, Kajetany, Poland, May 19-21, 2005.
7. Cartee LA, Finley CC, van den Honert C, Lawson DT, Wilson BS: Intracochlear evoked potential responses to biphasic pulses with an interphase gap. *2005 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, July 30 to August 4, 2005. (poster presentation)

Chaired Conferences

1. Miyamoto RT, Wilson BS (Co-Chairs): *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, November 8-10, 2002.
2. Roland PS, Wilson BS (Co-Chairs): *Third Hearing Preservation Workshop*, Dallas, TX, October 15-16, 2004.
3. Eddington DK, Wilson BS (Co-Organizers with the assistance of JF Patrick and C van den Honert): Special retreat on *Future Directions for Cochlear Implants*, Boston, MA, March 17-19, 2006. (This retreat included approximately 20 invited participants.)
4. Wilson BS, Dorman MF (Co-Chairs): *Hearing Preservation Workshop V*, to be held in the Research Triangle Park, NC, October 13-14, 2006.

Chaired Sessions

1. Wilson BS (Session Moderator): Evaluation of combined electric and acoustic stimulation of the auditory system. *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, November 8-10, 2002.
2. Hochmair E, Wilson B, Lenhardt M, Czyzewski A (Co-Chairs): Session on "Cochlear and Brain Stem Implants and Related Audiological Problems." *VII International Conference on Cochlear Implants and Related Audiological Sciences*, Warsaw – Kajetany, Poland, May 22-25, 2003.
3. Wilson B, Skarzynski H (Co-Chairs): Satellite Symposium on "Partial deafness cochlear implantation." *VII International Conference on Cochlear Implants and Related Audiological Sciences*, Warsaw – Kajetany, Poland, May 22-25, 2003.
4. Wilson BS, Hartmann R, Klinke R (Co-Chairs): Special session on "Future directions for cochlear implants," Department of Physiology, Institute of Physiology III, JW Goethe Universität, Frankfurt, Germany, October 16, 2003. (This session was held the day before the *Hearing Preservation Workshop II*, also held in Frankfurt. The session included approximately 30 participants.)
5. Wilson BS (Chair): Session on "Clinical Issues." *Hearing Preservation Workshop II*, Frankfurt, Germany, October 17-18, 2003.
6. Wilson BS, Talavage TM (Co-Chairs): Session 2C. *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004.
7. Wilson BS (Chair): Session on "Neural Enhancement." *Hearing Preservation Workshop III*, Dallas, TX, October 15-16, 2004.
8. Wilson BS (Moderator): Session on "Signal Processing and Speech in Noise." *2005 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, July 30 to August 4, 2005.

9. Wilson BS (Chair): Afternoon session on "Hearing Preservation, Partial Deafness Cochlear Implantation, and EAS." *Hearing Preservation Workshop IV*, Warsaw-Kajetany, Poland, October 14-15, 2005.

Major Awards and Honors (to Wilson)

Special Guest of Honor, *Ninth International Cochlear Implant Conference*, Vienna, Austria, June 14-17, 2006. (Blake Wilson, Graeme M. Clark, and James F. Battey, Jr. are the only people to be so honored in this series of the largest conferences in the field.)

Guest of Honor, *Hearing Preservation Workshop IV*, Warsaw-Kajetany, Poland, October 14-15, 2005.

The Keynote Speaker for the *Annual Meeting of the British Cochlear Implant Group: Pushing the Boundaries of Cochlear Implantation*, Birmingham, UK, April 18-19, 2005.

Visiting Professor, University of Toronto, February 2005

Guest of Honor, *Fifth Wullstein Symposium on Bilateral Cochlear Implants and Binaural Signal Processing*, Würzburg, Germany, December 2-5, 2004.

Designation as a "Friend Forever" to the International Center of Hearing and Speech in Kajetany (near Warsaw), Poland, October 14, 2004.

Special Guest, *Eighth International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004.

Guest of Honor, *Hearing Preservation Workshop II*, Frankfurt, Germany, October 17-18, 2003.

Guest of Honor, *Wullstein Symposium 2002* (*3rd Conference on Bilateral Cochlear Implantation and Bilateral Signal Processing*, *7th International Cochlear Implant Workshop*, and *1st Workshop on Binaural Rehabilitation*), Würzburg, Germany, December 12-17, 2002.

Named as an Honorary Member of the British Cochlear Implant Group, September 6, 2002.

V. Colleagues Collaborating in Work under this Contract

Our work under the present contract has greatly benefited from collaboration with many colleagues. A partial list follows, of those who participated directly in studies with research subjects in our labs.

Joachim Müller, M.D., Ph.D., University of Würzburg, Germany
Enrique A. Lopez-Poveda, Ph.D., University of Salamanca, Spain
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VI. Assistance from Device Manufacturers

The value of work done under this contract has been greatly increased by the cooperation and contributions of manufacturers of clinical cochlear implant systems.

In multiple instances, Med-El underwrote travel expenses for research subjects coming from Europe.

Cochlear Americas supplied and maintained the wearable devices, and underwrote medical and audiological costs for the Nucleus percutaneous study.

VII. Acknowledgments

This work would not have been possible without the participation of our many volunteer subjects, or without the tremendous assistance outlined in sections V and VI above.

Summary of Salient Results

"Speech Processors for Auditory Prostheses"
Contract No. N01-DC-8-2105
Research Triangle Institute
Blake S. Wilson and Dewey T. Lawson, Principal Investigators

Major areas of research under this contract included (1) studies of ways in which bilateral cochlear implants can be employed to improve speech reception (e.g. in competing directional speech-spectrum noise) or inform the design of better processing for unilateral implants (e.g. through additional stimulation channels and reduced channel interaction); (2) studies of ways in which simultaneous cochlear electric and amplified acoustic stimulation can be combined to improve speech reception, especially in the presence of competing speech-spectrum noise; (3) direct measurements of intracochlear potentials evoked by electrical stimulation, allowing processor designs based on knowledge of responses actually produced at the auditory nerve rather than on knowledge only of the electrical stimuli; (4) studies of new speech processing strategies that more closely mimic functions of normal hearing (including the development of new research tools in support of such studies); and (5) studies — using subjects with direct electrical access to their implanted electrodes — of processing strategies that would have been impossible to realize using any existing clinical system with implanted electronics. Across these areas, many cases were observed in which processor modifications developed under this contract substantially improved speech reception by human subjects using cochlear implants.