

Toward Better Representations of Sound with Cochlear Implants

by

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Dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy
in the Department of Electrical and Computer Engineering
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2015

ABSTRACT

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Abstract

This dissertation is about the first substantial restoration of human sense using a medical intervention. In particular, the development of the modern cochlear implant (CI) is described, with a focus on sound processors for CIs. As of October 2015, more than 460 thousand persons had each received a single CI on one side or bilateral CIs for both sides. More than 75 percent of users of the present-day devices use the telephone routinely, including conversations with previously unknown persons and with varying and unpredictable topics. That ability is a long trip indeed from severe or worse losses in hearing. The sound processors, in conjunction with multiple sites of highly-controlled electrical stimulation in the cochlea, made the trip possible.

Many methods and techniques were used in the described research, including but not limited to those of signal processing, electrical engineering, neuroscience, speech science, and hearing science. In addition, the results were the products of collaborative efforts, beginning in the late 1970s. For example, our teams at the Duke University Medical Center and the Research Triangle Institute worked closely with investigators at 27 other universities worldwide.

The most important outcome from the research was unprecedented levels of speech reception for users of CIs, which moved a previously experimental treatment into the mainstream of clinical practice.

Dedication

This dissertation is dedicated to my wonderful wife and two daughters, Doris Jane Rouse, Nadia Jacqueline Wilson, and Blair Elizabeth Wilson, and to my parents, Joseph Richard Hoyle (Hank) Wilson and Lucy Jacqueline Jones Wilson. They all have given me great joy and more than anyone else have made me who I am.



Hank Wilson soon after he graduated from the engineering school at Duke. He was in the class of 1947 and immediately thereafter served with great pride and distinction in the U.S. Navy. I was supremely fortunate to follow in my dad's footsteps at Duke, where I received a spectacular education and met my future wife. I am so very lucky.

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List of Abbreviations

APSCI 2015 10th Asia-Pacific Symposium on Cochlear Implants and Related Sciences

ASA	Acoustical Society of America
AzBio	Arizona Biomedical Institute (as in the AzBio sentences)
BM	basilar membrane
BTE	behind the ear (as in a BTE housing for a hearing aid)
CA	compressed analog
CI	cochlear implant
CID	Central Institute for the Deaf (as in the CID sentences)
CIS	continuous interleaved sampling
CNC	consonant-nucleus-consonant (as in the CNC words)
CSA	Chief Strategy Advisor
CT	computed tomography
CUNY	City University of New York (as in the CUNY sentences)
DUH	Duke University Hospital
EAS	electric and acoustic stimulation (as in combined EAS)
ECE	electrical and computer engineering
F0	fundamental frequency
F1	first formant frequency
F2	second formant frequency
GOH	Guest of Honor
HINT	Hearing in Noise Test (as in the HIHT sentences)
IHC	inner hair cell (in the cochlea)

ILD	interaural level difference
IP	interleaved pulses (as in the IP strategies)
LED	light emitting diode
LP	long play (as in a stereo LP record)
MED-EL	Medical Electronics GmbH, of Innsbruck, Austria
NIH	United States' National Institutes of Health
NPP	Neural Prosthesis Program
NU-6	Northwestern University Auditory Test 6 (as in the NU-6 words)
Nuc/Han	Nucleus/Hannover
Nuc/USA	Nucleus/USA
PDCI	partial deafness cochlear implantation
PI	Principal Investigator
PTA	pure tone average
RH	residual hearing
RTI	Research Triangle Institute
S/N	speech-to-noise ratio
SEM	standard error of the mean
SPIN	Speech Perception in Noise (as in the SPIN sentences)
ST	scala tympani
UCSF	University of California at San Francisco
UTD	University of Texas at Dallas
UTS	University of Technology, Sydney

Acknowledgements

I was encouraged by the Pratt Leadership team to apply for entry into the graduate program at Duke, in Electrical and Computer Engineering (ECE), even though I had had a decades-long and successful career in research and had earned two higher doctorates, one in science and the other in engineering. The team was extremely kind in their encouragement, and they knew I would love to have an even closer connection with Duke, my cherished alma mater. The team worked with others in ECE and with Liz Hutton and John Klingensmith in the graduate school to help me in the application process and to make pursuit of a Ph.D. a feasible possibility for me. In addition to Liz and John, I am so very grateful to Tom Katsouleas, Leslie Collins, Larry Carin, Guillermo Sapiro, George Truskey, and perhaps others who played key roles in enabling me to become a candidate for a Ph.D. at Duke. All of you are wonderful and generous and kind. You have made a dream come true for me!

I may be the eldest graduate student at Duke ever. I am proud and fortunate to have this singular opportunity.

My committee and advisor have to be the best anywhere and at any time. Each of the members is at the top of the “who’s who” list in her or his field(s). I am so privileged and humbled to have this most special committee and advisor, and I am overwhelmed by their generosity in spending time to help guide me in the Ph.D. program.

The committee members are Tom, Leslie, Guillermo, Bill Joines, Deb Tucci, and Warren Grill. Leslie is my advisor. Wow, what a group!

I am especially grateful to Leslie for her tremendous help every step of the way. Her great expertise is an inspiration to me, and her highly informed help has been invaluable.

And I am especially grateful to Tom for his idea to encourage me to become a candidate for a Ph.D. at Duke and for his many spectacular and generous efforts on my behalf, including nominating me and others for awards and asking me to give the *Duke Engineering 75th Anniversary Lecture*, in addition to his efforts related to the Ph.D. Thank you, Tom; thank you a million times over!

I also have been supremely fortunate to have known Deb, Bill, Leslie, and Warren for decades. Indeed, Bill was one of my first teachers; Leslie and I have been colleagues in research to develop cochlear implants (CIs); Warren and I were Principal Investigators within the Neural Prosthesis Program at the National Institutes of Health; and Deb and I have worked closely together since she arrived at Duke in 1994. Like Tom, Bill and Deb also have nominated me for wonderful awards. Knowing Leslie, Bill, Warren, and Deb for all of these years has been among the greatest joys in life for me.

And my newer friendships with Tom, Larry, Guillermo, and George have made my happy life even better and richer. They like Bill, Warren, Leslie, and Deb are spectacular people and I am so very lucky to know them!

This dissertation describes important advances in the development of the CI, a device that now can restore – or instate for the first time – highly useful hearing for persons with severe or worse losses in hearing. The advances were products of team efforts, as described in the Acknowledgements section and Appendix A in a recent book by me and Professor Michael F. Dorman, *Better Hearing with Cochlear Implants: Studies at the Research Triangle Institute* (Plural, 2012). The section and appendix from the book are included here as Appendices A and B.

As described in the Appendices A and B and Chapter 3 in this dissertation, much of the work was conducted by our joint Duke/Research Triangle Institute (Duke/RTI) team. One of our first laboratories was in the Baker House within the Duke University Medical Center, and in retrospect many of the most important discoveries were made in that (tiny, one-room) laboratory.

Members of that stellar team are shown in the photograph on the next page, a photo that brings back many fond memories for me. The team was special, and together we did something that was wonderful.



The Duke/RTI team in the late 1980s. The photo was taken at an entrance to the Baker House, and pictured from left to right are Dewey Lawson, Charles Finley, Robert Wolford, Joseph Farmer, Ronald Crenshaw, Patrick Kenan, and Blake Wilson.

1. Introduction

Unlike most graduate students, I was accepted into the program at Duke following a decades-long career in research. Thus, the order for me was reversed compared to the usual path, in which a relatively young person prepares for a career in research or other endeavors by first earning a Ph.D. and learning from that experience and her or his mentors and fellow students.

I had the great good fortune to serve as the Principal Investigator (PI) for 26 projects even though I didn't have a Ph.D. I subsequently earned two higher doctorates, one in science and the other in engineering, and received two honorary doctorates in medicine, but most of the work was done when my sole degree was a B.S.E.E. from Duke. That degree, along with the wonderful further instruction I received from Bill Joines, Pete Casseday, Don Wright, George Pearsall, Joe Farmer, and many other members of the Duke Faculty, enabled me to do something important later in life. I am so lucky and so very grateful to Duke and the many magnificent and generous people at Duke who took me under their broad wings.

My path also is counter to the usual path for earning a higher doctorate. Higher doctorates are only awarded at a much higher standard than the standard used for the Ph.D., and for that reason awards of higher doctorates are exceedingly rare and typically follow a Ph.D. or an M.D. degree by decades of singular achievements in research or the

arts. The higher doctorates are the highest among the terminal degrees in the arts, sciences, and engineering.

This dissertation reflects more than three decades of research that I directed. Most of the research was supported by the National Institutes of Health (the NIH) through its Neural Prosthesis Program (NPP). The support administered by the NPP was for seven large and contiguous projects that spanned 23 years and that all had the title “Speech Processors for Auditory Prostheses,” although a wide range of studies and activities was included in the projects that went well beyond the design and evaluation of novel speech processors.

These projects and their impact are described in the overview chapter in a recent book by me and Professor Michael F. Dorman of Arizona State University, *Better Hearing with Cochlear Implants: Studies at the Research Triangle Institute* (Wilson and Dorman, 2012a). In broad terms, the work contributed strongly to the development of progressively better strategies for transforming sound inputs into patterns of highly controlled electrical stimuli for users of cochlear implants (CIs), including a breakthrough in sound processing and implant performance in 1989.

The overview chapter (Chapter 1 in the book) is reproduced in Appendix C to this dissertation, with the permission of the publisher.

I also have served as the PI for additional projects supported by the NIH and other agencies such as the United States’ Environmental Protection Agency. My career

started at the Research Triangle Institute (the RTI) in 1974, where I began as a research (electrical) engineer and later served sequentially as the Head of the Neuroscience Program, the Director of the Center for Auditory Prosthesis Research, and finally as one of the first four RTI Senior Fellows. (The first four were appointed simultaneously.) In parallel with these positions, I have been a member of the Adjunct Faculty at Duke since 1984 and helped to create the Cochlear Implant Program in the same year and then the Duke Hearing Center in 2008. At present, I have seven appointments at Duke, including Co-Director (along with Co-Director Debara L. Tucci, M.D., M.S., M.B.A., F.A.C.S.) of the Duke Hearing Center; Adjunct Professor in the Departments of Surgery and of Electrical and Computer Engineering; Consulting Professor in the Department of Biomedical Engineering; the first Scholar in Residence for the Pratt School of Engineering (a position that was created for me and approved by the university administration); Investigator and member of the Affiliated Faculty for the Duke Institute for Brain Sciences; and member of the Affiliated Faculty for the Duke Global Health Institute. In addition, I presently serve as the Chief Strategy Advisor (CSA) for MED-EL Medical Electronics GmbH of Innsbruck, Austria, and as the Director of its Basic Research Laboratory, which is located in the Research Triangle Park, NC, USA. (MED-EL is the second largest and fastest growing manufacturer of hearing prostheses worldwide, with approximately 2000 employees as of November 2015; in my role as the CSA I provide evidence-based advice to the CEO on possible future directions for the company.) Further current

appointments for me include: Honorary Professor at the University of Warwick in Coventry, UK; Adjunct Professor in the School of Behavioral and Brain Sciences at the University of Texas at Dallas (UTD) in Richardson, TX, USA; Adjunct Professor in the Department of Electrical Engineering at the UTD; and Adjunct Professor in the Department of Bioengineering also at the UTD. (The latter departments are within the Erik Jonsson School of Engineering and Computer Science at the UTD.)

When I began my work in the CI field in the late 70s (please see Chapter 3 in this dissertation), CIs provided an awareness of environmental sounds but little discrimination among the sounds for their users. In addition, the CIs were a helpful adjunct to lipreading. Speech understanding with hearing alone was not possible and indeed many experts in otology and auditory science at the time thought that reinstatement of useful hearing – and certainly speech understanding – was a fool’s dream. For one example among many, the eminent and highly esteemed auditory physiologist Rainer Klinke said in 1978 that “From a physiological point of view, cochlear implants will not work.”

That was the context of our initial work in the field. But we and others persevered and ultimately were able to develop devices that in fact enabled high levels of speech recognition for their users, with the CI alone and in the absence of any visual cues. For example, telephone conversations are routine for most CI users today, even

with an unfamiliar person at the other end and even for varying and unpredictable topics. That ability is an amazing trip from total or nearly total deafness!

I am proud to say that I and the teams I directed played major roles in improving the performance of CIs to the point where they have become the standard of care for deaf and severely hearing impaired persons, and where the great majority of CI users can understand speech with high accuracy and relative ease in most everyday situations. This spectacular outcome could not have been reasonably imagined in 1978 (and for many years thereafter), even by the most ardent proponents of CIs.

1.1 Contributions to Date

My main contribution to date is development of sound processing strategies for CIs that produced unprecedented levels of speech reception for implant users. The strategies are used in all of the present-day CIs and have been used in all of the commercially available devices since the early 1990s.

Additional contributions are described in the aforementioned book and in many other publications. The book has received rave reviews, one of which is reproduced (with the permission of the publisher) in Appendix D to this dissertation.

I have approximately a hundred peer-reviewed publications, including the most highly cited publication in the specific field of CIs, published in the journal *Nature* in 1991. (The paper in *Nature* became the most highly cited publication in the field at the end of 1999 and has remained so ever since; it now has about twice as many citations as

the next most highly cited publication in the field.) In addition, I am the first author for 51 detailed quarterly and final progress reports for the NIH, and a coauthor for 40 more of the reports.

The work by me and the teams I have directed has been recognized by many awards and honors, including but not limited to the following: the 2015 Fritz J. and Dolores H. Russ Prize, “for engineering cochlear implants that enable the deaf to hear” (to me and four others); appointment in 2014 as a Life Fellow of the IEEE; the 2013 Lasker-DeBakey Clinical Medical Research Award, “for the development of the modern cochlear implant” (to me and two others); the American Otological Society President’s Citation in 1997, “for major contributions to the restoration of hearing in profoundly deaf persons” (to me and three others); and the 1996 Discover Award for Technological Innovation in the category of “sound.” In addition, I have been the Guest of Honor (GOH) at 13 international conferences and at three national conferences (in the UK, the Republic of Korea, and the USA) to date. I also have served as the Chair for two international conferences and as the Co-Chair for three others. I have given GOH, keynote, or other invited talks at more than 180 conferences, and I have given 13 named lectures to date, including the *Neel Distinguished Research Lecture*, a *Hopkins Medicine Distinguished Speaker Lecture*, one of the *Flexner Discovery Lectures*, and most notably the *Duke Engineering 75th Anniversary Lecture*.

I also am a distinguished alumnus of the Pratt School; that great honor was conferred to me in 2007, the year after Bill Hawkins won the distinguished alumnus award.

Among the honors, the Russ Prize and the Lasker Award are especially significant. The Russ Prize is the world's top honor for bioengineering. The two Lasker Awards for medical research (the Lasker-DeBakey Award and the Albert Lasker Basic Medical Research Award) are second only to the Nobel Prize in Physiology or Medicine for recognizing advances in medicine and medical science and indeed more than a third of Lasker Laureates go on to win the Nobel Prize at a later time. (For example, all three winners of the 2014 Nobel Prize in Physiology or Medicine were Lasker Laureates and one of the three winners of the 2015 Prize was a Lasker Laureate.) The Russ Prize is one of three awards conferred by the United States' National Academy of Engineering that are popularly known as the "Nobel Prizes for Engineering," and the two Lasker Awards for medical research are popularly known as "America's Nobels."

1.2 Accolades and Achievements during Blake's Time as a Graduate Student

I matriculated as a student in the Graduate School at Duke in early January 2015. In the ten months since then, I have been privileged to receive multiple awards and honors, including:

- The Russ Prize, announced on January 7, 2015, and conferred on February 24, 2015

- An honorary doctorate in medicine from Uppsala University in Sweden, January 30, 2015
- An honorary doctorate in medicine from the University of Salamanca in Spain, May 11, 2015
- The Gold Medal of the Paul Sabatier University in Toulouse, France, June 18, 2015, for “the development of the cochlear implant” (separate medals were conferred to me and three others)
- Appointments as an Adjunct Professor in multiple schools and departments at the UTD, spring 2015
- The cover story for the spring 2015 issue of the *DukeMed Alumni News* magazine, which has a circulation of more than 18,000
- Featured along with others including Dr. Tucci in one of three videos for the annual staff event for the Duke University Hospital (DUH), April 13, 2015; the video is “Walter’s Story” and is available at <https://today.duke.edu/2015/05/walters-story#video>
- The Physician Award from the DUH, April 20, 2015 (to me and three others, including Dr. Tucci)
- Promotion from Adjunct to Consulting Professor in the Department of Biomedical Engineering at Duke, August 17, 2015

- Invitation to be the Guest of Honor at the 4th Munich^{LMU} Hearing Implant Symposium 2015: *Hearing Implants Around the World*, to be held at the Ludwig-Maximilians-Universität München, in Munich, Germany, December 10-13, 2015
- Invitation to be the Guest of Honor at the 149th Annual Meeting of the American Otological Society, to be held in Chicago, IL, USA, May 18-22, 2016
- Invitation to be the Guest of Honor along with Andrej Kral, M.D., Ph.D., at the 2nd Global Otology Research Forum, to be held in Las Palmas de Gran Canaria, Spain, November 29 through December 2, 2017

Photos taken at the ceremonies for the Russ Prize and for the honorary doctorate from the University of Salamanca are presented in Figures 1.1 and 1.2, respectively, and the cover for the *DukeMed Alumni News* magazine is presented in Figure 1.3. The photos in particular bring back wonderful memories for me.

In addition to receiving the awards and honors just listed, I have given or have been asked to give 20 invited talks during the time I have been a graduate student at Duke, including the *Duke Engineering 75th Anniversary Lecture* given in the Baldwin Auditorium on March 5, 2015; the *Graham Fraser Memorial Lecture* given in Bristol, UK, on March 19, 2015; one of three speeches to inaugurate the Institute for Auditory Neuroscience at the University of Göttingen, given in Göttingen, Germany, on March 21, 2015; the inaugural *RTI Distinguished Lecture* given in the Research Triangle Park, NC, USA, on April 14, 2015; a Surgical Grand Rounds Presentation given at the



Figure 1.1: Tom Katsouleas, Blake Wilson, and Marnie Rhoads (l-r) at the ceremony for the Russ Prize, which was held at the National Academy of Sciences in Washington, DC, on February 24, 2015. Tom was the nominator for the Prize, and he was assisted in the preparation of the nomination by Marnie and by Peter S. Roland, M.D., of the University of Texas' Southwestern Medical Center in Dallas and who was the nominator for the 2013 Lasker-DeBakey Award.

Northwestern University Medical Center in Evanston, IL, USA, on April 16, 2015; the inaugural keynote speech for the *10th Asia Pacific Symposium on Cochlear Implants and Related Sciences* given in Beijing, China, on May 1, 2015; my acceptance speech for the honorary doctorate from the University of Salamanca, given in Salamanca, Spain, on May 11, 2015; and the inaugural keynote speech for the *Perth Auditory Implant Workshop* given via video link from the USA to Perth, Australia, on October 29, 2015. A complete



Figure 1.2: Conferment ceremony at the University of Salamanca, during which Blake Wilson received an honorary doctorate in medicine. The University is the fourth oldest in the world, and the ceremony was held in its venerated first hall. Pictured from left to right are Daniel Hernández Ruipérez, Enrique López-Poveda, and Blake. Daniel is the Rector of the University (equivalent to the President for universities in the USA), and Enrique is a full professor there and was the principal promoter for Blake to receive the doctorate. The ceremony included most professors from the University and many other guests, including recipients of cochlear implants. A video of the ceremony is available at <http://saladeprensa.usal.es/webusal/node/51499>, and the speeches given by the three persons in the photo are posted at <http://saladeprensa.usal.es/webusal/node/51401>. The University of Salamanca is the foremost and oldest university in Spain and all other Spanish-speaking countries.

list of the talks along with further details about each of the talks is presented in

Appendix E to this dissertation.



This man has helped restore hearing for nearly half a million people

BLAKE WILSON'S
JOURNEY
TO DEVELOP
THE COCHLEAR
IMPLANT.



Figure 1.3: Cover of the spring 2015 issue of the *DukeMed Alumni News* magazine.



Figure 1.4: Blake Wilson presenting the *Duke Engineering 75th Anniversary Lecture*. The Lecture was in the Baldwin Auditorium on March 5, 2015. A sign-language interpreter is shown to Blake’s right. (The photo is from the *DukeMed Alumni News* magazine and is reproduced here with permission.)

Of course, the *75th Anniversary Lecture* was most special to me. In it I recalled my father, who graduated from the Engineering School at Duke in 1947, in the class with Edmund T. Pratt, Jr., for whom the School was named in 1999. A photo taken during the *Anniversary Lecture* is presented in Figure 1.4. It was a grand occasion, full of meaning and with a wonderful audience and introductory speeches by Provost Sally Kornbluth and Dean Tom Katsouleas. (The *Lecture* was jointly supported by the Office of the Provost, the Pratt School of Engineering, and the School of Medicine.)

In addition to the aforementioned activities, I organized and chaired with Michael Dorman two special sessions at the *Annual Spring Meeting of the Acoustical Society of America (ASA)*, to celebrate the development of the modern cochlear implant and the first substantial restoration of human sense using a medical intervention. The special sessions were sponsored by the ASA Committees on Psychological and Physiological Acoustics; Biomedical Acoustics; Speech Communication; and Signal Processing in Acoustics. The *Spring Meeting* was held in Pittsburgh, PA, USA, on May 18-22, 2015, and the special sessions spanned the full day of May 19. The President of the ASA, Dr. Judy R. Dubno, asked us to organize and chair the sessions.

I also chaired two sessions at the *14th Hearing and Structure Preservation Workshop* held in Nashville, TN, USA, on October 8-11, 2015. The sessions were on “Outcome prediction and improvement” and “Assessment – From cortex to periphery.”

I further had five publications during the period, which were:

- Wilson BS: Getting a decent (but sparse) signal to the brain for users of cochlear implants. Special issue of *Hearing Research* on cochlear implants and in celebration of the 2013 Lasker-DeBakey Clinical Medical Research Award, “for the development of the modern cochlear implant, a device that bestows hearing to individuals with profound deafness.” *Hear Res* 322: 24-38, 2015. (The article is offered as an open access publication at <http://dx.doi.org/10.1016/j.heares.2014.11.009>.)

- Wilson BS, Dorman MF, Gifford RH, McAlpine D: Cochlear implant design considerations. In Young NM, Iler Kirk K (Eds.), *Cochlear Implants in Children: Learning and the Brain*. Springer, New York, 2015.
- Saunders JE, Barrs DM, Gong W, Wilson BS, Tucci DL: Cost effectiveness of childhood cochlear implantation *versus* deaf education in Nicaragua: a disability adjusted life year model. *Otol Neurotol* 36(8): 1349-1356, 2015.
- Wilson BS: Cochlear prosthesis. Reference module in *Neuroscience and Biobehavioral Psychology*. Elsevier, Oxford, UK, 2016a. (Scheduled for publication in January 2016)
- Wilson BS: Possibilities for narrowing the remaining gaps between prosthetic and normal hearing. *The Hearing Journal*, 2016b. (Scheduled for publication in February 2016)

The activities and events described in this section – on accolades and achievements since I have been a graduate student at Duke – were in addition to my ongoing projects and duties at Duke, at the UTD, at the University of Warwick, and as the CSA and Laboratory Director for MED-EL.

1.3 This Dissertation

Although this dissertation presents findings from decades of research, all but one of the remaining chapters are based exclusively or in part on papers published or accepted for publication during the time I have been a graduate student at Duke. In addition, Chapter 2 is based in part on the *75th Anniversary Lecture*.

The remaining chapters are:

- Chapter 2 – Background
- Chapter 3 – Toward Better Representations of Sound with Cochlear Implants
- Chapter 4 – Getting a Decent (but Sparse) Signal to the Brain for Users of Cochlear Implants
- Chapter 5 – Possibilities for Narrowing the Remaining Gaps Between Prosthetic and Normal Hearing

Chapter 2 is based in part on the paper by Wilson et al. (2015) cited in the previous section. The Chapter provides information about normal hearing, losses of hearing, the function of a cochlear prosthesis, electrical stimulation of the auditory nerve, components of CI systems, and transformation of a sound input into the electrical stimuli for a CI.

Chapters 3-5 have the same titles as their source publications and present my story and the stories of our teams (Chapter 3); a detailed technical exposition of an important advance in the NIH projects and in CI design and performance (Chapter 4); and a look toward the future (Chapter 5). The source publication for Chapter 3 is Wilson (2013), the one source publication that predates my time as a graduate student at Duke. The source publication for Chapter 4 is Wilson (2015), and Chapter 5 is a superset of Wilson (2016b). Chapter 3 and its source are included for completeness in presenting the progression of the research from its beginnings to the present and beyond.

The source for Chapter 3 was published in the special issue of *Nature Medicine* celebrating all three of the 2013 Lasker Awards (including the two medical research awards plus the Lasker~Bloomberg Public Service Award), and the source for Chapter 4 was published in the special issue of *Hearing Research* celebrating the 2013 Lasker~DeBaakey Award, as mentioned previously.

I am happy to note that Melinda and Bill Gates won the Public Service Award the same year I and two others won the Lasker~DeBaakey Award. The awards ceremony was a great event for Duke; with two of its graduates (Melinda and me) receiving awards (please see Figures 1.5 and 1.6 on the next two pages). Among the 300+ attendees were Duke's President Richard H. Brodhead and Dr. Tucci, who graced the occasion with their scintillating presence.

1.4 Concluding Remarks

This Introduction includes more information than is usual for a Ph.D. dissertation, reflecting my unusual path and providing a summary description of the research I conducted and directed before becoming a candidate for a Ph.D. at Duke. I hope the additional information will be helpful!



Figure 1.5: Photo taken just prior to the ceremony for the 2013 Lasker Awards. At the dais and in the upper right corner are Melinda Gates and Blake Wilson, and in the left foreground is Duke's President Richard H. Brodhead, who had just congratulated Melinda and Blake. At the top on the left is Professor Joseph L. Goldstein, Chair of the Lasker Jury for the two medical research awards, and in the center with the red coat is Claire Pomeroy, M.D., M.B.A., and President of the Lasker Foundation. Just behind Melinda is Professor Eric R. Kandel, who is a member of the Jury and gave a speech at the ceremony. Professors Goldstein and Kandel are Nobel Laureates, as were many others in the room.



Figure 1.6: Photo taken during the ceremony for the 2013 Lasker Awards. Persons on the right side of the dais are shown, including Professor Goldstein, Melinda Gates, Blake Wilson, and Graeme Clark, who also won the Lasker~DeBaakey Award along with Ingeborg Hochmair and Blake.

2. Background*

2.1 Aspects of Normal Hearing

In normal hearing, sound waves traveling through air reach the tympanic membrane via the ear canal, causing vibrations that move the three small bones of the middle ear. This action produces a piston-like movement of the stapes, the third bone in the chain. The “footplate” of the stapes is attached to a flexible membrane in the bony shell of the cochlea called the oval window. Inward and outward movements of this membrane induce pressure oscillations in the cochlear fluids, which in turn initiate a traveling wave of displacement along the basilar membrane (BM), a highly specialized structure that divides the cochlea along its length. This membrane has graded mechanical properties. At the base of the cochlea, near the stapes and oval window, it is narrow and stiff. At the other end, near the apex, the membrane is wide and flexible. These properties give rise to the traveling wave and to points of maximal response according to the frequency or frequencies of the pressure oscillations in the cochlear fluids. The traveling wave propagates from the base to the apex. For an oscillation with a single frequency, the magnitude of displacements increases up to a particular point along the length of the membrane and then drops precipitously thereafter. High

* Sections of this chapter are reproduced or adapted from Wilson and Dorman (2011) with the permission of the publisher. Additional sources include Wilson et al. (2015), also with the permission of the publisher, and the *Duke Engineering 75th Anniversary Lecture*, given at Duke by Wilson in March 2015.

frequencies produce maxima near the base of the cochlea, whereas low frequencies produce maxima near the apex.

Motion of the BM is sensed by the inner hair cells (IHCs) in the cochlea, which are attached to the top of the BM in a matrix of cells called the organ of Corti. Each hair cell has fine rods of protein, called stereocilia, emerging from one end. When the BM moves at the location of a hair cell, the rods are deflected as if hinged at their bases. Such deflections in one direction increase the release of chemical transmitter substance at the base (other end) of the cells, and deflections in the other direction inhibit the release. The variations in the concentration of the chemical transmitter substance act at the terminal ends of auditory neurons, which are immediately adjacent to the bases of the IHCs. Increases in chemical transmitter substance increase discharge activity in the nearby neurons, whereas decrements in the substance inhibit activity. Changes in neural activity thus reflect events at the BM. These changes are transmitted to the brain via the auditory nerve, the collection of all neurons that innervate the cochlea.

The steps described above are illustrated in the top panel of Figure 2.1. This panel shows a cartoon of the main anatomical structures, including the tympanic membrane, the three bones of the middle ear, the oval window, the BM, the IHCs, and the adjacent neurons of the auditory nerve.

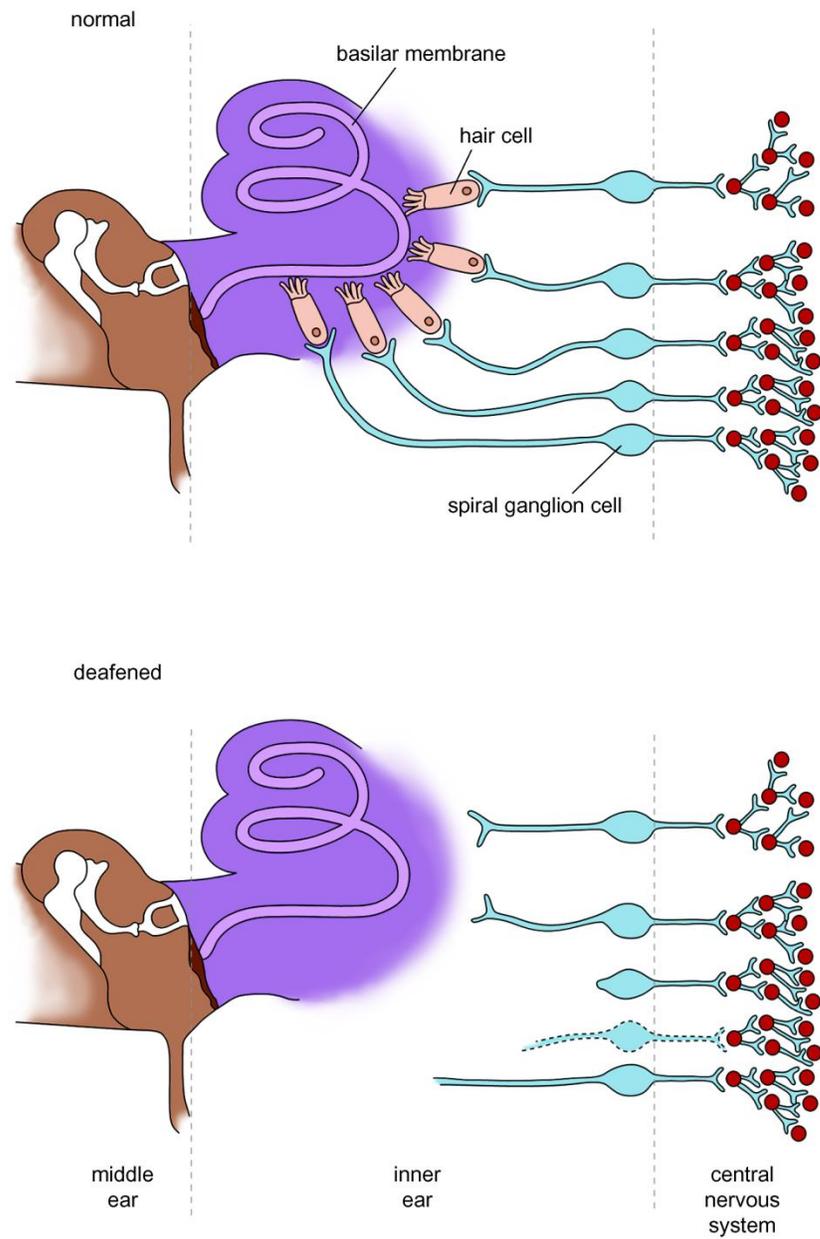


Figure 2.1: Illustrations of anatomical structures in the normal and deafened ears. Note the absence of sensory hair cells in the deafened ear. Also note the incomplete survival of spiral ganglion cells and of neural processes peripheral to cells that are still viable. For simplicity, the illustrations do not reflect the details of the structures or use a consistent scale for the different structures. (Figure is reproduced from Dorman and Wilson, 2004, with the permission of the American Scientist and Sigma Xi, The Scientific Research Society.)

2.2 Loss of Hearing and the Function of a Cochlear Prosthesis

The principal cause of hearing loss is damage to or complete destruction of the sensory hair cells. Unfortunately, the hair cells are fragile structures and are subject to a wide variety of insults, including but not limited to genetic defects (e.g., the defects producing Usher syndrome Type I), infectious diseases (e.g., rubella and meningitis), overexposure to loud sounds, certain drugs (e.g., kanamycin, streptomycin, and cisplatin), and aging. In the deaf or deafened cochlea, the hair cells are largely or completely absent, severing the connection between the peripheral and central auditory systems. The function of a cochlear prosthesis is to bypass the (missing or damaged) hair cells by stimulating directly the surviving neurons in the auditory nerve.

The anatomical situation faced by designers of cochlear implants (CIs) is illustrated in the bottom panel of Figure 2.1. The panel shows a complete absence of hair cells. In general, cells may remain for some patients, usually in the apical (low frequency) part of the cochlea.

Without the normal stimulation provided by the hair cells, the peripheral parts of the neurons – between the cell bodies in the spiral ganglion and the terminals within the organ of Corti – undergo “retrograde degeneration” and eventually die (Hinojosa and Marion, 1983). Fortunately, the cell bodies are far more robust. At least some cell bodies usually survive, even for prolonged deafness or for virulent etiologies such as meningitis (Hinojosa and Marion, 1983; Miura et al., 2002; Leake and Rebscher, 2004).

2.3 Electrical Stimulation of the Auditory Nerve

Direct stimulation of the nerve is produced by currents delivered through electrodes placed in the scala tympani (ST), one of three fluid-filled chambers along the length of the cochlea. A cutaway drawing of the implanted cochlea is presented in Figure 2.2. The figure shows a partial insertion of an array of electrodes into the ST. The array is inserted through a drilled opening made by the surgeon in the bony shell of the cochlea overlying the ST (called a “cochleostomy”) and close to the base of the cochlea. Alternatively, the array may be inserted through the second flexible membrane of the cochlea, the round window membrane, which also is close to the basal end of the cochlea and ST.

Different electrodes in the implanted array may stimulate different subpopulations of neurons. As described above, neurons at different positions along the length of the cochlea respond to different frequencies of acoustic stimulation in normal hearing. Implant systems attempt to mimic or reproduce this “tonotopic” encoding by stimulating basally situated electrodes (first turn of the cochlea and lower part of the drawing) to indicate the presence of high-frequency sounds, and by stimulating electrodes at more apical positions (deeper into the ST and ascending along the first and second turns in the drawing) to indicate the presence of sounds with lower frequencies. Closely spaced pairs of bipolar electrodes are illustrated here, but arrays of single electrodes that are each referenced to a remote electrode outside the cochlea also may be

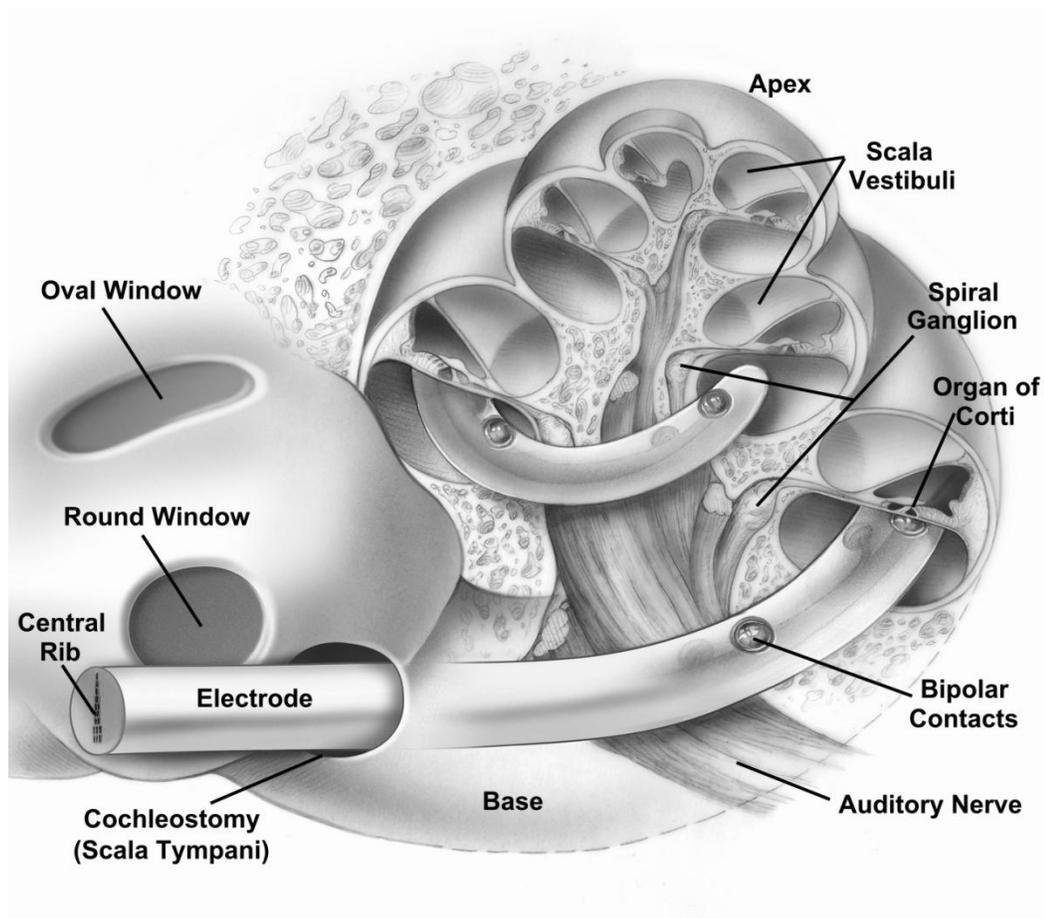


Figure 2.2: Cutaway drawing of the implanted cochlea. The electrode array developed at the University of California at San Francisco is illustrated (Loeb et al., 1983). That array includes eight pairs of bipolar electrodes, spaced at 2 mm intervals and with the electrodes in each pair oriented in an “offset radial” arrangement with respect to the neural processes peripheral to the ganglion cells in the intact cochlea. Only four of the bipolar pairs are visible in the drawing, as the others are “hidden” by cochlear structures. This array was used in the UCSF/Storz and Clarion® 1.0 devices. (Figure is reproduced from Leake and Rebscher, 2004, with the permission of Springer Science + Business Media.)

used. This latter arrangement is called a “monopolar coupling configuration” and is used in all present-day CI systems that are applied in standard clinical practice.

The spatial specificity of stimulation with a ST electrode most likely depends on variety of factors, including the orientation and geometric arrangement of the electrodes, the proximity of the electrodes to the target neural structures, and the condition of the implanted cochlea in terms of nerve survival and ossification. An important goal of electrode design is to maximize the number of largely non-overlapping populations of neurons that can be addressed with the electrode array. Present evidence suggests, however, that no more than 4–8 independent sites are available using current designs, even for arrays with as many as 22 electrodes, as described in section 5.2 in this dissertation. Possibly, the number of independent sites is limited by substantial overlaps in the electric fields from adjacent (and more distant) electrodes. The overlaps are unavoidable for electrode placements in the ST, as the electrodes are “sitting” in the highly conductive fluid of the perilymph and additionally are relatively far away from the target neural tissue in the spiral ganglion. A closer apposition of the electrodes next to the inner wall of the ST would move them a bit closer to the target cells (see Figure 2.2), and such placements have been shown in some cases to produce an improvement in the spatial specificity of stimulation (Cohen et al., 2006). However, a large gain in the number of independent sites may well require a fundamentally new type of electrode, or a fundamentally different placement of electrodes. The many issues related to electrode design, along with prospects for the future, are discussed for example in Wilson (2004), Spelman (2006), and Wilson and Dorman (2008b).

Figure 2.2 shows a complete presence of hair cells (in the labeled organ of Corti) and a pristine survival of cochlear neurons. However, the number of functional hair cells is zero or close to it in cases of total deafness. In addition, survival of neural processes peripheral to the ganglion cells (the “dendrites”) is at least unusual in the deafened cochlea. Survival of the ganglion cells and central processes (the axons) ranges from sparse to substantial. The pattern of survival is in general not uniform, with reduced or sharply reduced counts of cells in certain regions of the cochlea. In all, the neural substrate or target for a CI can be quite different from one patient to the next. A detailed review of these observations and issues is presented in Leake and Rebscher (2004).

A more modern electrode array is shown in Figure 2.3. It includes wave-shaped interconnecting wires and small cross-sectional areas that provide great flexibility for the insertions. That flexibility minimizes trauma and allows for deeper insertions into the ST compared with other types of electrodes (Hochmair, 2013). The relative absence of trauma may help to preserve any hair cells and remaining hearing in the apical region of the cochlea, and the deeper insertions may provide access to most or all surviving neural structures in the cochlea, including the structures in the apical region (Hochmair, 2013; Hochmair et al., 2015).

Electrode arrays like the one shown in Figure 2.2 are no longer used. In addition, bipolar stimulation is no longer used at least in the commercially available devices, as mentioned previously.

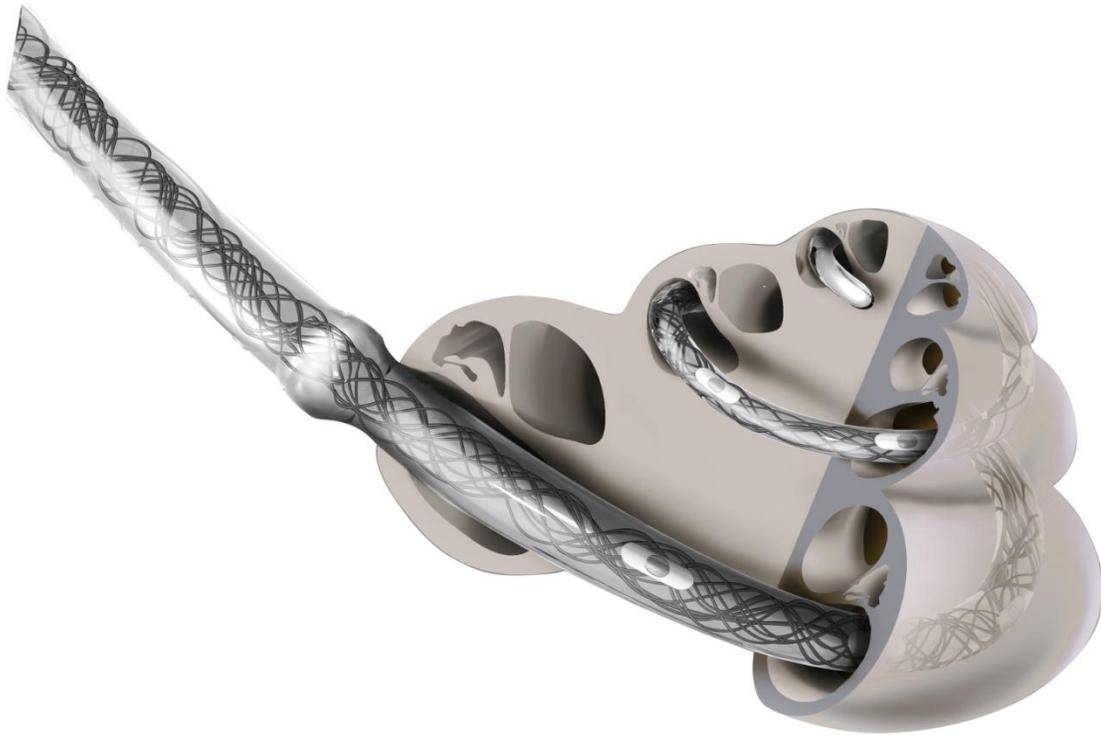


Figure 2.3: Drawing of a modern electrode array for cochlear implants. (Drawing courtesy of MED-EL GmbH, of Innsbruck, Austria)

2.4 Components of Cochlear Implant Systems

The essential components in a cochlear prosthesis system are illustrated in Figure 2.4 and include: (1) a microphone for sensing sound in the environment; (2) a speech processor to transform the microphone input into a set of stimuli for the implanted array of electrodes; (3) a transcutaneous link for the transmission of power and stimulus information across the skin; (4) an implanted receiver/stimulator to decode the information received from the radio-frequency signal produced by an external

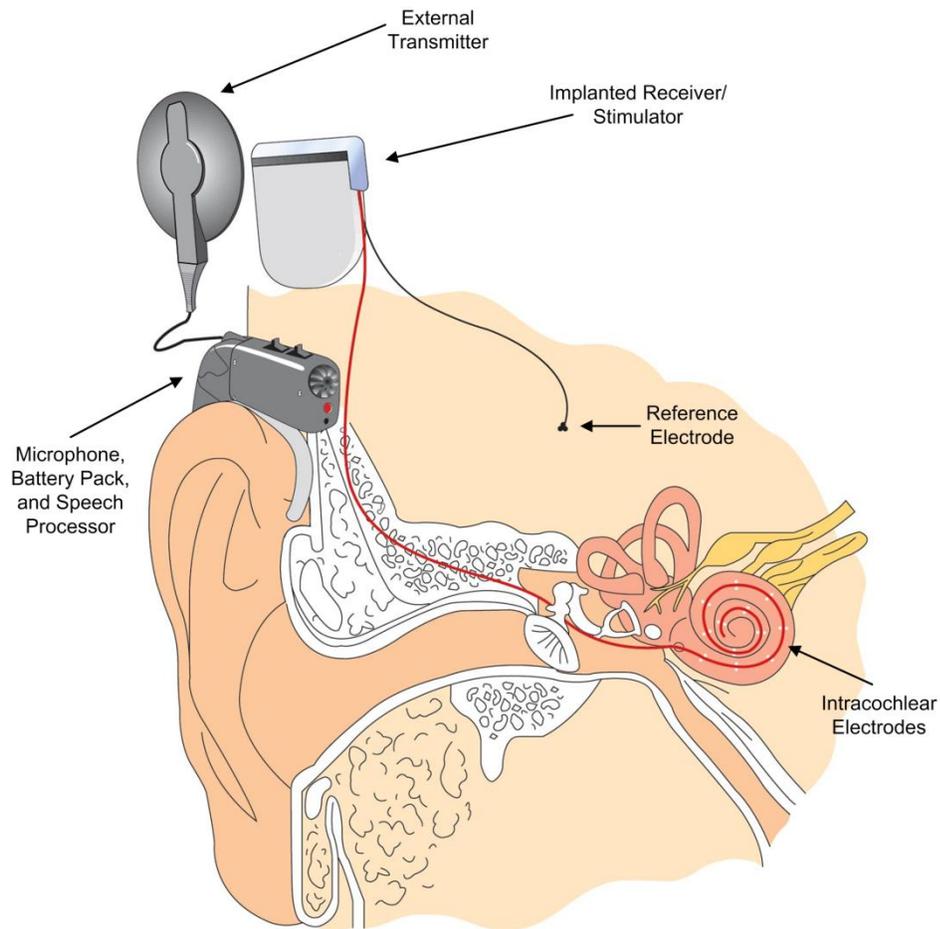


Figure 2.4: Components of a cochlear implant system. The TEMPO+ system is illustrated, but all present-day implant systems share the same basic components. The microphone, battery pack, and speech processor are incorporated into a behind-the-ear (BTE) housing in the illustrated system, much like the BTEs of hearing aids. A thin cable connects the output of the speech processor (a radiofrequency signal with encoded stimulus information) to an external transmitting coil that is positioned opposite to an implanted receiver/stimulator. The transmitting coil is held in place with a pair of magnets, one in the center of the coil and the other in the case of the implanted receiver/stimulator. The receiver/stimulator is implanted in a flattened or recessed portion of the skull, posterior to and slightly above the pinna. The reference (or “ground”) electrode is implanted at a location remote from the cochlea, usually in the temporalis muscle. For some implant systems, a metallic band around the outside of the receiver/stimulator package serves as the reference electrode. An array of active electrodes is inserted into the scala tympani (ST) through the round window membrane or through a larger drilled opening in the bony shell of the cochlea (a cochleostomy) near the round window. (Diagram courtesy of MED EL GmbH, of Innsbruck, Austria)

transmitting coil and then to generate stimuli using the instructions obtained from the decoded information; (5) a cable to connect the outputs of the receiver/stimulator to the electrodes; and (6) the array of electrodes. These components must work together as a system to support good performance and a weakness in a component can degrade performance significantly. For example, a limitation in the data bandwidth of the transcutaneous link can restrict the types and rates of stimuli that can be specified by the external speech processor and that limitation in turn can limit performance.

One “component” that is not illustrated in Figure 2.4 is the biological part central to the auditory nerve (colored yellow in the figure), including the auditory pathways in the brainstem and the auditory cortices of the implant recipient. As described in Wilson et al. (2011) and in many other papers (e.g., Lee et al., 2001; Shepherd and Hardie, 2001; Rauschecker and Shannon, 2002; Sharma et al., 2002; Tobey et al., 2005; Kral et al., 2006; Kral and Eggermont, 2007; Fallon et al., 2008; Moore and Shannon, 2009; Lazard et al., 2012, 2014), this part varies in its functional integrity and capabilities across patients, and is at least as important as the other parts in determining outcomes with CIs.

2.5 Transformation of a Microphone Input into Stimuli for the Implant

An important aspect of the design for any type of sensory neural prosthesis is how to transform an input from a sensor or array of sensors into a set of stimuli that can be interpreted by the nervous system. The stimuli can be electrical or tactile, for examples, and usually involve multiple sites of stimulation, corresponding to the spatial

mapping of inputs and representations of those inputs in the nervous system. One approach to the transformation – and probably the most effective approach – is to mimic or replicate at least to some extent the damaged or missing physiological functions that are bypassed or replaced by the prosthesis.

For CIs, this part of the design is called the processing strategy. As described in all histories of CIs published after the early 1990s (e.g., Finn et al., 1998, and Wilson and Dorman, 2008a), and in the remainder of this dissertation, advances in processing strategies have produced quite large improvements in the speech reception performance for users of CIs, from recognition of a tiny percentage of monosyllabic words with the first strategies and multi-site stimulation, for example, to recognition of a high percentage of the words with the present strategies and multi-site stimulation.

3. Toward Better Representations of Sound with Cochlear Implants*

“From a physiological point of view, cochlear implants will not work.”

This statement by Professor Rainer Klinke in 1978 was not the first criticism of efforts to develop a treatment for deafness using electrical stimulation of the auditory nerve. Klinke was accompanied and preceded by a chorus of experts in otology and hearing science who proclaimed that such an idea was a fool’s dream. The cochlea, with its exquisite mechanical machinery, its complex arrangement of more than 15,000 sensory hair cells, and its 30,000 neurons, could not possibly be replaced by a crude and undifferentiated stimulation of many neurons *en mass*. The argument was a good one. However, the pioneers in the field persevered in the face of the vociferous criticism. Foremost among these pioneers was William F. House, who developed with Jack Urban the first cochlear implant system that could be safely applied over a patient’s lifetime and that generally provided an awareness of environmental sounds and an aid to lipreading (Bilger et al., 1977). This achievement was a huge step forward.

* This chapter is from Wilson (2013), published in the special issue of *Nature Medicine* celebrating the 2013 Lasker Awards. Copyrights to articles published in any of the journals in the Nature Publishing Group are retained by the author(s), and *Nature Medicine* is in the Group. This article also was included as one of the ten articles and a book in the successful submission by the author for a higher doctorate in engineering from the University of Technology, Sydney (the UTS), in Sydney, Australia. The article is included as a source in the present dissertation for completeness and with the permission of the UTS.

The House system and other early systems used a single channel of processing to transform sound sensed by a microphone into patterns of electrical stimulation, as well as a single site of stimulation in or on the cochlea. Many or most surviving neurons were stimulated synchronously and in more or less the same way with the single site of stimulation. Only temporal information could be conveyed with these early implants, but it was enough to provide the aforementioned benefits, and it was sufficient in other single-site systems to support some speech recognition for some patients, most notably in the early systems developed by Ingeborg and Erwin Hochmair.

Some of the early developers believed that temporal information was paramount for auditory perception, but other early developers believed that representation of different frequencies with different sites of stimulation in the cochlea was also important, if not the dominant or even the sole code for frequencies. These latter persons included, but were not limited to, Graeme Clark, Donald Eddington, and Michael Merzenich, as well as their respective teams (Wilson and Dorman, 2008a).

3.1 My Entry into the Field

I was trained initially as an electrical engineer but became interested in hearing research first through my solo project to recreate the perception of three-dimensional hearing from the two tracks of information in a stereo long-play (LP) record. I learned aspects of auditory psychophysics in the project and was fascinated by the intricacies of hearing.

I later became keenly aware of the problems of deafness and severe hearing losses through another project, which aimed to provide supplementary information for deaf persons automatically and in real time to disambiguate the challenges of lipreading. This project involved analyzing speech with a small computer and relaying the output of the speech analysis to a set of light-emitting diode (LED) displays mounted on the stems of eyeglasses, such that the LED displays projected virtual images that the user could see to either side of the lips of a person speaking to her or him. This second project was directed by Robert L. Beadles and was conducted at the Research Triangle Institute (RTI) in the Research Triangle Park in North Carolina, USA, where I also was employed. I assisted Bob in the project from 1974 through much of 1978.

In 1977 I applied for and won an RTI professional development award to visit three of the four centers in the United States that were then active in the development and first applications of cochlear implants. I wanted to learn more about what these centers were doing and whether I could be helpful in any of their ongoing efforts, such as in the area of speech analysis.

I visited Bill House and members of his team in Los Angeles; Blair Simmons, Robert White, and other members of the team at Stanford University; and Mike Merzenich and his team at the University of California at San Francisco (UCSF). The visits were in 1978, the same year Professor Klinke made the statement I quoted above. After my visit to UCSF, Mike asked me to be a consultant for the project there. I happily

agreed, and that was the beginning of my direct involvement in the field of cochlear implants.

3.2 ‘Speech Processors’ Projects

A few years later, in 1983, I won the first in a series of seven contiguous projects to develop cochlear implants, with an emphasis on design and evaluation of novel processing strategies for implants. These projects were supported through the Neural Prosthesis Program at the US National Institutes of Health (NIH), and spanned 23 years. Advances we made in these projects are among the advances being honored by the 2013 Lasker-DeBakey Clinical Medical Research Award.

Our first studies with implant patients were conducted at UCSF. Mike Merzenich and many others there were our gracious hosts, and they all helped us mightily in getting started.

In late 1984, I received a call from Joseph C. Farmer Jr., who was an otologic surgeon at Duke. Joe mentioned that he had heard about our work at UCSF and wondered whether we might want to work a little closer to home, at Duke University, less than ten miles from the RTI. Of course, I thought Joe’s idea was wonderful and welcomed it, so long as we could continue our partnership with UCSF, which we did for many years. We built a laboratory at Duke in 1985 and conducted most of our patient studies there for the next ten years, at which point we built two new laboratories at the RTI, one for speech-reception studies and the other for evoked-potential studies. We

made a transition to the RTI laboratories over the next two years and all subsequent studies were conducted at the RTI.

Joe, I and others also founded the Cochlear Implant Program at Duke in 1985, which was one of the first such programs in the US. The first two implants in the program were experimental devices provided by UCSF. The implant recipients fit with these devices were studied intensively in the Duke laboratory and in close cooperation with investigators at UCSF.

A comprehensive description of the seven NIH projects – and the studies in the UCSF, Duke, and RTI laboratories – is presented in a recent book (Wilson and Dorman, 2012a).

3.3 Composition of the Teams

The projects started small, but they grew in scope and size across the years. By the fall of 1984 we had a core team of three investigators (Figure 3.1) and a part-time administrative assistant. In late 1990 the core team included four investigators and a full time administrative assistant, and by 1996 the number of investigators had grown to five and then in 2000 to six. The team in 2001 along with two visitors is shown in Figure 3.2, and the changing composition of the teams over the years is depicted on page 7 in Wilson and Dorman (2012a) and on page 144 in this dissertation.

Although our focus was on development of better processing strategies for implants, the work also included tool building and many other areas of research that are



Figure 3.1: The RTI team in 1986. From left to right are Charles Finley, Blake Wilson and Dewey Lawson.

listed on pages 16 and 17 in Wilson and Dorman (2012a) and on page 151 in this dissertation. A hallmark of the projects was joint efforts with many investigators worldwide. These partnerships greatly extended the reach of our core teams.



Figure 3.2: Members of the RTI team in 2001 along with a research subject and his wife. From left to right are Jeannie Cox, Stefan Brill, Reinhold Schatzer, Denis Fitzgerald (the research subject), Heather Fitzgerald (Denis’s wife), Robert Wolford, Dewey Lawson and Blake Wilson. Not shown is team member Lianne Cartee. The Fitzgeralds visited the RTI laboratories from their home in St. Asaph, Wales, UK.

3.4 Continuous Interleaved Sampling

We developed and tested many processing strategies during the projects, and many of the strategies are in widespread clinical use today. However, one strategy towers above the rest in terms of the improvement in performance over its predecessors and in terms of impact. That strategy is the continuous interleaved sampling (CIS)

strategy, invented in 1989 and tested with an initial set of implant patients in 1989 and 1990. The results from those studies were published in *Nature* in 1991 (Wilson et al., 1991). This publication became the most highly cited publication in the specific field of cochlear implants at the end of 1999 and has remained so ever since.

By 1989, groups in Australia, Europe, and the US had developed multielectrode arrays that could be safely inserted into the scala tympani of the cochlea and that could excite different sectors (or tonotopic regions) of the auditory nerve, depending on which intracochlear electrode or which closely spaced pair of intracochlear electrodes was activated. Thus, stimulation of an electrode near the basal end of the cochlea would elicit a high-pitched percept, stimulation at the other end of the cochlea would elicit a low-pitched percept, and stimulation at intermediate positions would elicit intermediate pitches.

The status of the field at that time is accurately expressed in the conclusions from the first NIH Consensus Development Conference on Cochlear Implants, which was convened in 1988. Two of these conclusions were that multisite systems were more likely to be effective than single-site systems, and that “about 1 in 20 patients could carry out a normal conversation without lipreading,” using the best of the multisite systems (National Institutes of Health, 1988). The introduction of the multisite systems was another great step forward for cochlear implants, but even moderate levels of speech recognition using the restored hearing alone were still rare.

CIS was a breakthrough in sound processing that used the multiple sites far better than before, and thereby enabled high levels of speech recognition for the great majority of cochlear implant users. Unlike some prior strategies (including strategies we developed), this new strategy did not make any assumptions about how speech is produced or perceived, or about what might be important in the input. That is, the new strategy did not extract and then represent any specific features in the input, such as the fundamental frequency of voiced speech sounds, the periodicity or aperiodicity of inputs, or an inferred resonance frequency of the vocal tract in producing a speech sound. Instead, the strategy was designed to reproduce as many aspects of the input as possible, and then to allow the user's brain to decide what was (or was not) important in the input. This design decision proved to be crucial, as considerable information that could be perceived was discarded in the previous approaches, and the accuracy of feature extraction was very poor in typical acoustic environments with noise, reverberation and multiple talkers, even using the most advanced signal processing techniques of the time.

In addition, unlike some other previous strategies, the new strategy did not stimulate the multiple electrodes in the implant simultaneously but instead sequenced brief stimulus pulses from one electrode to the next until all of the used electrodes had been stimulated. This pattern of stimulation across electrodes was repeated continuously, and each such 'stimulus frame' presented updated information. This

decision also proved to be crucial, in that the simultaneous stimulation produced spurious interactions ('cross talk') among the electrodes and thereby greatly degraded the perception of the 'place of stimulation' (frequency based) cues.

A further departure from the past was that, for pulsatile processors, the rate of stimulation was very much higher than had been used previously. The high rates allowed a fine-grained representation of temporal information at each of the used electrodes; thus, both place information and temporal information were represented with CIS, up to or near the limits of perception for both codes.

Many additional aspects and features of CIS are listed on page 10 in Wilson and Dorman (2012a) and on page 146 in this dissertation, and details about the design are presented in elsewhere in the same book and in Wilson et al. (1991) and Wilson and Dorman (2008a). In broad terms, CIS combined the best elements from disparate prior strategies and added some new elements as well. The combination produced unprecedented levels of speech recognition with cochlear implants. After this and other advances, the NIH convened another conference in 1995, the Consensus Development Conference on Cochlear Implants in Adults and Children (National Institutes of Health, 1995). A principal conclusion from that conference was that "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" (National Institutes of Health, 1995).

The introduction of CIS into widespread clinical use in the early 1990s was soon followed by an exponential growth in the number of implant recipients, which persists to this day. CIS is still used and is the basis for many of the strategies developed subsequently, which also no doubt helped to fuel the growth in implant numbers. Even today, CIS remains as the standard against which other promising strategies are compared.

In retrospect, those of us who designed implant systems had to 'get out of the way' and allow the brain to do its work. Once given a relatively clear and unfiltered input, the brain could do the rest.

3.5 Transition from Speech Processors to Sound Processors

At the beginning of our work, we were delighted when a research subject could recognize, with hearing alone, even short fragments of ongoing speech or more than two or three single-syllable words in a list of 50. The sole emphasis of our group and others was to convey more information about speech. We designers did not think about other sounds.

Happily, those early days are history and today many patients score at or near 100% correct in recognizing sentences and above 80% correct in recognizing single-syllable words, with the speech items presented in quiet and using the restored hearing alone. In fact, we are now at the point at which investigators are calling for more difficult tests because the standard audiological tests are no longer sufficiently sensitive

to detect differences among implant systems, patients or processing strategies, at least for the top-performing patients (Gifford et al., 2008). Such a lack of sensitivity (due to ceiling effects) is a happy problem to have.

With these great advances in prosthesis design and performance, the emphasis has shifted to music reception and to recognition of speech in especially adverse acoustic environments, such as noisy restaurants or workplaces. We now think in terms of sound processors rather than speech processors. The present goal is to represent sound as faithfully as possible so that the brain will have access to the greatest possible amount of information, and not just to speech information or features abstracted from speech. This shift in emphasis is a sign of the progress that has been made.

3.6 A Lucky Engineer

Ronald Vale wrote a wonderful essay (Vale, 2012) for last year's special issue of *Nature Medicine* celebrating the Lasker Awards. The title of his essay was: 'How lucky can one be? A perspective from a young scientist at the right place at the right time.' The essay resonated with me, as I experienced many of the same feelings and learned some of the same lessons Ron so eloquently described. I would only substitute the word 'engineer' for the word 'scientist' to describe my own experience. I had the great fortune to work on a problem that so adversely affected millions of people, and to do that work in the company of spectacular colleagues.

3.7 A Few Further Lessons Learned Along the Way

Further lessons I learned that pertain more directly to the development of neural prostheses are:

- Persevere: the experts are not always correct.
- Try not to make assumptions about what the brain might need for optimal perception.
- Know that a surprisingly sparse representation may be adequate for a substantial restoration of function with neural prostheses.
- However, also know that a threshold of quality and quantity of information probably needs to be exceeded before the brain can do its work or at least work effectively.
- Respect the brain for its enormous capabilities and work to forge a good partnership between the brain and the prosthesis.
- Evaluate many ideas, because only a tiny fraction may emerge as good ones in practice; as Alfred Nobel famously said, “If I have 300 ideas in a year and just one turns out to work I am satisfied.”
- Multidisciplinary teams are needed to create successful neural prostheses.

3.8 Concluding Remarks

Even though I have been working in the field of cochlear implants for well over 30 years, I am as excited as ever about possibilities for the future (Wilson and Dorman,



Figure 3.3: The payoff: what the intervention and associated technology can do for deaf and severely hearing-impaired persons. A user of a cochlear implant is conversing with the author. The joy in the exchange is obvious, and she clearly is not having any difficulty in understanding me even though she is not looking at my lip movements and the conversation included many different and unpredictable topics. The cochlear implant user is Lilo Baumgartner from Vienna, Austria; the photo was taken at an outside location near our RTI laboratories in September 2003.

2008a; Wilson et al., 2011; Wilson and Dorman, 2012b). The work has been one incredible ride and among the great adventures of my life. The best parts have been the interactions with patients (Figure 3.3) and seeing them flourish with their restored hearing.

3.9 Acknowledgements Specifically for Chapter 3

The principal support for our work was provided by the NIH. This support included funding for the seven projects described in this essay plus additional projects also in the field of cochlear implants. Further financial and other support was provided by the RTI, Duke University, UCSF, the University of Iowa, MED-EL, Cochlear Americas, Advanced Bionics and the Storz Instrument Company. Of course, we could not have done anything without our research subjects, and we were blessed with some of the best. Indeed, we were continually amazed by their engagement in the studies, and by their generosity in spending time with us and in helping to improve the human condition. Many sponsors, research subjects, administrators, collaborating investigators and colleagues at the cochlear-implant companies made essential contributions to our shared efforts. The most important source of support for me is my wonderful family. We have had spectacularly good times together, and my wife and our two daughters have tolerated with gracious good humor my 'day dreams' and my time away in intense work or protracted travel. I am so very lucky.

4. Getting a Decent (but Sparse) Signal to the Brain for Users of Cochlear Implants*

4.1 Introduction

This chapter describes the surprising finding that a decidedly sparse and unnatural input at the auditory periphery can support a remarkable restoration of hearing function. In retrospect, the finding is a testament to the brain and its ability over time to utilize such an input. However, this is not to say that any input will do, as different representations at the periphery can produce different outcomes. The chapter traces the steps that led up to the present-day cochlear implants (CIs) and the representations that are most effective. In addition, some remaining problems with CIs and possibilities for addressing those problems are mentioned. Portions of the chapter are based on recent speeches by me and my essay (Wilson, 2013) in the special issue of *Nature Medicine* celebrating the 2013 Lasker Awards. The speeches are listed in section 4.13.

4.2 Five Large Steps Forward

Today, most users of CIs can communicate in everyday listening situations by speaking and using their restored hearing in the absence of any visual cues. For

* This chapter is reproduced from Wilson (2015), published in the special issue of *Hearing Research* celebrating the 2013 Lasker-DeBakey Clinical Medical Research Award and the first substantial restoration of a human sense using a medical intervention. The article is an open-access article.

example, telephone conversations are routine for most users. That ability is a long trip indeed from total or nearly-total deafness.

In my view, five large steps forward led to the modern CI: (1) proof-of-concept demonstrations that electrical stimulation of the auditory nerve in deaf patients could elicit potentially useful auditory sensations; (2) development of devices that were safe and could function reliably for many years in the hostile environment of the body; (3) development of devices that provided multiple and perceptually separable sites of stimulation in the cochlea; (4) discovery of processing strategies that utilized the multiple sites far better than before; and (5) stimulation in addition to that provided by a unilateral CI, either with bilateral electrical stimulation or with combined electric and acoustic stimulation (EAS), the latter for persons with useful residual hearing in one or both ears. This chapter is mainly but not exclusively about steps 4 and 5; more information about the preceding steps is presented in the essays by Professor Graeme M. Clark and by Dr. Ingeborg J. Hochmair in the special issue of *Nature Medicine* (Clark, 2013; Hochmair, 2013), and in Wilson and Dorman (2008a), Zeng et al. (2008), and Mudry and Mills (2013).

I note that, at the beginning, the development of the CI was regarded by many experts as a fool's dream or worse (e.g., as unethical experimentation with human subjects). For example, Professor Rainer Klinke said in 1978 that "From a physiological point of view, cochlear implants will not work." He was among the chorus of vocal

skeptics. Their basic argument was that the cochlea, with its exquisite mechanical machinery, its complex arrangement of more than 15,000 sensory hair cells, and its 30,000 neurons, could not possibly be replaced by crude and undifferentiated stimulation of many neurons *en masse*, as would be produced by the early CI systems.

Of course, the naysayers were ultimately proven to be wrong as a result of the perseverance of pioneers in the face of vociferous criticism and the later development of CI systems that could stimulate different populations of neurons more or less independently and in effective ways. In addition, no one, including the naysayers, appreciated at the outset the power of the brain to utilize a sparse and distorted input. That ability, in conjunction with a reasonably good representation at the periphery, enables the performance of the present devices.

We as a field and our patients owe the greatest debt of gratitude to the pioneers, and most especially to William F. House, D.D.S., M.D., who was foremost among them. Without his perseverance the development of the CI certainly would have been delayed or perhaps not even started.

A telling quote on the wall of his office before he died is “Everything I did in my life that was worthwhile, I caught hell for” (Stark, 2012). He took most of the arrows but remained standing.

4.3 Place and Temporal Codes for Frequency

Most of the early CI systems used a single channel of sound processing and a single site of stimulation in or on the cochlea. Those systems could convey temporal information only. However, the information was enough to provide an awareness of environmental sounds and an aid to lipreading (Bilger et al., 1977). And in some cases, some recognition of speech from open sets (lists of previously unknown words or sentences) was achieved (Hochmair-Desoyer et al., 1981; Tyler, 1988a, 1988b).

These “single channel” systems had strong adherents; they believed that much if not all of the frequency information in sounds was represented to the brain in the cadences of neural discharges that were synchronized to the cycles of the sound waveforms for single or multiple frequencies. Indeed, this possible temporal coding of frequencies was the “volley” theory of sound perception (Weaver and Bray, 1937), which was one of two leading theories at the time.

The other leading theory was the “place” theory, in which different sites (or places) of stimulation along the helical course (length) of the cochlea would represent different frequencies in the sound input. This theory had its genesis in first the supposition and then the observations that sound vibrations of different frequencies produced maximal responses at different positions along the length of the basilar membrane (von Helmholtz, 1863; von Békésy, 1960).

In one of the most important studies in the development of CIs, F. Blair Simmons, M.D., and his coworkers demonstrated that both codes can represent frequency information to the brain (Simmons et al., 1965; Simmons, 1966). Simmons implanted a deaf-blind volunteer with an array of six electrodes in the modiolus, the axonal part of the auditory nerve. Stimulation of each electrode in isolation at a fixed rate of pulse presentations produced a distinct pitch percept that was different from the percepts elicited by stimulation of any of the other electrodes. The different electrodes were inserted to different depths into the modiolus and thus addressed different tonotopic (or cochleotopic) projections of the nerve. The differences in pitch according to the site of stimulation affirmed the place theory.

In addition, stimulation of each electrode at different rates produced different pitches, up to a "pitch saturation limit" that occurred at the rate of approximately 300 pulses/s. For example, presentation of pulses at 100/s produced a relatively low pitch for any of the electrodes, whereas stimulation at 200 pulses/s invariably produced a higher pitch. Further increases in pulse rate could produce further increases in pitch, but increases in rate beyond about 300 pulses/s did not produce further increases in pitch.

The finding that the subject was sensitive to manipulations in rate at any of the single electrodes affirmed the volley theory, but only up to a point, the pitch saturation limit. Results from subsequent studies have shown that the limit can vary among subjects and electrodes within subjects, with some subjects having limits up to or a bit

beyond 1 kHz for at least one of their electrodes (Hochmair-Desoyer et al., 1983; Townshend et al., 1987; Zeng, 2002), for placements of electrodes on or within the cochlea. Such abilities are unusual, however, and most subjects studied to date have limits of around 300 pulses/s for pulsatile stimuli and 300 Hz for sinusoidal stimuli.

The results from the studies by Simmons et al. were important not only for the subsequent development of CIs (and especially processing strategies for multisite CIs), but also for auditory neuroscience. The debate about the volley *versus* place theories had been raging for decades, in large part because the two codes are inextricably intertwined in normal hearing, i.e., for a given sinusoidal input the basilar membrane responds maximally at a particular position along its length but also vibrates at the frequency of the sinusoid at that position. Thus, separation of the two variables – volleys of neural discharges and place of maximal excitation – is not straightforward in a normally hearing animal or human subject and definitive experiments to test the theories could not be easily conducted if at all. In contrast, the variables can be separated cleanly in the electrically stimulated auditory system by varying site and rate (or frequency) of stimulation independently. These stimulus controls allowed confirmation of both the place and volley theories and demonstrated the operating range of each code for frequency, at least for electrical stimulation of the auditory nerve. (The ranges may well be different for acoustic stimulation of the normally hearing ear; see, e.g., Moore and

Carlyon, 2005. However, the confirmation of both theories was made possible by the unique stimulus controls provided with electrical stimulation.)

4.4 Status as of the Late 1980s

By the late 1980s, steps 1 and 2 had been achieved and step 3 had been largely achieved (Wilson and Dorman, 2008a; Zeng et al., 2008). Both single-site and multisite systems were being applied clinically. Claims and counterclaims about the performances of different devices and about the “single channel” *versus* “multichannel” systems were in full force. The debates prompted the United States’ National Institutes of Health (NIH) to convene its first consensus development conference on cochlear implants in 1988 (National Institutes of Health, 1988). The report from the conference suggested that the multichannel systems were more likely to be effective than the single channel systems, and indicated that about 1 in 20 patients could carry out a normal conversation with the best of the available systems and without the assistance of lipreading or other visual cues. Approximately 3000 persons had received a CI as of 1988.

The various claims also were examined in a landmark study by Richard S. Tyler, Ph.D., and his coworkers, who traveled to implant centers around the world to test various devices in a uniform and highly controlled way (Tyler et al., 1989; Tyler and Moore, 1992). Included among the comparisons were the Chorimac, Duren/Cologne, 3M/Vienna, Nucleus, and Symbion devices. (The Symbion device also is known as the Ineraid® device.) The 3M/Vienna device used a single channel of sound processing and a

single site of stimulation; the Duren/Cologne device used one, eight, or 16 channels and corresponding sites of stimulation; and the other devices used multiple channels and multiple sites. The Chorimac device was tested with six subjects in Paris; the Duren/Cologne device with 10 subjects in Duren, Germany; the 3M/Vienna device with nine subjects in Innsbruck, Austria; the Nucleus device with nine subjects in Hannover, Germany, and with 10 subjects from the USA; and the Symbion device with 10 subjects also from the USA. Among the Duren/Cologne subjects, eight used the single-channel implementation and two used the multisite implementations. (The performances of the multisite users were in the middle of the range of the measured performances.) Each of the referring centers was asked to select their better performing patients for the tests and the results are therefore likely to be representative of the upper echelon of outcomes that could be obtained at the time and with those devices.

The principal results are shown in Figure 4.1. The tests included recognition of single words (upper left panel); recognition of key words in everyday sentences with between four and seven key words in addition to the article words (upper right panel); identification of 13 consonants presented in an /i/-consonant-/i/ context and with appropriate accents for French, German, or English (lower left panel); and identification of eight “language independent” consonants presented in the same context and whose accents are the same across the languages (lower right panel). The single words were “mostly three- or four-phoneme nouns.” The words and sentences were presented in

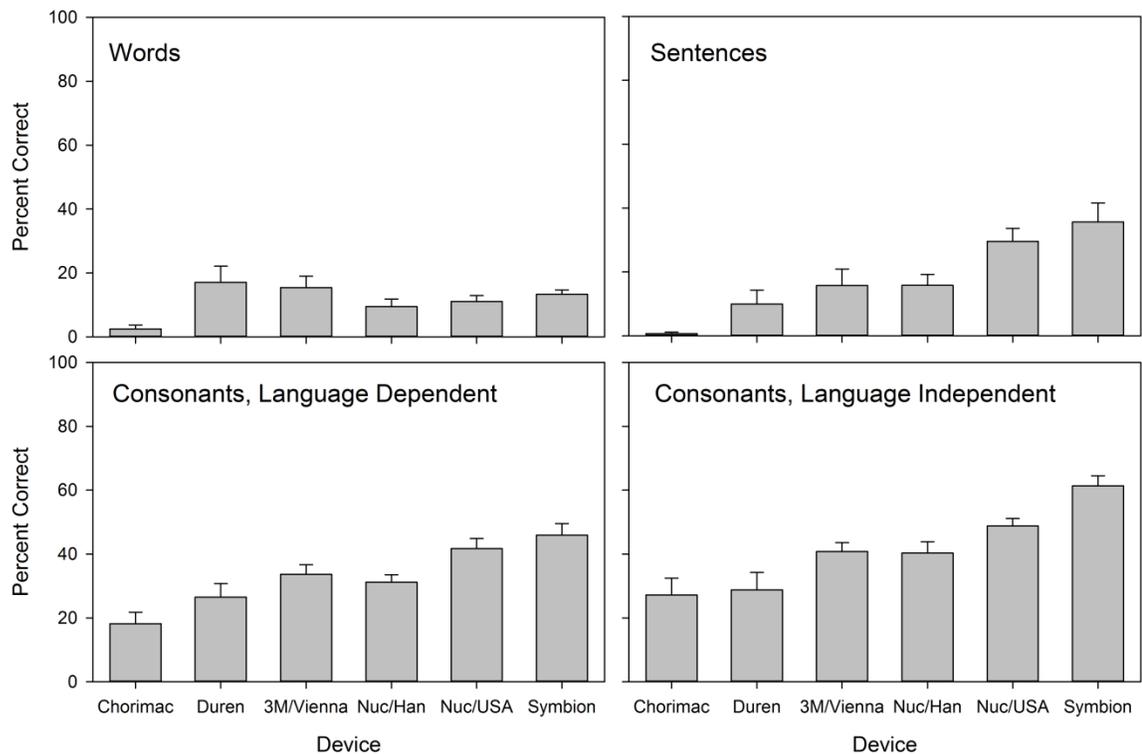


Figure 4.1: Data from Tyler et al. (1989) (top panels), and from Tyler and Moore (1992) (bottom panels). Means and standard errors of the means are shown for a variety of tests and cochlear implant devices. The tests are identified in the upper left corners of the panels. The devices included the Chorimac, Duren/Cologne (Duren), 3M/Vienna, Nucleus, and Symbion devices. The Nucleus device was tested with separate groups of subjects in Hannover, Germany (Nuc/Han), and in the USA (Nuc/USA). Chance performance on the language-dependent consonant test was 7.7 percent correct, and chance performance on the language-independent consonant test was 12.5 percent correct.

French for the Chorimac subjects; in German for the Duren/Cologne (Duren), 3M/Vienna, and Nucleus/Hannover (Nuc/Han) subjects; and in English for the Nucleus/USA (Nuc/USA) and Symbion subjects. Controls were included to maintain the same level of difficulty across the languages for each test. The word and sentence data

are from Tyler et al. (1989), and the consonant data are from Tyler and Moore (1992). Means and standard errors of the means (SEMs) are shown.

Among these results, results from the sentence test are perhaps the most indicative of performance in the daily lives of the subjects. Mean scores range from close to zero for the Chorimac subjects to about 36 percent correct for the Symbion subjects, although that latter score is not significantly different from the mean score for the Nuc/USA subjects. Tyler et al. emphasize that comparisons across languages should be made with caution.

The sentence results are paralleled by the consonant results. For the language-independent consonants, for example, the mean for the Symbion subjects is significantly higher than the means for all of the other sets of subjects, using the other devices. At the other end, the means for the Chorimac and Duren subjects are significantly lower than the other means. Chance scores for the language-dependent and language-independent consonant tests are 7.7 and 12.5 percent correct, respectively. To exceed chance performance using a $p < 0.05$ criterion, scores for individuals must be higher than 22 percent correct for the language-dependent test and 30 percent correct for the language-independent test. The numbers of subjects exceeding chance performance for each device and test are presented in Table 4.1 and show high incidences of chance performances by the Chorimac and Duren subjects and zero incidences for the Nuc/USA and Symbion subjects.

Table 4.1: Numbers of subjects scoring significantly above chance in the consonant tests conducted by Tyler and Moore (1992).

Device	Subjects scoring above chance, $p < 0.05$	
	Language-dependent consonants	Language-independent consonants
Chorimac	3/6	2/6
Duren/Cologne	6/10	2/10
3M/Vienna	8/9	7/9
Nucleus/Hannover	9/10	7/10
Nucleus/USA	10/10	10/10
Symbion	9/9	9/9

The differences in the mean scores for the Nucleus device between the Hannover and USA testing sites are not significant for some tests. For the other tests, the differences may have been the result of the larger pool from which the USA subjects were drawn. In particular, the better performers from the larger pool may have been somewhat better overall than the better performers from the smaller pool.

Ranges of the scores for each device, test, and testing site are presented in Table 4.2. Ranges are wide in all cases except for the word and sentence tests for the Chorimac subjects. One of the Duren subjects had exceptionally high scores across the tests compared with the other Duren subjects, and that subject was the one subject using any

Table 4.2: Ranges of scores in the word and sentence tests conducted by Tyler et al. (1989) and the language-dependent (Lang-dep) and language-independent (Lang-indep) consonant tests conducted by Tyler and Moore (1992).

Device	Language	Ranges of scores in percent correct			
		Words	Sentences	Lang-dep consonants	Lang-indep consonants
Chorimac	French	0-6	0-2	6-29	13-48
Duren/Cologne	German	0-57	0-47	10-56	15-75
3M/Vienna	German	0-34	0-42	17-44	29-52
Nucleus/Hannover	German	3-26	0-34	19-42	25-58
Nucleus/USA	English	3-20	14-57	29-62	40-60
Symbion	English	9-20	20-72	31-69	40-75

of the devices who had substantial residual hearing (at low frequencies only). This subject used the single-channel implementation of the Duren device.

Results from many other studies are consistent with the results just presented, from the studies by Tyler et al. and Tyler and Moore. For example, results reported by Morgon et al. (1984) demonstrate relatively poor performance with the Chorimac device, whereas results reported by Youngblood and Robinson (1988) demonstrate relatively good performance with the Symbion device.

As of the late 1980s, few users of CIs could carry out a normal conversation without the assistance of visual cues in conjunction with the implant. In addition, the speech reception scores for the top performers then would be below (usually far below) average by the mid 1990s, when for example the average was 90 percent correct for recognition of everyday sentences in one representative study (Helms et al., 1997), with a 2 percent SEM. (In contrast to the Tyler et al. and Tyler and Moore studies, the subjects in the Helms et al. study were not selected for high levels of performance.)

An important aspect not illustrated in Figure 4.1 is the progression in CI designs and performance during the 1980s. For example, the first instance of open-set speech recognition by an implant patient was in 1980, well before the “snapshot” of performances in the late 1980s presented in Fig 4.1. That patient was subject CK in the Vienna series, who used a prior version of the Vienna device. Her story is beautifully told in the essay in *Nature Medicine* by Hochmair (2013).

CK was not included among the subjects tested by Tyler et al. Had she been included, results for the “Vienna” device almost certainly would have been better.

4.5 Discovery and Development of Continuous Interleaved Sampling (CIS)

4.5.1 Context

My involvement with CIs began in 1978, when I visited three of the four centers in the USA that at the time were conducting research on CIs. No clinical programs existed then, and only about 20 patients had been implanted worldwide (all patients

received their devices through participation in research programs). In addition, that was the same year Professor Klinke made his categorical statement about CIs.

I visited Bill House and his group at the House Ear Institute in Los Angeles; Blair Simmons, Robert L. White, Ph.D., and others at Stanford University; and Michael M. Merzenich, Ph.D., and his team at the University of California at San Francisco (UCSF). Soon after the visit to UCSF, Mike asked me to become a consultant for the UCSF team and I happily accepted his flattering invitation.

A few years later, in 1983, I won the first of seven contiguous projects from the NIH to develop CIs, with an emphasis on the design and evaluation of novel processing strategies for auditory prostheses including CIs. These projects were administered through the Neural Prosthesis Program at the NIH and continued through March 2006.

Further details about my path and the paths of our teams are presented in the essay by me in *Nature Medicine* (Wilson, 2013). In addition, a comprehensive description of the studies conducted by the teams and their co-investigators at many centers worldwide is provided in the book “Better Hearing with Cochlear Implants: Studies at the Research Triangle Institute” (Wilson and Dorman, 2012a; also see Svirsky, 2014, for a review of the book).

We and others worked hard to develop better processing strategies for both single-site and multisite implants during the 1980s and late 1970s. Some of the leading strategies that emerged from this work included the broadband analog strategy used

with the Vienna implants; the “F0/F1/F2” strategy used with the Nucleus implant; the compressed analog (CA) strategies used with the Symbion and UCSF/Storz implants; and two variations of “interleaved pulses” (IP) strategies that were developed by our team at the time and evaluated in tests with UCSF/Storz and Symbion subjects. Each of these strategies is described in detail in at least one of the following reviews: Wilson (1993, 2004, 2006). In broad terms, the broadband analog strategy presented a compressed and frequency-equalized analog waveform to a single site of stimulation on or within the cochlea. The F0/F1/F2 strategy extracted features from the input sound that ideally corresponded to the fundamental frequency (F0), the first formant frequency (F1), and the second formant frequency (F2) of voiced speech sounds – and to the distinction between voiced (periodic) and unvoiced (aperiodic) speech sounds – and then represented those features at multiple sites of stimulation within the cochlea. The CA strategies first compressed the input sound using an automatic gain control and then filtered the compressed signal into multiple bands spanning the range of speech frequencies. Gain controls at the outputs of the bandpass filters adjusted the amplitudes of the signals (analog waveforms) that were delivered to multiple intracochlear electrodes, with the adjusted output of the bandpass filter with the lowest center frequency delivered to the apicalmost of the utilized electrodes, the adjusted output of the bandpass filter with the highest center frequency delivered to the basalmost of the utilized electrodes, and the adjusted outputs of the other bandpass filters delivered to

electrodes at intermediate positions in the implant. Variation 1 of the IP strategies included m processing channels, each with a bandpass filter, an energy detector (also called an envelope detector), a nonlinear mapping function, and a modulator. The outputs of the energy detectors were scanned for each “frame” of stimulation across the electrodes in the implant, and the channels with the n highest energies in the frame were selected for stimulation; in particular, the modulated pulses for those channels were delivered to the corresponding electrodes in the implant. This variation of the IP strategies was the first implementation of what is now known as the n -of- m strategy for CIs, in which n is lower than m . In the second variation of the IP strategies, F0 and voiced/unvoiced distinctions were extracted from the input sound and used to represent those features with the rates of pulsatile stimulation at each of the selected electrodes (again using the n -of- m approach to select the electrodes). For voiced speech sounds, the electrodes were stimulated at the detected (estimated) F0 rates, and for unvoiced speech sounds (or any aperiodic sound), the electrodes were stimulated either at randomized intervals or at a fixed high rate. The F0/F1/F2 and IP strategies all used nonsimultaneous pulses for stimulation at the different electrodes. The stimulus sites used for the F0/F1/F2, CA, and IP strategies were in the scala tympani and distributed along the basal and mid portions of the cochlea.

As noted in section 4.4, speech reception scores seemed to be a little bit better with the CA and F0/F1/F2 strategies than with the broadband analog strategy, although

there was considerable overlap in the scores among those strategies. Performances with the two variations of the IP strategies were comparable with and for some subjects better than the performance of the CA strategy, which was the control strategy in our tests (Wilson et al., 1988a, 1988b). The F0/F1/F2 strategy used a feature extraction approach; the CA strategy represented bandpass outputs; the IP strategies represented bandpass energies; and the second variation of the IP strategies represented features of the input sound as well. These and other characteristics of the more effective processing strategies used for multisite implants as of the late 1980s are summarized in Table 4.3. In retrospect, none of the strategies provided high levels of speech recognition for CI users, at least using hearing alone and without the additional information provided with lipreading or other visual cues.

4.5.2 CIS

A breakthrough came in 1989, when I wondered what might happen if we abandoned feature extraction altogether and simply represented most or all of the spatial (place) and temporal information that could be perceived with implants and thereby allow the user's brain to make decisions about what was or was not important in the input. This approach was motivated in part by the great difficulty in extracting features reliably and accurately in realistic acoustic environments, even using the most sophisticated signal processing techniques of the time. I thought – and our team thought – that the brain might be far better at gleaning the important parts of the input than any

Table 4.3: Some of the more effective processing strategies for multisite implants as of the late 1980s.

Strategy	Approach	Stimuli	Comment(s)
F0/F1/F2	Feature extraction	Interlaced pulses	Voiced/unvoiced distinctions were represented as well
Compressed analog	Bandpass (BP) outputs	Analog waveforms	Bandpass signals presented simultaneously to the electrodes
Interleaved pulses, variation 1	BP energies	Interlaced pulses	Compressed envelope signals to each of n electrodes among m bandpass processing channels
Interleaved pulses, variation 2	Mixed feature extraction and BP energies	Interlaced pulses	F0, voiced/unvoiced, and n -of- m envelope signals were presented

hardware or software algorithm that we could possibly devise. In addition, we were concerned about the pruning of information implicit in the n -of- m approach, at least as it was implemented at the time and with the relatively small numbers of electrodes that were then used in conjunction with the IP strategies (which set m to a low number by today's standards and of course n to an even lower number).

The breakthrough strategy was first called the “supersampler” and later “continuous interleaved sampling” (CIS) (Wilson et al., 1989). We designed and tested literally hundreds of processing strategies over the years, and many of the strategies are in widespread clinical use today, but CIS towers above the rest in terms of the improvement in performance over its predecessors and in terms of impact.

A block diagram of the strategy is presented in Figure 4.2. Multiple channels of sound processing are used and the output of each channel is directed to a corresponding site of stimulation (electrode) in the cochlea, as indicated by the inset in the figure. Each channel includes a bandpass filter, an energy detector, a nonlinear mapping function, and a multiplier, the latter for modulating a train of balanced biphasic pulses. The only difference among the channels is the frequency response of the bandpass filters. In particular, the responses range from low to high frequencies along a logarithmic scale. For a six channel processor, for example, the pass bands of the filters for the different channels might be 300-494, 494-814, 814-1342, 1342-2210, 2210-3642, and 3642-6000 Hz. The logarithmic spacing follows the frequency map of the cochlea for most of the cochlea’s length. The output of the channel with the lowest center frequency for the bandpass filter is directed to the apicalmost among the utilized electrodes in the implant; the output of the channel for the highest center frequency is directed to the basalmost of the utilized electrodes; and the outputs of the channels with intermediate center frequencies are directed to the utilized electrodes at intermediate positions in the

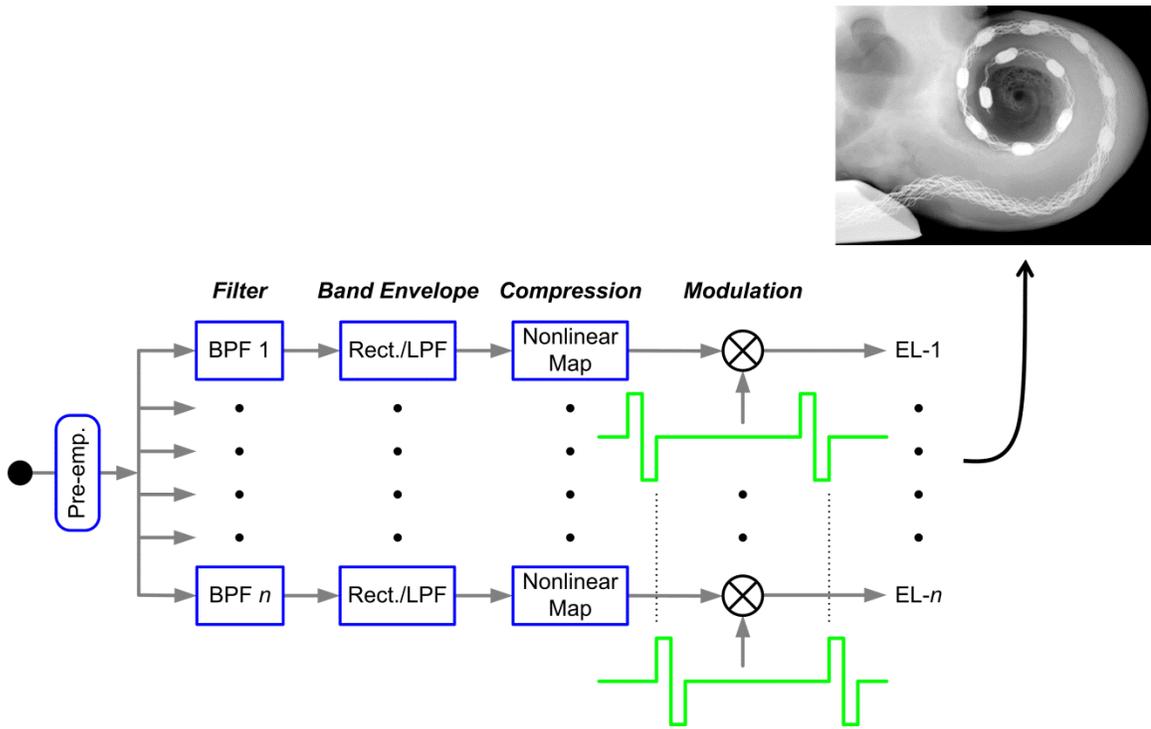


Figure 4.2: Block diagram of the continuous interleaved sampling (CIS) processing strategy for cochlear implants. The input is at the left-most part of the diagram. Following the input, a pre-emphasis filter (Pre-emp.) is used to attenuate strong components in the input at frequencies below 1.2 kHz. This filter is followed by multiple channels of processing. Each channel includes stages of bandpass filtering (BPF), energy (or “envelope”) detection, compression, and modulation. The energy detectors generally use a full-wave or half-wave rectifier (Rect.) followed by a lowpass filter (LPF). A Hilbert Transform or a half-wave rectifier without the LPF also may be used. Carrier waveforms for two of the modulators are shown immediately below the two corresponding multiplier blocks (circles with an “x” mark within them). The outputs of the multipliers are directed to intracochlear electrodes (EL-1 to EL- n), via a transcutaneous link or a percutaneous connector. The inset shows an x-ray micrograph of the implanted cochlea, which displays the targeted electrodes. (Block diagram is adapted from Wilson et al., 1991, and is used here with the permission of the Nature Publishing Group. Inset is from Hüttenbrink et al., 2002, and is used here with the permission of Lippincott Williams & Wilkins.)

implant. This representation addresses the tonotopic organization of the auditory system and provides the “place” coding of frequencies mentioned previously.

The simplest form of an energy (or “envelope”) detector is shown in the block diagram and it consists of a rectifier followed by a lowpass filter. Other forms may be used, such as a Hilbert Transform, but this simplest form works well and its function is similar to that of the other forms.

The effective cutoff frequency for the envelope detector is set by the frequency response of the lowpass filter. In most implementations of CIS, the upper end of the frequency response is set somewhere between 200 and 400 Hz, typically 400 Hz. With that typical setting, frequencies in the derived envelope (energy) signal range up to 400 Hz, which is a little above the pitch saturation limit of about 300 Hz for the great majority of patients. Thus, all the temporal information within channels that can be perceived by most patients as a variety of different pitches is represented in the envelope signal. There is little or no point in including more temporal information (at higher frequencies), as the additional information would not add anything and indeed might present conflicting cues.

A nonlinear (typically logarithmic) mapping function is used in each channel to compress the wide dynamic range of sounds in the environment, which might range up to 90 or 100 dB, into the narrow dynamic range of electrically evoked hearing, which for short-duration pulses usually is between 5 and 20 dB, depending on the patient and the

different electrodes within a patient's implant. The mapping allows the patient to perceive low-level sounds in the environment as soft or very soft percepts and high-level sounds as comfortably loud percepts. In addition, the mapping preserves a high number of discriminable loudnesses across the dynamic range of the input.

The output of this compression stage is used to modulate the train of stimulus pulses for each channel. The modulated pulse train is then directed to the appropriate electrode, as described previously.

The pulses for the different channels are interlaced in time such that stimulation at any one electrode is not accompanied by simultaneous or overlapping stimulation at any other electrode. This interleaving of stimuli eliminates a principal component of electrode or channel interaction that is produced by direct vector summation of the electric fields in the cochlea from simultaneously stimulated electrodes. Without the interleaving, the interaction or "crosstalk" among the electrodes would reduce their independence substantially and thereby degrade the representation of the place cues with the implant.

According to the Nyquist theorem, the pulse rate for each channel and associated electrode should be at least twice as high as the highest frequency in the modulation waveform. However, the theorem applies to linear systems and the responses of auditory neurons to electrical stimuli are highly nonlinear. We later discovered using electrophysiological measures that the pulse rate needed to be at least four times higher

than the highest frequency in the modulation waveform to provide an undistorted representation of the waveform in the population responses of the auditory nerve (e.g., Wilson et al., 1997). In addition, Busby and coworkers demonstrated the same phenomenon using psychophysical measures (Busby et al., 1993), i.e., perceptual distortions were eliminated when the pulse rate was at least four times higher than the frequencies of the sinusoidal modulation used in their study. These findings together became known as the “4x oversampling rule” for CIs. Thus, in a typical implementation of CIS the cutoff frequency for the energy detectors might be around 400 Hz and the pulse rate for each channel and addressed electrode might be around 1600/s or higher. (Both of these numbers may necessarily be reduced for transcutaneous transmission links that impose low limits on pulse rates.)

The pitch saturation limit and the corresponding cutoff frequency for the envelope detectors are fortuitous in that they encompass at least most of the range of F0s in human speech. In particular, F0s for an adult male speaker with a deep voice can be as low as about 80 Hz, whereas F0s for children can be as high as about 400 Hz but typically approximate 300 Hz. These numbers are near or below the pitch saturation limit and the envelope cutoff frequency, and thus at least most F0s are represented in the modulations of the pulse trains and may be perceived by the patients. Also, distinctions between periodic and aperiodic sounds – such as voiced *versus* unvoiced consonants in speech – are most salient in this range of relatively low frequencies. Thus, the

modulation waveforms may convey information about the overall (slowly varying) energy in a band; F0 and F0 variations; and distinctions among periodic, aperiodic, and mixed periodic and aperiodic sounds.

CIS was not based on any assumptions about how speech is produced or perceived, and it represented an attempt to present in a clear way most of the information that could be perceived by implant patients. The details of the mapping functions, filter frequency responses, filter corner frequencies, and other aspects of the processing were chosen to minimize if not eliminate perceptual distortions that were produced with prior strategies. In addition, unlike some prior strategies, CIS did not extract and represent selected features of the input. And unlike some other prior strategies, CIS did not stimulate multiple electrodes in the implant simultaneously but instead sequenced brief stimulus pulses from one electrode to the next until all of the utilized electrodes had been stimulated. This pattern of stimulation across electrodes was repeated continuously, and each such “stimulus frame” presented updated information. The rate of stimulation was constant and the same for all channels and utilized electrodes. CIS got its name from the continuous sampling of the (mapped) envelope signals by rapidly presented pulses that were interleaved in time across the electrodes.

A further departure from the past was that, for strategies that used pulses as stimuli, the rates of stimulation typically used with CIS were very much higher than the

rates that had been used previously. The high rates allowed the representation of F0 and voiced/unvoiced information without explicit (and often inaccurate) extraction of those features. Instead, the information was presented as an integral part of the whole rather than separately. In addition, the high rates allowed representation of most or all of the (other) temporal information that could be perceived within channels. A more complete list of the features of CIS is presented in section 4.5.6.

With CIS, the sites of stimulation may represent frequencies above about 300 Hz well, whereas temporal variations in the modulation waveforms may represent frequencies below about 300 Hz well. Magnitudes of energies within and across bands may be represented well with appropriate mapping functions whose parameter values are tailored for each channel and its associated electrode, in the fitting for each patient.

Once we “got out of the way” and presented a minimally processed and relatively clear signal to the brain, the results were nothing short of remarkable. Experienced research subjects said things like “now you’ve got it” or “hot damn, I want to take this one home with me,” when first hearing with CIS in the laboratory. CIS provided an immediate and large jump up in performance compared with anything they had heard with their implants before.

4.5.3 Initial Comparisons with the Compressed Analog (CA) Strategy

Results from some of the initial tests to evaluate CIS are presented in Figure 4.3. Two studies were conducted. The first study included only subjects who had

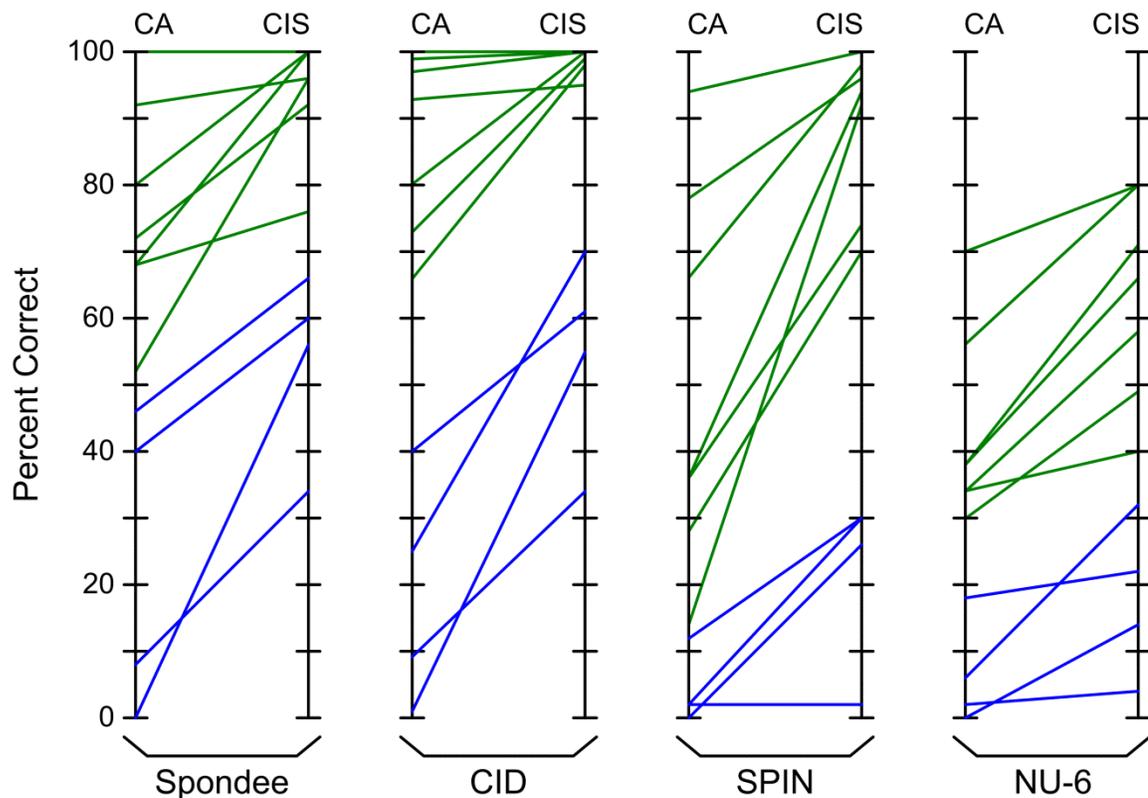


Figure 4.3: Results from initial comparisons of the compressed analog (CA) and continuous interleaved sampling (CIS) strategies for cochlear implants. Scores for subjects selected for their exceptionally high levels of speech reception performance with the CA strategy are shown with the green lines, and scores for subjects selected for their more typical levels of performance with that strategy are shown with the blue lines. The tests are identified in the text. (Figure is adapted from Wilson et al., 1991, with updates from Wilson et al., 1992. The template of the original figure is used here with the permission of the Nature Publishing Group.)

exceptionally high performance with the Symbion device and whose speech reception scores were fully representative of the very best outcomes that had been obtained with CIs up to the time of testing. The second study was motivated by positive results from the first study and included subjects who also used the Symbion device but instead were

selected for more typical levels of performance (which were quite poor by today's standards). All subjects had used their clinical device and its CA strategy all day every day for more than a year prior to testing. In contrast, experience for each subject with CIS was no more than several hours prior to testing. In previous studies with CI subjects, such differences in experience had strongly favored the strategy with the greatest duration of use (e.g., Tyler et al., 1986). A battery of tests was used for comparing the two strategies; the tests included recognition of: (1) two-syllable (spondee) words; (2) key words in the Central Institute for the Deaf (CID) sentences; (3) key words in the more difficult "Speech Perception in Noise" (SPIN) sentences (presented in these studies without noise); and (4) monosyllabic words from the Northwestern University Auditory Test 6 (NU-6). The NU-6 test was and is the most difficult test of speech reception given in standard audiological practice. Scores for the "high performance" subjects are shown with the green lines, and scores for the "typical performance" subjects are shown with the blue lines. The CA and CIS stimuli were presented to each subject's intracochlear and reference electrodes via the direct electrical access provided by the percutaneous connector of the Symbion device. The tests were conducted with hearing alone, using recorded voices, without repetition of any test items, without any practice by the subjects, and without any prior knowledge of the test items by the subjects. All subjects were profoundly deaf without their implants.

The results demonstrated immediate and highly significant improvements in speech reception for each of the subjects, across each set of subjects, and across all subjects. The improvements for the “typical performance” set of subjects were just as large as the improvements for the “high performance” set of subjects. For example, the subject with the lowest scores with the CA strategy immediately obtained much higher scores with CIS – he went from 0 to 56 percent correct in the spondee word tests; from 1 to 55 percent correct in the CID sentence tests; from 0 to 26 percent correct in the SPIN sentence tests; and from 0 to 14 percent correct in the NU-6 word tests. In addition, the scores achieved with CIS by the high performance subjects were far higher than anything that had been achieved before with CIs. The subjects were ecstatic and we were ecstatic.

Findings from the study with the high performance set of subjects were published in the journal *Nature* in 1991 (Wilson et al., 1991). That paper became the most highly cited publication in the specific field of CIs at the end of 1999 and has remained so ever since.

4.5.4 Introduction of CIS into Widespread Clinical Use

CIS was introduced into widespread clinical use very soon after the findings described in section 4.5.3 were presented in our NIH progress reports, at various conferences, and in the *Nature* paper. Each of the three largest CI companies (known as the “big three,” which have more than 99 percent of the world market for CIs)

developed new products that incorporated CIS. This rapid transition from research to clinical applications (now called “translational research” or “translational medicine”) was greatly facilitated by a policy our team suggested and our management approved, to donate the results from all of our NIH-sponsored research on CIs to the public domain. With that policy, the thought was that all companies would quickly utilize any major advances emerging from the NIH projects and thereby make the advances available to the highest possible number of CI users and prospective CI users. The swift utilization by all of the companies is exactly what happened, and the growth in the cumulative number of persons receiving CIs began to increase exponentially once CIS and strategies that followed it became available for routine clinical applications. As shown in Figure 4.4 (updated and adapted from Wilson and Dorman, 2008b), the exponential growth was clearly evident by the mid 1990s and has continued unabated ever since. (The correlation for an exponential fit to the data points in the graph exceeds 0.99.)

Results from the clinical trial of one of these new implant systems are presented in Figure 4.5. The system was the COMBI 40 that used CIS and supported a maximum of eight channels of processing and associated stimulus sites. The COMBI 40 was introduced by MED-EL GmbH in 1994.

The tests were conducted at 19 centers in Europe and included recognition with hearing alone of monosyllabic words and of key words in everyday sentences, among

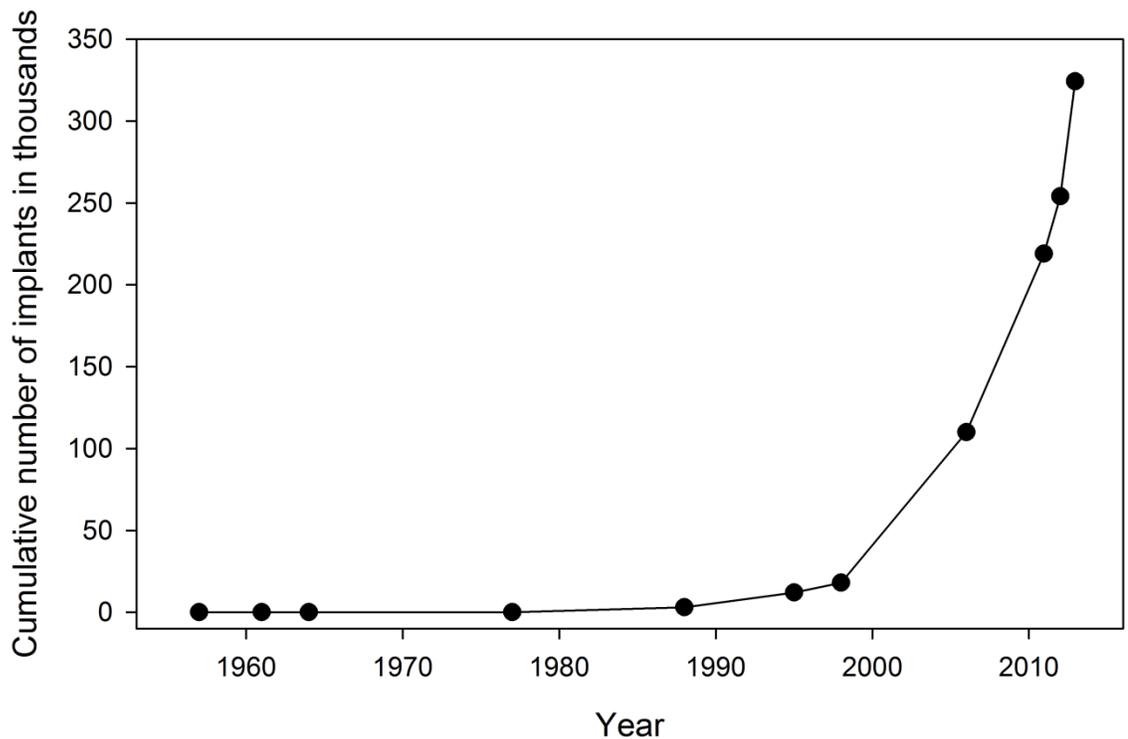


Figure 4.4: Cumulative number of implant recipients across years. Each dot represents a published datum. (Figure is adapted and updated from Wilson and Dorman, 2008b, and is used here with the permission of the IEEE.)

other tests. The data presented in the figure are from Helms et al. (1997) plus further data kindly provided by Professor Helms to me (and reported in Wilson, 2006), which were collected in additional tests with the same subjects after the Helms et al. paper was published.

Scores for the sentence test are shown in the upper panel of Figure 4.5 and scores for the word test are shown in the lower panel. Individual scores for the subjects are indicated by the open circles, and scores for different times after the initial fitting of the implant system for each subject are shown in the different columns in the panels. Those

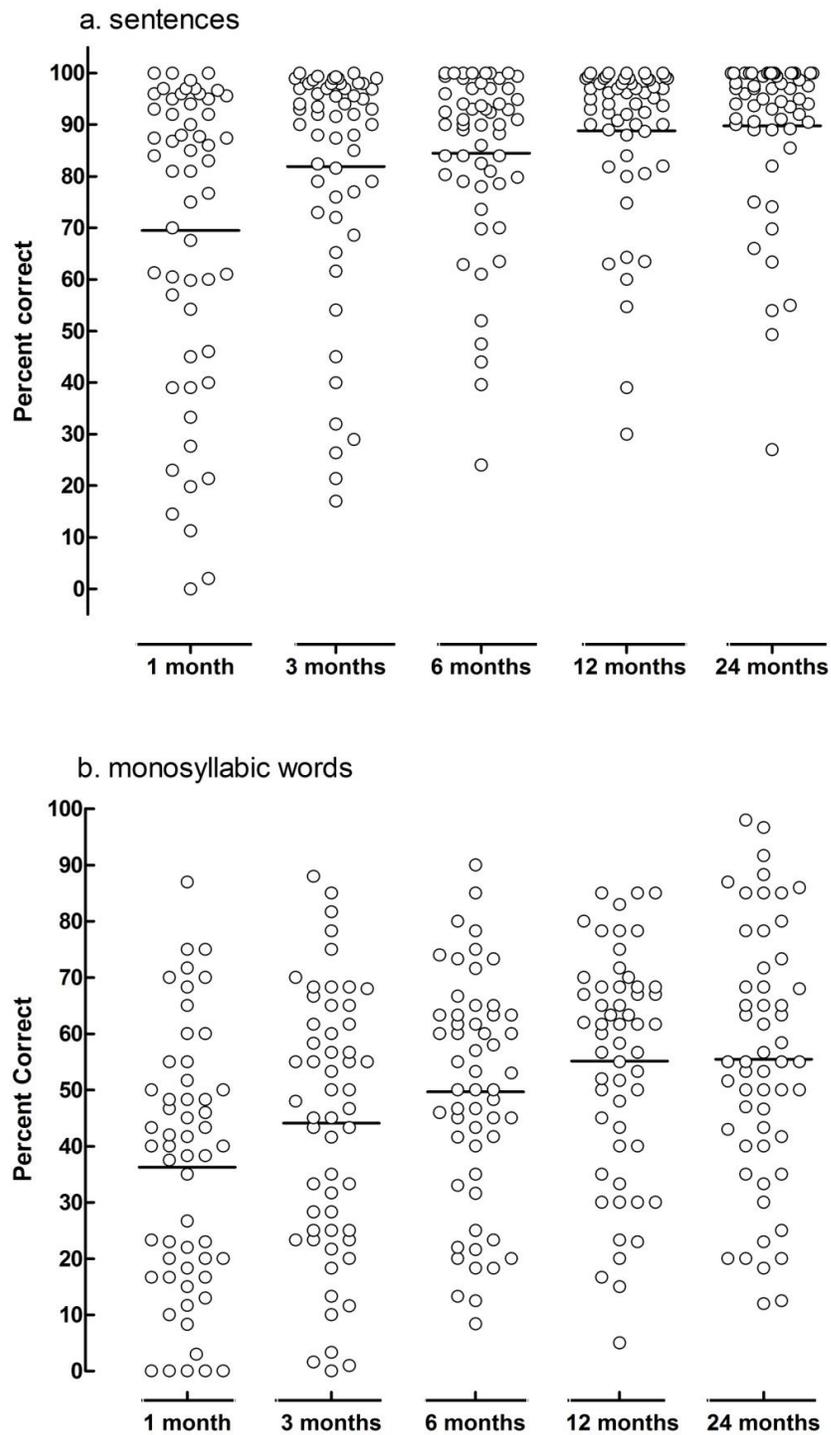


Figure 4.5: Percent correct scores for 55 adult users of the COMBI 40 cochlear implant and the continuous interleaved sampling (CIS) processing strategy. (Please see full caption on the next page.)

Figure 4.5: Percent correct scores for 55 adult users of the COMBI 40 cochlear implant and the continuous interleaved sampling (CIS) processing strategy. Scores for recognition of everyday sentences are shown in the top panel, and scores for the recognition of monosyllabic words are shown in the bottom panel. The columns in each panel show scores for different times after the initial fitting of the device. Scores for individual subjects are indicated by the open circles. The horizontal lines in each panel show the means of the individual scores. (The great majority of the data in the figure are from Helms et al., 1997, with an update of additional data reported in Wilson, 2006. The figure originally appeared in Wilson and Dorman, 2008a, and is used here with the permission of Elsevier B.V.)

times range from one month to two years. The means of the scores are shown by the horizontal lines in the columns. Sixty postlingually deafened adults participated as subjects in the trial, and 55 of them completed the tests for all five intervals following the initial fitting. Results for the 55 are presented in the figure. All subjects were profoundly deaf before receiving their CIs.

Scores for both tests are widely distributed across subjects, and scores for both tests show progressive improvements in speech reception out to about one year after the initial fitting, with plateaus in the means of the scores thereafter. At the two-year interval, 46 (84 percent of the subjects) scored higher than 80 percent correct on the sentence test, and 15 (27 percent of the subjects) “aced” the test with perfect scores. Such high scores are completely consistent with everyday communication using speaking and hearing alone, without any assistance from lipreading. The scores also indicate an amazing trip from deafness to highly useful hearing.

The means of the scores for the word test are lower than the means for the sentence test, at each of the intervals. In addition, the distributions of the scores for the word test are more uniform than the distributions for the sentence test, which demonstrate a clustering of scores near the top for most intervals. Scores for the word test at the two-year interval are uniformly distributed between about 10 percent correct and nearly 100 percent correct, with a mean of about 55 percent correct. At the same interval, scores for the sentence test are clustered at or near the top for all but a small percentage of the subjects, with a range of scores from 27 to 100 percent correct, and with a mean of about 90 percent correct and a median of 95 percent correct. A large difference between the word and sentence tests occurs because the sentence test includes contextual cues whereas the word test does not. The mean of the scores for the word test also is completely consistent with everyday communication, including telephone conversations.

An interesting aspect of the data is the improvement in scores over time. That aspect is easier to see in Figure 4.6, which shows means and SEMs for the sentence and word tests at each of the intervals after the initial fittings. (The sentence test was administered at more intervals than the word test.) The increases in percent correct scores out to one year after the initial fitting are similar for the two tests (even with the high likelihood of ceiling effects for the sentence test at the 3-month interval and beyond). The long time course of the increases is consistent with changes in brain

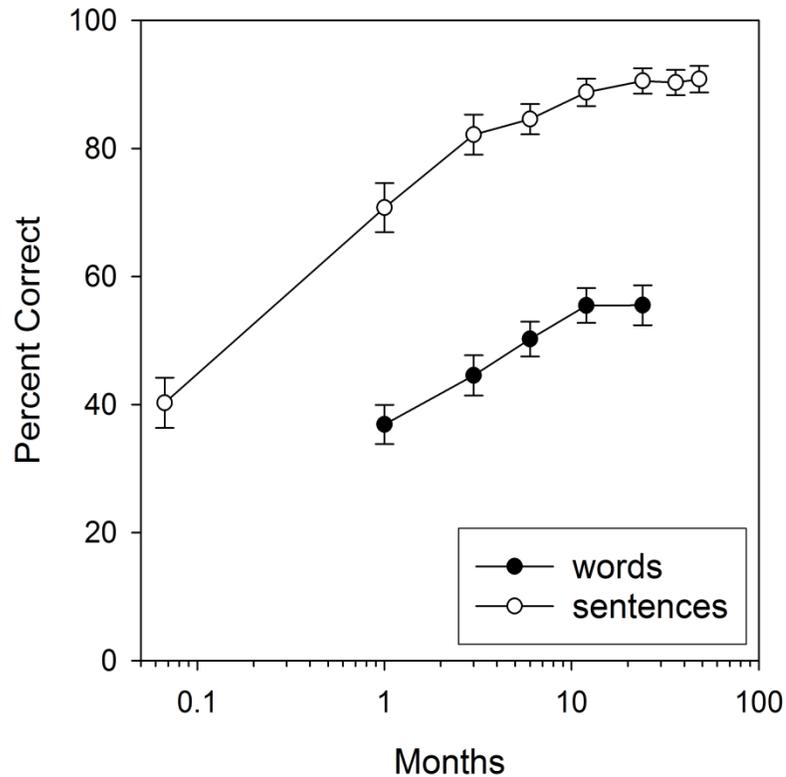


Figure 4.6: Means and standard errors of the means for the data in Fig. 4.5 plus data from three additional intervals for the sentence test. Note that the time scale is logarithmic. (Figure is from Wilson, 2006, and is reproduced here with the permission of John Wiley & Sons.)

function – in making progressively better use of the sparse input from the periphery – and is not consistent with changes at the periphery, which would be far more rapid.

4.5.5 The Surprising Performance of CIS and Modern Cochlear Implants in General

The scores presented in Figures 4.5 and 4.6 are all the more remarkable when one considers that only a maximum of eight broadly overlapping sectors of the auditory nerve are stimulated with this device. That number is miniscule in comparison with the

30,000 neurons in the fully intact auditory nerve in humans, and is small in comparison with the 3500 inner hair cells distributed along the length of the healthy human cochlea. Somehow, the brains of CI users are able to make sense of the sparse input at the periphery, and to make progressively better sense of it over time.

Indeed, a sparse representation is all that is needed to support a stunning restoration of function for some users of CIs. This fact is illustrated in Figure 4.7, which shows speech reception scores for a top performer with a CI and the CIS strategy, compared with scores for the same tests for six undergraduate students at Arizona State University with clinically normal hearing (data from Wilson and Dorman, 2007). The tests included recognition of monosyllabic words with a consonant-nucleus-consonant (CNC) structure; recognition of key words in the City University of New York (CUNY) sentences; recognition of key words in the Hearing in Noise Test (HINT) sentences; recognition of key words in the Arizona Biomedical Institute (AzBio) sentences; identification of 20 consonants in an /e/-consonant-/e/ context; identification of 13 vowels in a /b/-vowel-/t/ context; and recognition of the key words in different lists of the CUNY and AzBio sentences with the sentences presented in competition with a four-talker speech babble, at a speech-to-babble ratio of +10 dB for the CUNY sentences and at that ratio and +5 dB for the AzBio sentences. The AzBio sentences are considerably more difficult than the CUNY or HINT sentences (Spahr et al., 2012). The CI subject used a Clarion® CI, manufactured by Advanced Bionics LLC and using 16 channels and

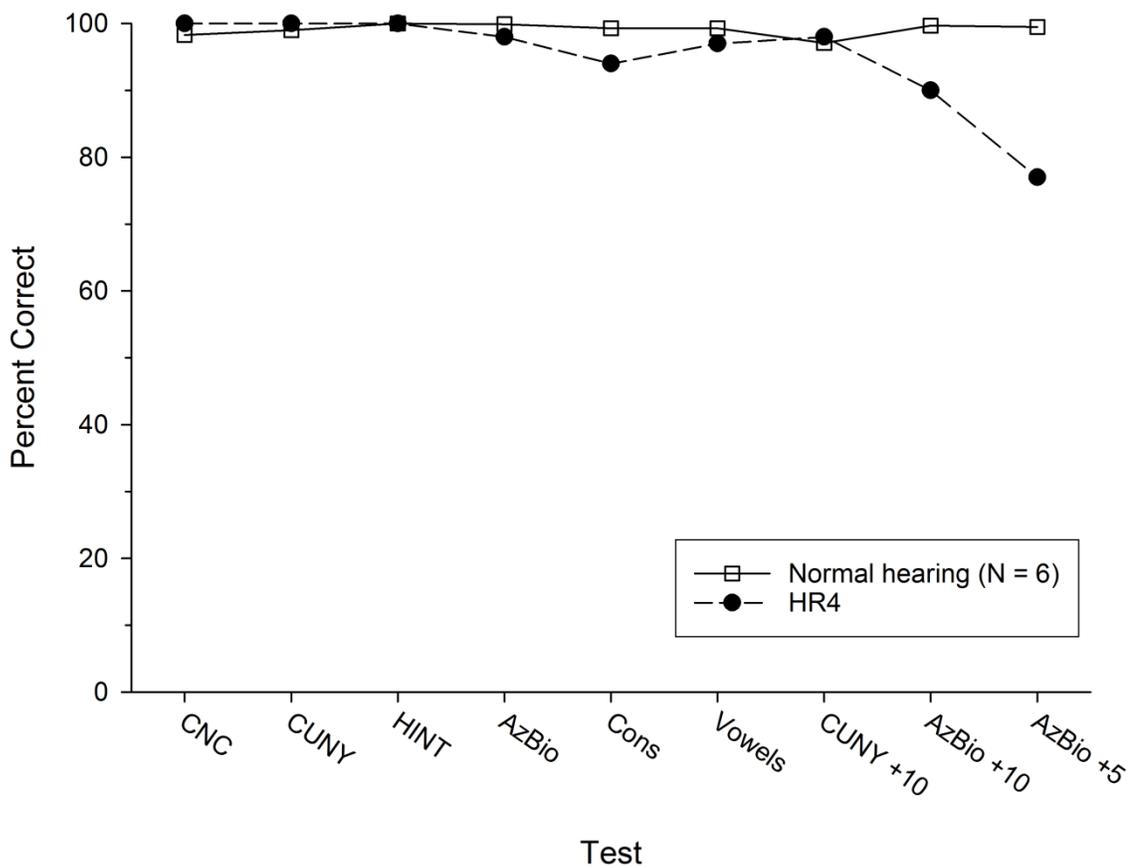


Figure 4.7: Percent correct scores for cochlear implant subject HR4 and six subjects with normal hearing. The tests are identified in the text. Means are shown for the subjects with normal hearing; the maximum standard error of the means for those subjects was 1.1 percent. The abbreviation AzBio is further abbreviated to AzB in the labels for this figure. (Data are from Wilson and Dorman, 2007.)

associated sites of stimulation. The test items for all subjects were drawn from computer-disk recordings and presented from a loudspeaker in an audiometric test room at 74 dBA. All test items were unknown to the subjects prior to the tests; repetition of items was not permitted; and the tests were conducted with hearing alone and without feedback as to correct or incorrect responses.

Scores for the CI subject (HR4) are statistically indistinguishable from the scores for the normally hearing subjects for all tests but the AzBio sentences presented in competition with the speech babble. For those latter two tests, scores for HR4 are 77 percent correct or higher but nonetheless significantly below the scores for the normally hearing subjects. These two tests are far more difficult than would be administered in audiology clinics, and, as mentioned previously, recognition of monosyllabic words is *the* most difficult test given in standard audiological practice. HR4 achieved a perfect score in the monosyllabic word test and high scores in the other two tests.

Other CI subjects have achieved similarly high scores, e.g., scores higher than 90 percent correct in the recognition of monosyllabic words. For example, three of the 55 subjects in the Helms et al. study achieved those scores (see the right column in the bottom panel in Figure 4.5.)

This is not to say that HR4 and others with high performance using their CIs have normal hearing. These persons still have difficulty in listening to a selected speaker in adverse acoustic situations, and these persons must devote considerable concentration in achieving their high scores, which are achieved without conscious effort by the normally hearing subjects. In addition, reception of sounds more complex than speech – such as most music – remains poor for the great majority of CI users, including many of the top performers. Thus, although a remarkable distance has been traversed, there still is room for improvement, even for the top performers.

Results like those shown in Figures 4.3-4.7 could not have been reasonably imagined prior to the advent of CIS and the strategies that followed it. Although completely normal hearing has yet to be achieved, high levels of auditory function are now the norm for CI users and some users produce ceiling effects in even the most difficult tests of speech reception normally administered to detect problems in hearing.

In retrospect, I believe the brain “saved us” in producing these wonderful outcomes with CIs. We designers of CI systems most likely had to exceed a threshold of quality and quantity of information in the representation at the periphery, and then the brain could “take it from there” and do the rest. The prior devices and processing strategies probably did not exceed the threshold – or exceed it reliably – and performance was generally poor. Once we provided the brain with something it could work with, results were much better.

The results obtained with the CIs of the 1990s and beyond have surprised me and many others. I think what we all missed at the beginning is the power of the brain to utilize a sparse and otherwise highly unnatural input. Instead, we were focused on the periphery and its complexity. We now know that a sparse representation can enable a remarkable restoration of function and additionally that reproducing many aspects of the normal processing at the periphery is not essential for the restoration (some of those aspects are listed and described in Wilson and Dorman, 2007). These facts bode well for

the development or further development of other types of neural prostheses, e.g., vestibular or visual prostheses.

Professor Klinke was among the early critics who graciously (and I expect happily) acknowledged the advances in the development of the CI. Indeed, he became an especially active participant in CI research beginning in the 1980s (e.g., Klinke et al., 1999), continuing up to two years before his death in 2008. I recall with the greatest fondness a special symposium he, Rainer Hartmann, Ph.D., and I organized in 2003, which was held in Frankfurt, Germany, and had the title *Future Directions for the Further Development of Cochlear Implants*.

4.5.6 Comment

CIS was a unique combination of new and prior elements, including but not limited to: (1) a full representation of energies in multiple frequency bands spanning a wide range of frequencies; (2) no further analysis of, or “feature extraction” from, this or other information; (3) a logarithmic spacing of center and corner frequencies for the bandpass filters; (4) a logarithmic or power law transformation of band energies into pulse amplitudes (or pulse charges); (5) customization of the transformation for each of the utilized electrodes in a multi-electrode implant, for each patient; (6) nonsimultaneous stimulation with charge-balanced biphasic pulses across the electrodes; (7) stimulation at relatively high rates at each of the electrodes; (8) stimulation of all of the electrodes at the same, fixed rate; (9) use of cutoff frequencies in

the energy detectors that include most or all of the F0s and F0 variations in human speech; (10) use of those same cutoff frequencies to include most or all of the frequencies below the pitch saturation limits for implant patients; (11) use of the “4x oversampling” rule for determining minimum rates of stimulation; (12) use of current sources rather than the relatively uncontrolled voltage sources that had been used in some prior implant systems; and (13) a relatively high number of processing channels and associated electrodes (at least four but generally higher and not limited in number). No assumptions about sounds in the environment, or in particular how speech is produced or perceived, were made in the way CIS was constructed. The overarching aim was to present in the clearest possible way most of the information that could be perceived with CIs, and then to “get out of the way” and allow the user’s brain to do the rest.

I note that the gains in performance with CIS have sometimes been attributed to the nonsimultaneous stimulation across electrodes. However, the gains were produced with the discovery of the combination of many elements and not just nonsimultaneous stimulation, which had been used before (e.g., Doyle et al., 1964) but not in conjunction with the other elements. The breakthrough was in: (1) the combination; (2) exactly how the parts were put together; and (3) the details in the implementation of each part.

Similarly, some have claimed that CIS existed prior to 1989, pointing to one or a small subset of the elements. These claims are erroneous as well. The combination did not exist before, and it was the combination that enabled high levels of speech reception

for the great majority of CI users. No prior strategy did that, and no prior strategy produced top and average scores that were anywhere near those produced with CIS.

4.6 Strategies Developed after CIS

Many strategies were developed after CIS by our teams (over the years) and others. The strategies included an updated version of the *n-of-m* strategy, which utilized many aspects of CIS such as relatively high rates of stimulation, and the CIS+, “high definition” CIS (HDCIS), advanced combination encoder (ACE), spectral peak (SPEAK), HiResolution (HiRes), HiRes with the Fidelity 120 option (HiRes 120), and fine structure processing (FSP) strategies among others. Most of these listed strategies remain in widespread clinical use, and most of the strategies are based on CIS or used CIS as the starting point in their designs. The listed strategies and others are described in detail in Wilson and Dorman (2008a, 2012b). In broad terms, the newer strategies did not produce large if any improvements in speech reception performance compared with CIS as implemented in the COMBI 40 device. This finding is presented in greater detail in section 4.9.

4.7 Status as of the Mid 1990s

By the mid 1990s multisite implants had almost completely supplanted single-site implants, due in large part to the results from two studies that clearly indicated superiority of the multisite implants (Gantz et al., 1988; Cohen et al., 1993).

Also by the mid 1990s, the new processing strategies were in widespread use, and results produced with them along with the findings about single-site *versus* multisite implants prompted another NIH consensus development conference, which was convened in 1995 (National Institutes of Health, 1995). The statement from that conference affirmed the superiority of the multisite implants and included the conclusion that “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.” (Recall that the data presented in Figure 4.5 are consistent with this conclusion.) As of 1995, approximately 12,000 persons had received a CI. The 1995 consensus statement was vastly more optimistic than the 1988 statement, and the 1995 statement was unequivocal in its recommendation for multisite implants.

4.8 Stimulation in Addition to that Provided by a Unilateral Cochlear Implant

The next large advance (step 5 in section 4.2) was to augment the stimuli provided by a unilateral CI. As mentioned previously, two ways to do that are with: (1) a second CI on the contralateral side or (2) combined EAS, for persons with residual hearing at low frequencies in either or both ears. An additional possibility is to present acoustic stimuli in conjunction with bilateral CIs, again for persons who have (preserved) residual hearing in either or both ears (Dorman et al., 2013).

An example of the benefits of adjunctive stimulation is presented in Figure 4.8, which shows results from a study by Dorman et al. (2008) and reprises results from the

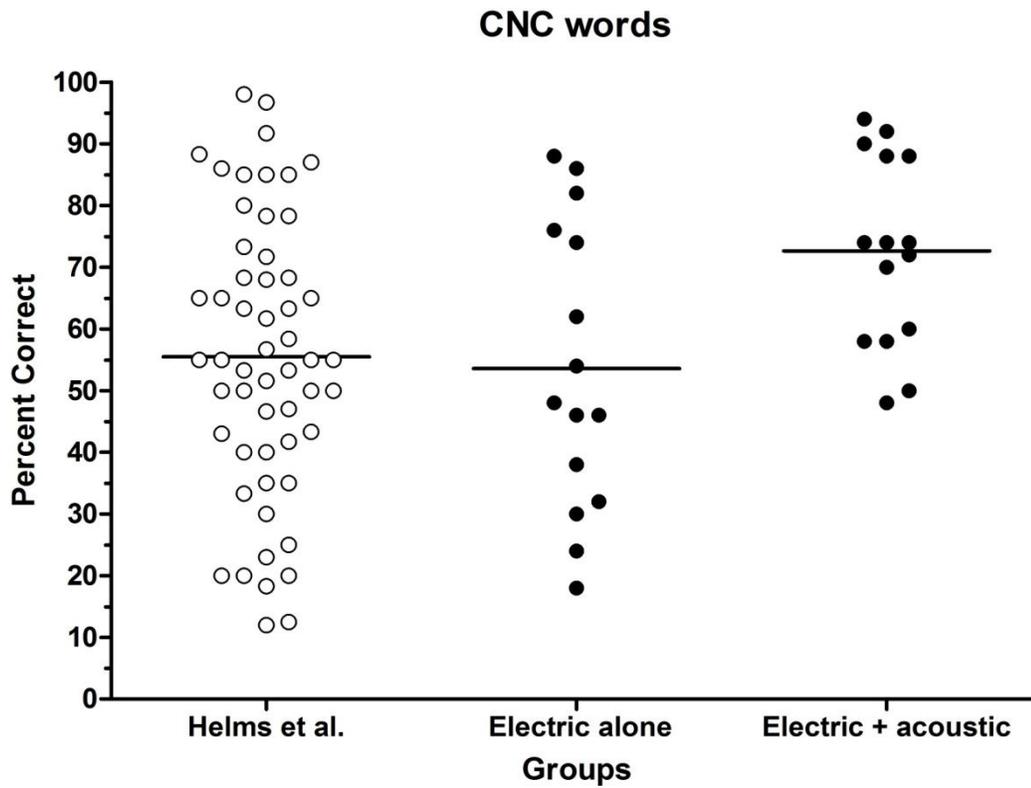


Figure 4.8: Percent correct scores for the recognition of monosyllabic words by cochlear implant subjects. Scores for the 55 subjects at the two-year test interval from the study by Helms et al. are presented in the left column, and are the same scores presented in the lower right column in Fig. 4.5. Scores for the 15 subjects in a study by Dorman et al. (2008) are shown in the remaining columns of the present figure. The center column shows scores with electrical stimulation by a unilateral cochlear implant only, and the right column shows scores with that stimulation plus acoustic stimulation of the contralateral ear. The horizontal lines indicate the means of the scores. All of the subjects in the Dorman et al. study had a full insertion of a cochlear implant on one side, and residual hearing at low frequencies in the other ear. The Helms et al. subjects were tested with the Freiburger monosyllabic words or their equivalents in languages other than German, and the Dorman et al. subjects were tested with the consonant-nucleus-consonant (CNC) words in English. (Figure is from Dorman et al., 2008, and is used here with the permission of Karger AG.)

Helms et al. study (1997). Scores for the recognition of monosyllabic words by the 55 subjects at the two-year interval in the latter study are shown in the left column, and

scores for the recognition of monosyllabic words for the 15 subjects in the Dorman et al. study are shown in the remaining two columns. The subjects in the Dorman et al. study each had a full insertion of a CI on one side and residual hearing at low frequencies on the contralateral side. The center column shows the scores achieved by the 15 subjects with the CI only, and the right column shows the scores achieved by the same subjects with the CI plus acoustic stimulation of the contralateral ear. All tests were conducted with hearing alone, without feedback as to correct or incorrect responses, and with lists of words that were previously unknown by the subjects. The subjects in the Dorman et al. study used a variety of implant devices and processing strategies, and the subjects in the Helms et al. study used the COMBI 40 device and CIS, as mentioned previously. The subjects in the Dorman et al. study had between five months and seven years of daily experience with their CIs at the time of the tests.

Comparison of the first two columns in the figure demonstrates that performance of unilateral CIs did not change from the mid 1990s, when the Helms et al. study was conducted, to the time of the study by Dorman et al., in 2007 and 2008. The means and the variances of the scores from the two studies are statistically identical. Thus, the COMBI 40 device and CIS were not surpassed in the intervening period, despite our best efforts and the best efforts by multiple other teams worldwide to achieve this. (Further evidence of no change in performance across the decade and beyond is presented in section 4.9.)

Comparison of the middle and right columns demonstrates a significant improvement in speech reception with the addition of the acoustic stimulus. The mean score increased from 54 to 73 percent correct, and the variance in the scores was reduced substantially with combined EAS.

Dorman et al. also demonstrated large benefits of combined EAS for recognition of sentences in quiet; recognition of sentences presented in competition with multitalker speech babble; identification of melodies; and discrimination among voices. However, in a separate set of comparisons with 65 subjects who were selected for their high levels of performance using a unilateral CI only (subjects who scored 50 percent correct or higher in recognizing monosyllabic words), scores for the 15 subjects using combined EAS were not significantly higher than the scores for the 65 subjects using a unilateral CI only, for all of the above tests. Thus, the subjects with excellent results using a unilateral CI only may have had access to the same or equally-useful information, compared to the information that was provided with combined EAS for the subjects with the generally lower levels of performance with the unilateral CI only. Combined EAS can help many but not all patients and can reduce the variance in outcomes across (unselected) patients.

The conditions for high benefits from combined EAS are described in a later paper by Dorman et al. (2015), in the special issue of *Hearing Research* celebrating the 2013 Lasker-DeBaakey Award. Such benefits can be obtained for a high proportion of patients when: (1) recognition of monosyllabic words with the implant alone is less than

60 percent correct; (2) the average of pure tone thresholds for the audiometric frequencies of 125, 250, and 500 Hz is less than or equal to 60 dB HL; and (3) the test material is sentences presented in competition with noise.

Large benefits also have been demonstrated for electrical stimulation on both sides, particularly for speech reception in noise, and particularly for situations in which the noise and the speech arrive from different locations. The benefits may be progressively greater at progressively more adverse speech-to-noise ratios or with progressively more difficult speech items presented in quiet (e.g., Wilson et al., 2003; Wackym et al., 2007). In addition, and like combined EAS, the variability in outcomes is reduced with bilateral CIs, compared to the variability in outcomes observed with unilateral CIs. (But again, the top performers with unilateral CIs match the top performers with bilateral CIs, at least for speech reception in quiet.)

A further benefit usually obtained with bilateral CIs is at least some ability to localize sounds in the environment, an ability that is absent or largely absent when using a single CI on one side only (e.g., Schön et al., 2005). The better recognition of speech presented in competition with spatially distinct noise may well be a result of head-shadow effects and the brain's ability to attend to the ear (and its CI) with the better signal-to-noise ratio. In addition, binaural squelch effects may contribute to the better recognition for some patients.

Many of the benefits of bilateral CIs were first described by Joachim M. Müller, M.D., Ph.D., and his coworkers at the Julius-Maximilians-Universität in Würzburg, Germany (Müller et al., 2002), and the idea of presenting both electric and acoustic stimuli to the same cochlea was first described by Christoph von Ilberg, M.D., and his coworkers at the J.W. Goethe Universität in Frankfurt, Germany (von Ilberg et al., 1999). Like Bill House, they each received a high number of awards for their pioneering efforts. And like Bill they persevered and thereby opened a new chapter for CIs and their users.

Today, bilateral cochlear implantation and combined EAS are common procedures. However, an important role remains for unilateral CIs, as some patients do not have useful or any residual hearing and therefore cannot benefit from combined EAS, and as patients in many countries do not have access to bilateral CIs due to national policies or restricted coverage by insurance companies. In low- and mid-income countries in particular, access to bilateral CIs can be limited at best.

In addition, improvements in unilateral CIs – or the processing strategies for them – would be expected to produce improvements in the performance of bilateral CIs and combined EAS as well. That is, the unilateral CI is the “bedrock” for each of these treatments using adjunctive stimulation, and an improvement in that principal part should contribute to the whole.

Professors Müller and von Ilberg each kindly asked us (the team at the Research Triangle Institute and Duke University Medical Center in North Carolina, USA) to

evaluate their first patients who had been implanted bilaterally in Würzburg or who had been treated with combined EAS in Frankfurt. We happily accepted these flattering invitations and thus had the singular privilege of conducting the first independent studies with these special subjects. Our results were completely consistent with the initial findings from both centers, and our results extended the findings (e.g., Wilson et al., 2003).

4.9 Status as of 2008 and Beyond

By 2008, progress had been made with bilateral CIs and combined EAS but not in the performance of unilateral implants, as mentioned in section 4.8. The lack of progress for unilateral CIs also is illustrated in Figure 4.9, which shows recognition of monosyllabic words by users of unilateral CIs who: (1) were from unselected cohorts; (2) had postlingual onsets of severe or profound hearing loss; (3) were implanted either in the mid 1990s, the early-to-mid 2000s, or from 2011 to 2014; and (4) were 18 years old or older when they received their first (and usually only) CI. Thus, three “snapshots” in time are presented. The data for the first snapshot are from the 55 recipients of unilateral implants studied by Helms et al. (1997). Each of these subjects used the COMBI 40 implant device and CIS, as mentioned previously, and was tested with the Freiburger monosyllabic words or their equivalents for languages other than German (some of the 19 test sites were not in German-speaking countries). The data for the second snapshot are from the 310 subjects in Group 5 in the study by Krueger et al. (2008). Those subjects

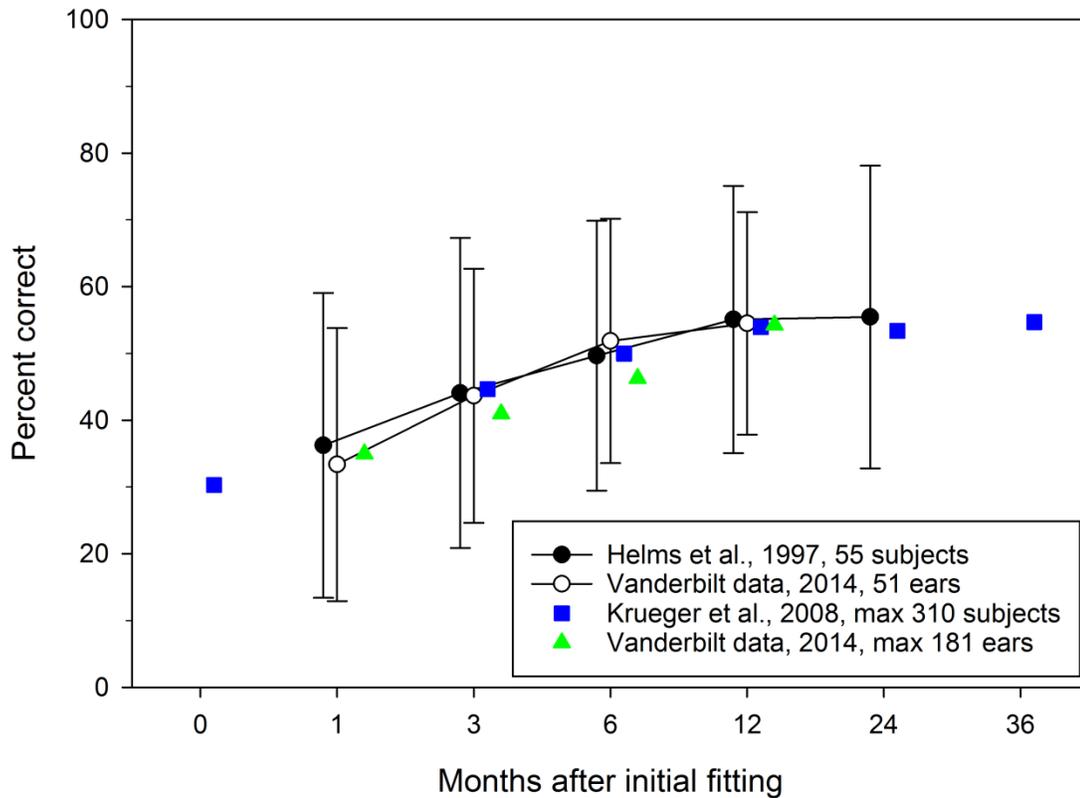


Figure 4.9: Means of percent correct scores for the recognition of monosyllabic words by cochlear implant subjects at the indicated times after the initial fitting of the device for each subject. The sources of the data are described in the text. Standard deviations are shown for the Helms et al. data and for the 51 ears in the Vanderbilt data set that were tested at all four intervals.

used the latest implant devices and processing strategies as of 2008. All of the subjects in the Krueger et al. study were implanted unilaterally at the Medizinische Hochschule Hannover in Hannover, Germany, and the speech reception performances for the subjects were evaluated with the Freiburger test and other tests in German. The data for the final snapshot are from all adult patients with postlingual onsets who were implanted at the Vanderbilt University Medical Center, in Nashville, TN, USA, from

2011 to mid 2014 (data kindly supplied by René H. Gifford, Ph.D., and reported in Wilson et al., 2015; please see the reference for further details about the Vanderbilt measures). That cohort included 218 subjects, 49 of whom received bilateral CIs either sequentially or simultaneously. Those 218 subjects used the latest devices and processing strategies as of the beginning of 2014. The speech reception performance for all 267 ears was evaluated with the CNC monosyllabic word test and other tests in English, with each ear tested separately for the bilateral subjects. The results presented in Figure 4.9 are the means and standard deviations for all 55 subjects in the Helms et al. study (closed circles) at each of the test intervals in the study (see Figure 4.5), and for all 51 ears (from 46 subjects) that were tested at all four of the intervals in the Vanderbilt data set (open circles). Only the means are presented for the Krueger et al. data (filled blue squares), as different numbers of subjects were tested at the different intervals. In addition, the means for all ears that were tested at each interval at Vanderbilt are shown with the filled green triangles. The maximum number of ears among the intervals was 181, and, as in the Krueger et al. data, the number varied across the intervals with a general reduction in the numbers with increasing intervals. Results from the monosyllabic word tests are shown because ceiling effects have yet to be encountered with those tests for any implant system or processing strategy, i.e., full sensitivity for detecting possible differences in performance is maintained across time, devices, and

strategies. (Some subjects score at or near the ceiling, as shown for instance in Figures 4.5 and 4.7, but those subjects are a tiny fraction of the total.)

The means from the various sets of data overlap almost completely for all shared intervals among the sets. For the two sets of data that included measures for all subjects at all intervals (the data shown with the error bars), results at all of the common intervals are statistically indistinguishable. That is, no difference in performance is observed between: (1) the results obtained in the mid 1990s with the COMBI 40 device and CIS and (2) the results obtained quite recently at Vanderbilt with a variety of the latest devices and processing strategies. Even the variances are the same, and apparently the substantial relaxations in the criteria for implant candidacy over the years did not make a difference either.

The findings presented in Figure 4.9 are representative of findings from unselected populations of adult patients with postlingual onsets of severe or profound hearing losses and who received their implants in the mid 1990s or afterward. In general, scores for the recognition of monosyllabic words improve with time out to 6-12 months after the initial fitting and then plateau at about 55 percent correct or a bit higher.

In retrospect, the COMBI 40 device and the CIS strategy set a high bar. The engineering for the device and its implementation of CIS were outstanding. The device's eight channels of processing and associated sites of stimulation proved to be enough,

perhaps helped by the relatively wide spacing of the intracochlear electrodes. CIS is still in widespread clinical use, is still offered as a processing option in each of the current devices manufactured by the “big three” companies, and remains as the principal standard (control condition) by which new and potentially better strategies are compared. These facts are a little frustrating, of course, as we and others have tried mightily to produce another large jump up in scores but have not succeeded.

That said, performance with the present unilateral CIs is generally wonderful, and improvements in performance may be obtained with adjunctive stimulation for many (but not all) patients who either have useful residual hearing or access to bilateral CIs. In addition, hundreds of thousands of patients have benefited from the advances made in the early and mid 1990s (see Figure 4.4).

4.10 Remaining Problems

Although today’s implant systems are great, they are not perfect. Table 4.4 presents some among the remaining problems associated with unilateral CIs, bilateral CIs, and combined EAS. A large dot in the table indicates a relatively large problem and a smaller dot indicates a smaller problem. Using unilateral CIs as the baseline, adjunctive stimulation with a contralateral CI or with acoustic stimulation delivered to either or both ears in conjunction with a unilateral CI ameliorates but does not eliminate many of the problems. For example, the ranges of outcomes are reduced with the use of adjunctive stimulation but the ranges are still large. Substantial improvements can be

Table 4.4: Remaining problems with unilateral cochlear implants (CIs), bilateral CIs, and combined electric and acoustic stimulation (EAS) of the peripheral auditory system. Combined EAS can be achieved with the acoustic stimulus delivered to the same ear as the CI (ipsi), to the opposite ear (contra), or to both ears. Large dots indicate relatively large problems and the baseline of performance with unilateral CIs. Smaller dots indicate smaller problems. Reception of complex sounds refers to reception of sounds that are more complex than speech, e.g., most music.

Problem	Unilateral CIs	Bilateral CIs	EAS, ipsi	EAS, contra	EAS, both
Wide range of outcomes	●	●	●	●	●
Speech reception in noise	●	●	●	●	●
Sound localization	●	•	●	●	•
Reception of complex sounds	●	?	•	•	•
Reception of tone languages	●	?	?	?	?
High listening effort for most users	●	●	●	●	●

produced for many patients with combined EAS for reception of signals more complex than speech, e.g., most music. The basis for these improvements might be a good or even an excellent representation with the acoustic stimulus of F0s and the first one, two, or three harmonics for periodic sounds. This representation, if present, also might help in the reception of tone languages, which include F0 contours as phonetic elements.

However, this possibility has not yet been tested, at least to my knowledge, and that is

why question marks are entered in the row of the table titled “Reception of tone languages.” Bilateral CIs or combined EAS with the acoustic stimulus delivered to both sides can be effective in reinstating sound localization abilities. And, as mentioned previously, such abilities may well be helpful in listening to speech presented in competition with interfering sounds at other locations. To my knowledge, reception of complex sounds has not been thoroughly tested for bilateral CIs yet, and that is why another question mark is presented in the appropriate cell in the table. Although a better representation of F0 contours might help in the reception of tone languages, open set recognition of speech for CI recipients using tone languages is not obviously different from the recognition achieved by CI recipients using other (e.g., western) languages (see, e.g., Zeng et al., 2015a). Possibly, redundant cues allow high levels of speech understanding for the users of tone languages, even if the representation of F0 contours is less than optimal. In any case, we do not yet know whether reception of tone languages is more difficult than reception of other languages with present-day CIs and thus the dot for that cell in the table is gray rather than black.

Much of the progress that has been made in the design and applications of CIs and related treatments since the early 1990s is in the provision of adjunctive stimulation. The gains for some patients can be large. In contrast, the performance of unilateral CIs has remained relatively stable throughout the same period. That doesn’t mean that unilateral CIs cannot be improved – they just haven’t been improved at least

substantially with the changes tested thus far. Many more possibilities exist, such as a greater spatial specificity of neural excitation at each of the stimulus sites in the cochlea, and some of those possibilities are listed and described in Wilson et al. (2015).

In addition, the efficacy of combined EAS could be increased by a further relaxation in the criteria for implant candidacy. That is, the more residual hearing can contribute to the whole, the more the problems associated with unilateral CIs will be reduced.

Such a further relaxation in the criteria also could be a boon to persons with debilitating hearing loss who do not meet the present criteria but do not benefit much if at all from hearing aids, either. The number of persons who could benefit from CIs would skyrocket with even a slight relaxation in the criteria and could include for example sufferers from certain types of presbycusis. Recent results have shown that persons with relatively high levels of residual hearing can still receive large benefits from a CI (Gifford et al., 2010; Lorens et al., 2014), in fact just as large as the benefits received by persons with lower levels of residual hearing, including little or no residual hearing. Indeed, a point of diminishing returns with ever increasing amounts of residual hearing has yet to be identified. The audiometric boundaries should be gently explored to help establish the point at which the benefit of a CI begins to decline, and perhaps then a data-based relaxation in the present criteria could include as many persons as

possible who are likely to receive large benefits from a CI, when combined with the residual hearing.

In cases of substantial residual hearing, the CI would be the adjunctive stimulation, providing a “light tonotopic touch” in the basal part of the cochlea that would complement the acoustic stimulation for the other parts. It could be a powerful combination.

The possibilities for further improvements are promising. And most fortunately, talented teams worldwide are pursuing them.

4.11 Concluding Remarks

Immense progress has been made since the late 1970s. As of 1977, CIs could provide an awareness of environmental sounds and an aid to lipreading. By the mid 1990s, the great majority of implant users had high levels of speech reception using their restored hearing alone, at least for recognizing sentences in quiet conditions. And starting in the late 1990s and early 2000s, stimulation in addition to that provided by a unilateral CI produced further gains in performance for a substantial fraction of patients.

In hindsight, we have learned that a decent signal can be conveyed to (at least) the fully functional brain with a unilateral CI by: (1) representing all or nearly all of the information that can be perceived both temporally and spatially, within the constraints of the designs and placements of the existing multisite electrode arrays; (2) minimizing deleterious interactions among the electrodes; and (3) using appropriate mapping

functions and other aspects of processing to minimize perceptual distortions. A sparse representation is sufficient for a stunning restoration of function for some patients. Also, leaving out the details of the normal processing is OK. That said, not any representation will do and it seems quite likely that a threshold of quality and quantity of information needs to be exceeded before the brain can “take over” and assume a major share of the necessary processing.

Adjunctive stimulation with a second CI or combined EAS can improve performance in difficult listening situations for many but not all users. Some users of unilateral CIs and nothing else have spectacularly high levels of performance across a broad spectrum of measures and results for those users may not be improved with the additional stimulation. However, an exception is sound localization abilities, which are poor or absent for all users of unilateral CIs only and may be largely reinstated with electric or acoustic stimulation on both sides.

No one could have reasonably imagined before the 1990s that CIs would work so well. The present performance is a testament to the courage of the pioneers, good design, and the unexpected power of the brain to utilize a sparse input. In addition, one can look back now and appreciate that key discoveries were essential to the development of the modern CI. We as a field and CI users are lucky that all of the pieces came together.

4.12 Dedication Specific to Chapter 4

The source publication for this chapter (Wilson, 2015) was dedicated to the memory of Joseph C. Farmer, Jr., M.D., who died on March 19, 2014. Among his many contributions to medicine and medical science, he founded with me and others the Cochlear Implant Program at Duke in 1984 and he helped me and our teams mightily in our research. He treated countless patients and was revered by everyone who knew him. We all miss him; he was my hero.

4.13 Acknowledgements Specific to Chapter 4

The title for the source publication for this chapter was suggested by my wonderful friend and colleague Michael F. Dorman, Ph.D. As mentioned in section 4.1, the publication was based in part on the essay I wrote for the special issue of *Nature Medicine* celebrating the 2013 Lasker Awards (Wilson, 2013) and on recent speeches I have given, including an invited talk for the *Workshop on Neural Imaging: From Cochlea to Cortex*, at Arizona State University, November 4, 2013; an invited seminar presentation for the Instituto de Neurociencias de Castilla y León, at the University of Salamanca, December 16, 2013; the *Hopkins Medicine Distinguished Speaker Lecture* at the Johns Hopkins University School of Medicine, February 4, 2014; a *Surgical Grand Rounds* presentation at the Duke University Medical Center, March 5, 2014; the *Flexner Discovery Lecture* at the Vanderbilt University Medical Center, March 13, 2014; one of the *2014 Lasker Lectures* at the University of Southern California, April 10, 2014; and a keynote

speech in the special session honoring the development of the modern cochlear implant and the recipients of the 2013 Lasker-DeBakey Clinical Medical Research Award, during the 13th *International Conference on Cochlear Implants and Other Implantable Auditory Prostheses* held in Munich, Germany, June 18-21, 2014. I am a consultant for MED-EL GmbH. None of the statements in this chapter favor that or any other company. The described work by our teams from 26 September 1983 through 31 March 2006 was supported by projects administered through the Neural Prosthesis Program at the NIH, NIH projects N01-NS-3-2356, N01-NS-5-2396, N01-DC-9-2401, N01-DC-2-2401, N01-DC-5-2103, N01-DC-8-2105, and N01-DC-2-1002. My visits in 1978 to three implant centers in the USA were supported by a professional development award from the Research Triangle Institute (RTI) in the Research Triangle Park, NC, USA. Space or equipment grants or both for our work were provided by the RTI, the Duke University Medical Center, and the University of California at San Francisco (UCSF). Travel and per diem support for scientists and research subjects visiting our laboratories was provided by MED-EL GmbH. Separate projects conducted by our teams during the period were supported by the NIH; Cochlear Corp.; MED-EL; MiniMed, Inc.; Advanced Bionics LLC; the Storz Instrument Company; and the University of Iowa. I was a consultant for many NIH projects on cochlear implants and related topics from 1978 through 2006 and beyond, including the project directed by Professor Merzenich at the UCSF in the late 1970s and early 1980s. I am so very grateful to the two reviewers of the submitted

manuscript for the source publication for this chapter, who offered many “spot on” and highly insightful suggestions for improvement. Most of those suggestions were incorporated in the final product and the source publication is theirs as well as mine.

5. Possibilities for Narrowing the Remaining Gaps between Prosthetic and Normal Hearing*

I had the great privilege of presenting the opening keynote address for the 10th *Asia-Pacific Symposium on Cochlear Implants and Related Sciences (APSCI 2015)*, which was held in Beijing, China, from April 30 through May 3, 2015. The *Symposium* and its grand spirit are beautifully described in the July 2015 issue of *The Hearing Journal* (Zeng et al., 2015b). The present chapter and its source publication are based on my lecture.

In the lecture, I first recalled with the greatest fondness a trip Fan-Gang Zeng, Steve Rebscher, Bob Shannon, Gerry Loeb, and I made in 1993 to participate in the *Zhengzhou International Symposium on Electrical Hearing and Linguistics*, which I believe was the first conference of its type in China. Approximately 130 persons attended the conference. Fan-Gang, Steve, Bob, and I are shown in Figure 5.1, a photo that brings back happy memories indeed, including memories of all the wonderful people we met at the conference and our marvelous tour of China after the conference.

Everyone in the photo was at the *APSCI 2015*, which was a lovely reunion for us. We noticed that we are a bit younger in the photo!

1993 was at about the time that new and highly effective processing strategies were introduced into clinical practice and after implants with multiple sites of stimulation in the cochlea had been developed. 1993 was near the clear onset of what

* This chapter is a superset Wilson (2016b). Sections of the chapter are reproduced or adapted from that article with the permission of the publisher.



Figure 5.1: Fan-Gang Zeng, Steve Rebscher, Bob Shannon, and Blake Wilson (l-r) in China in 1993.

later would prove to be an exponential growth in the number of implant recipients worldwide, a growth that continues to this day (Figure 5.2). (This figure is the same as Figure 4.4, except that Figure 5.2 includes milestones in the development of CIs and related treatments.)

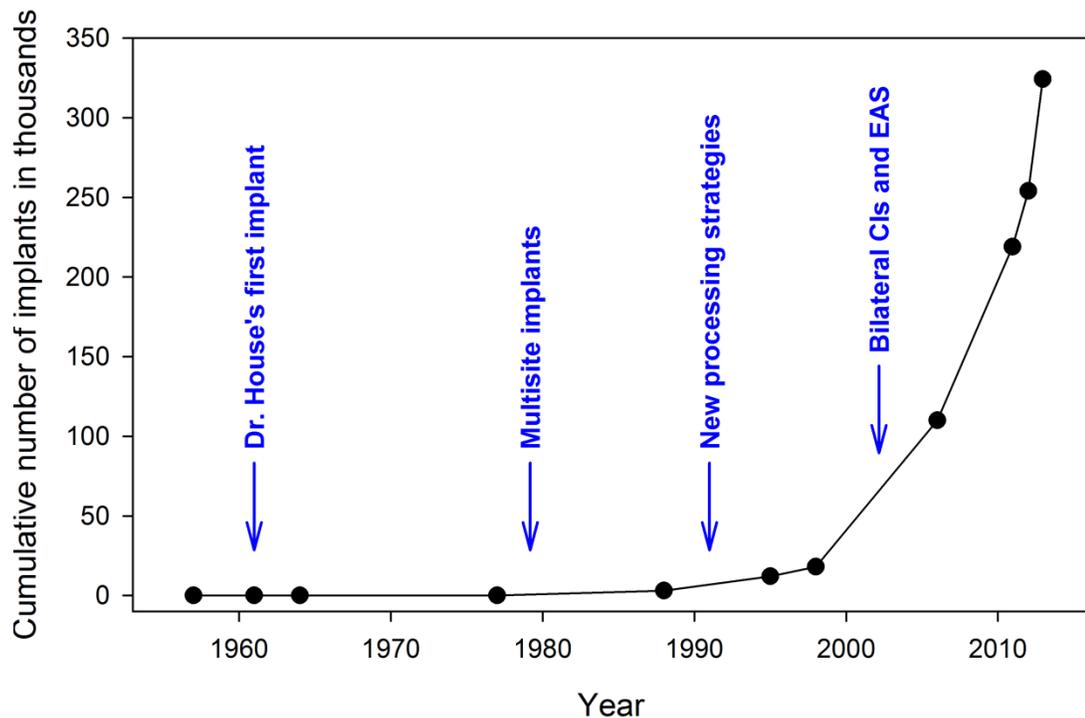


Figure 5.2: Cumulative number of implant recipients over the years. The dots represent published numbers. Industry records indicate that the number approximated 460,000 in June 2015. Major events in the development of the cochlear implant (CI) are also indicated in the figure. Abbreviations in the figure are: CIs for cochlear implants and EAS for combined electric and acoustic stimulation. Dr. House is Dr. William F. House, M.D., D.D.S., who contributed strongly to the development of the CI and performed his first implant operation in Los Angeles, CA, USA, in 1961. (This figure is the same as Figure 4.4, except that the present figure includes the milestones in the development of the CI and related treatments.)

The cochlear implant (CI) is by far the most successful neural prosthesis to date, both in terms of restoration of function and the number of people helped. Indeed, the CI has become the foremost model for the development or further development of other types of neural prostheses, e.g., visual and vestibular prostheses.

In the remainder of this chapter, I present a snapshot of where we are with the CI devices now in widespread use and then offer some suggestions for narrowing the remaining gaps between prosthetic and normal hearing. I note that we now have a happy problem to solve, in making highly effective devices even better.

5.1 Where Are We?

The data shown previously in Figures 4.5 and 4.6 are still largely representative of the performance of the present-day unilateral CIs, even though the data were collected in the mid 1990s. (The data are from Helms et al., 1997.) Percent correct scores are shown in the figures for 55 adult users of the COMBI 40 CI, for recognition of speech using their restored hearing alone and without any visual cues such as those provided with lipreading.

The COMBI 40 used only eight intracochlear electrodes, and yet that number is adequate for high levels of speech reception. That was a surprise at the time and is no doubt a testament to the power of the brain to utilize a decidedly sparse input and to make progressively better sense of the input over time.

Results like those shown in Figures 4.5 and 4.6 propelled the CI into widespread use. It is now the standard of care for persons with severe or profound losses in hearing.

Despite many efforts to produce further improvements in the performance of unilateral CIs, only modest progress has been made since the mid 1990s. This fact also was illustrated previously in Figure 4.9, which shows the means of scores for recognition

of monosyllabic words by postlingually deafened adults who received their CIs in the mid 1990s, the mid 2000s, or recently, up to early 2014. The scores were obtained with the CI alone and each of the studies included large cohorts of unselected patients.

As is evident from the figure, no improvement was made across the decades, at least for the recognition of monosyllabic words and for large cohorts of postlingually deafened adults, even though many changes were introduced during the period including: (1) more channels of sound processing and associated intracochlear electrodes; (2) newer processing strategies; and (3) substantial relaxations in the criteria for implant candidacy. These results indicate the broad clinical experience with unilateral CIs to date and the results are especially informative as the word tests are still largely immune to possible ceiling effects (the exception is the relatively few subjects who score at or near 100 percent correct in the tests). The means of the word scores asymptote at about 55 percent correct for all devices in widespread use since the mid 1990s. Sentence scores are much higher, of course, and those scores (and the word scores) are fully consistent with fluent verbal communications with and by CI users.

5.2 A Vexing Limitation

A likely roadblock to further improvements is illustrated in Figure 5.3, which shows speech reception scores as a function of the number of processing channels and associated intracochlear electrodes for users of unilateral CIs. The top panel presents data from one of my earlier laboratories (at the Research Triangle Institute in North

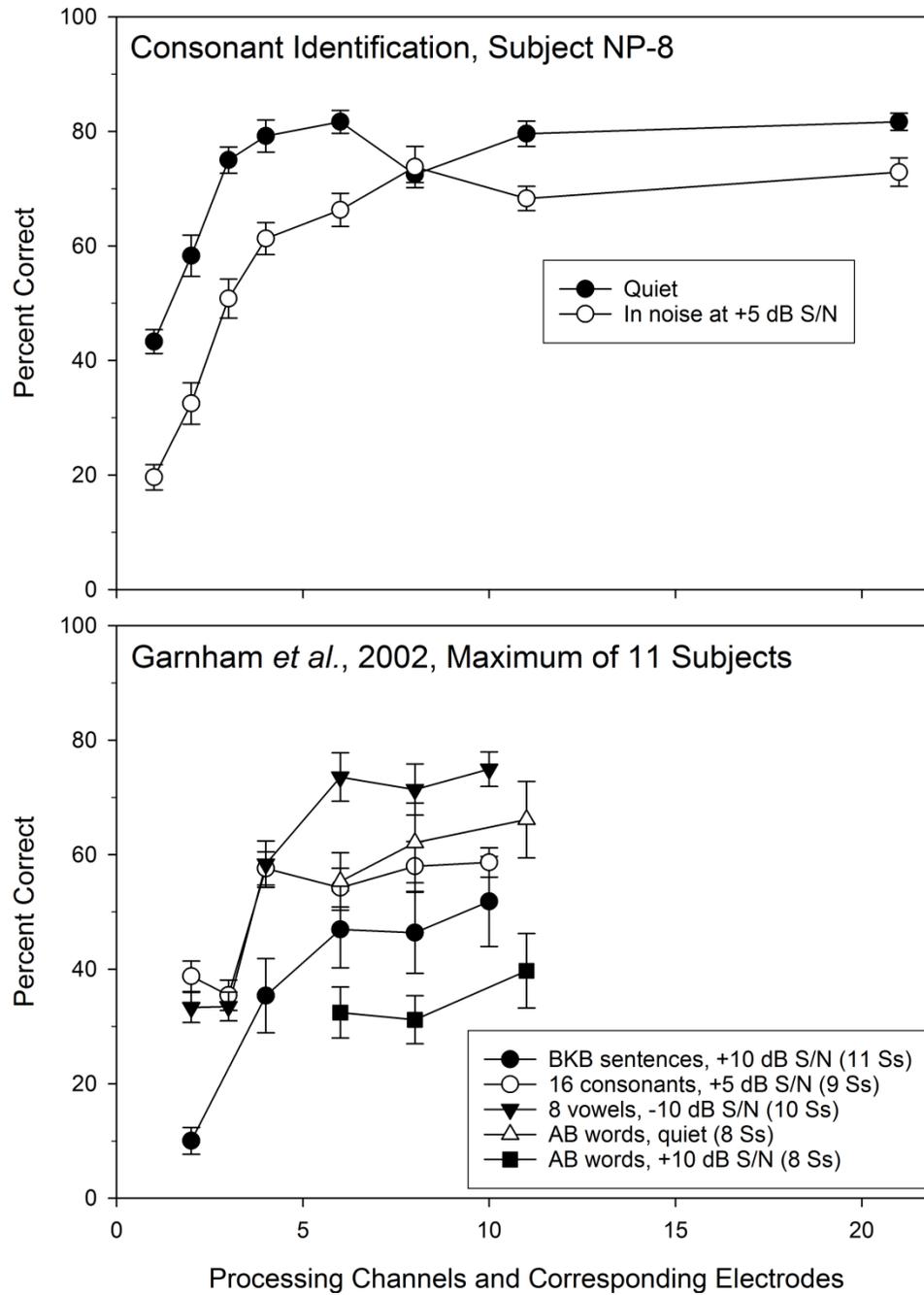


Figure 5.3: Means and standard errors of the means for tests of speech reception conducted in one of the author's earlier laboratories, at the Research Triangle Institute (RTI) in North Carolina, USA, and by Garnham et al. (2002). (Please see full caption on the next page.)

Figure 5.3: Means and standard errors of the means for tests of speech reception conducted in one of the author's earlier laboratories, at the Research Triangle Institute (RTI) in North Carolina, USA, and by Garnham et al. (2002). The subjects were users of unilateral cochlear implants and the continuous interleaved sampling (CIS) processing strategy. The tests included identification of consonants in quiet and in noise; recognition of the Bamford-Kowal-Bench (BKB) sentences in noise; identification of vowels in noise; and recognition of the Arthur Boothroyd (AB) monosyllabic words in quiet and in noise. The speech-to-noise ratios (S/Ns) for the tests in noise are indicated in the legends. Scores for sound processors using different numbers of channels – and the electrodes associated with those channels – are shown along the abscissa in each panel. The tests of consonant identification at the RTI included 24 consonants. Additional information about the tests at the RTI is presented in Wilson (1997). (The figure is from Wilson and Dorman, 2008a, and is reproduced here with permission.)

Carolina, USA) and the bottom panel presents data from Garnham et al. (2002). The data in both panels are representative of findings from other studies. The subject in the top panel used a Cochlear Ltd (Nucleus) implant with its 22 intracochlear electrodes, and the 11 subjects in the bottom panel used MED EL GmbH implants with 12 intracochlear electrodes. (Today's CIs use 12-24 intracochlear electrodes.) Tests of consonant identification in quiet and in noise were administered for the subject in the top panel, and various tests of speech recognition in quiet and in noise were administered for the subjects in the bottom panel. The panels show the means and SEMs of the scores for the tests.

Both panels indicate an asymptote in the scores once the number of channels rises above 3-6 depending on the test. Indeed, no implant subject tested to date has reached more than eight channels in any test before encountering asymptotic

performance. That means that the number of effective channels with the present-day unilateral CIs is below, and often far below, the number of intracochlear electrodes and the maximum possible number of channels.

The reason(s) for the limitations in the numbers of effective channels remain to be identified. A lack of discrimination among electrodes is not a candidate reason, as many subjects can discriminate most or all of their intracochlear electrodes when the electrodes are stimulated in isolation, one after the other and with a delay in between. For example, the subject in the top panel could reliably discriminate any two electrodes from the available 22 and yet the number of effective channels for the subject was three for consonant identification in quiet and four for consonant identification in noise. That is, an apparent disconnect exists between the number of discriminable electrodes on the one hand, and the number of effective channels on the other hand. Possibly, temporal interactions that are produced in the speech processor context, with rapid sequential presentations of overlapping electric fields, and that are not produced in the electrode discrimination context, may provide a partial or complete explanation for the disconnect. However, that is speculation at this point and more research is needed to learn why the numbers of effective channels are so low and why those numbers are so different from the numbers of discriminable electrodes.

Given what we know now, the eight electrodes used in the COMBI 40 CI may have been the ideal number, in that no more than eight electrodes can be effective, at

least with the existing devices and processing strategies. In addition, limiting the number to eight allows for a relatively wide spacing between the intracochlear electrodes, which would be expected to reduce interactions among the electrodes, compared with the interactions produced with shorter inter-electrode distances.

An increase in the number of effective channels up to eight for all cases that fall short of that mark would be expected to produce perfect or nearly perfect scores in even the most difficult tests of speech reception in quiet for most or all users of unilateral CIs (Dorman et al., 2002). In addition, increments beyond eight, even as small as 1-3 more channels, would be expected to produce substantial improvements in speech reception in noise for the same users (Dorman et al., 2002). Such gains – however achieved – would be a breakthrough in implant design and performance.

According to some measures, e.g., critical bands, there are more than 20 effective channels in normal hearing across speech range of frequencies. The 20 is far greater than the maximum of eight that we have with the present-day CIs.

5.3 Benefits of Adjunctive Stimulation

As noted previously, the performance of unilateral CIs has remained relatively stable since the mid 1990s. Fortunately, however, another way has been found to improve performance and that is to present stimuli in addition to those provided with a unilateral CI. This can be done in either of two ways and one is to present electric stimuli on both sides with bilateral CIs and the other is to present acoustic stimuli on one or

both sides, the latter for persons with useful residual hearing at low frequencies. For the combination of electric plus acoustic stimuli (combined EAS), the electric stimuli represent high frequencies in the sound input and the acoustic stimuli represent low frequencies in the input.

An example of the benefits of such adjunctive stimulation was presented previously in Figure 4.8. In this case, acoustic stimuli were delivered to the ear contralateral to the ear with a fully inserted CI. (This arrangement of electric and acoustic stimuli is sometimes called “hybrid” stimulation.) The middle column in the figure shows scores for recognition of monosyllabic words with the CI alone for 15 subjects, and the right column shows scores for the same subjects and test but with electric plus acoustic stimuli. The left column reprises the word scores at the two-year interval for the 55 subjects in Helms et al. study, who were tested in the mid 1990s. The 15 subjects in the other two columns were tested by Michael Dorman and his coworkers a little more than a decade later (Dorman et al., 2008).

The scores in the left and middle columns are indistinguishable, again showing the same performance for unilateral CIs between the mid 1990s and the mid-to-late 2000s. In contrast, the scores in the right column are significantly higher than the scores in the middle and left columns.

Of course, the top scores with the unilateral CI only can't be improved much if at all for this particular test. The effect of the adjunctive stimulation is to “bring up the

bottom” such that the number of subjects with scores below 55 percent correct is greatly diminished compared with the number for electric stimulation alone. And as mentioned previously as well, results from further studies by Dorman et al. have shown that the greatest benefits of combined EAS generally are obtained when: (1) the CI-only scores for a given test are below 60 percent correct; (2) the pure tone average (PTA) of thresholds in the hearing ear(s) for the frequencies of 125, 250, and 500 Hz is better than 60 dB HL; and (3) the test material is sentences presented in competition with noise or other talkers (Dorman et al., 2015).

Bilateral electrical stimulation can produce similar gains in speech reception and additionally can reinstate to some extent sound localization abilities through a representation of the interaural level difference (ILD) cues that can indicate the lateral positions of sound sources. Combined EAS also greatly enhances music reception, perhaps through a representation with the acoustic stimulus of the first several harmonics for periodic sounds, which are critical for robust perception of the fundamental frequencies for those sounds. In addition, acoustic stimulation on both sides (in conjunction with the electric stimulation on one or both sides) can reinstate some sound localization abilities for some patients.

5.4 The Continued Importance of Unilateral Implants

Despite these wonderful gains with adjunctive stimulation, unilateral CIs are still vitally important. In particular, not all patients have useful residual hearing (although

many do); not all patients or prospective patients have access to bilateral CIs due to national health policies or restrictions in insurance coverage; and the unilateral CI and its performance is the “bedrock” of the adjunctive stimulation treatments. With respect to the last point, improvements in the performance of unilateral CIs would be expected to boost the performance of the adjunctive stimulation treatments as well.

5.5 Remaining Gaps

Although the present-day CIs and related treatments are great, they are not perfect. Some of the remaining gaps between prosthetic and normal hearing are that:

- Some users of CIs still do not have high levels of speech reception
- Speech reception in adverse acoustic environments such as noisy restaurants or workplaces is worse for even the best CI users compared to listeners with normal hearing
- The averages of scores for difficult tests in quiet, such as recognition of monosyllabic words, are still far lower for CI users than for listeners with normal hearing, although some CI users score at or near 100 percent correct in these tests
- Sound localization is absent or nearly so for users of unilateral CIs
- Reception of sounds more complex than speech, e.g., most music, is impaired for CI users

In addition, some experts have suggested that reception of tone languages may pose special difficulties for CI users, in that perception of fundamental frequencies (and

therefore the tone contours in the tone languages) may be at least somewhat impaired with the present-day devices. However, results from the recent clinical trial in China of the Nurotron device indicate that recognition of sentences in Mandarin (a tone language) is just as good as recognition of sentences in languages that do not use tone contours to convey phonetic information (Zeng et al., 2015a). Possibly, the perception of tone contours is at least adequate with the present-day CIs for robust reception of tone languages, or co-varying cues convey the necessary phonetic information in any case. The CI works well and similarly for all languages tested to date.

5.6 Possibilities for Narrowing the Gaps

Each of the gaps listed in the preceding section can be narrowed but not eliminated with adjunctive stimulation. Combined EAS is especially helpful for music reception, and bilateral CIs are especially helpful for restoring sound localization abilities. Either mode can produce substantial improvements in speech reception in noise and in the recognition of difficult speech items in quiet.

Additional possibilities for narrowing the gaps include: (1) identifying the mechanism(s) underlying the difference between the number of discriminable electrodes and the lower number of effective channels; (2) an increase in the latter number, perhaps with a greater spatial specificity of stimulation at different sites in the cochlea or auditory nerve; (3) prudent pruning of interfering or otherwise detrimental electrodes; (4) a further relaxation in the criteria for implant candidacy, based on recent evidence

from persons with high levels of residual hearing; and (5) a “brain centric” approach to designs and applications of CIs that takes the brain into account and makes appropriate adjustments for persons whose “hearing brains” have been compromised by long periods of sensory deprivation or a myriad of other causes. Many other possibilities could be suggested and indeed are being pursued. However, the listed possibilities are the most promising in my opinion.

Understanding the apparent disconnect between the number of discriminable electrodes *versus* the number of effective channels is vital for guidance in increasing the latter number. Modeling studies are in progress in my present laboratory to evaluate various possible mechanisms for the observed effects. (Josh Stohl, Ph.D., is our highly able leader in this research for the laboratory.) Results from the studies may inform the design of electrodes or stimuli or both that will produce increases in the number of effective channels. As noted previously, even small increases would be a boon to CI users.

Based on what we know now, increases also might be produced with greater spatial specificities of stimulation at different sites in the cochlea or auditory nerve. Three promising possibilities along these lines are optical rather than electric stimulation in the cochlea (Jeschke and Moser, 2015); delivery of electrical stimuli within the auditory nerve rather than in the scala tympani (ST) of the cochlea (Middlebrooks and Snyder, 2007); and promotion of the growth of neural processes from the spiral ganglion

cells toward electrodes in the ST (Pinyon et al., 2014). Each of these approaches may sharpen the neural excitation fields.

Pruning of interfering or otherwise detrimental electrodes makes great sense for the present-day CIs, in that those devices can support only a maximum of eight effective channels. Choosing the best eight among the higher numbers of available electrodes, and deactivating the others, may produce improvements in performance compared with using most or all of the available electrodes. Certainly, deleterious interactions among electrodes would be reduced in each case with the smaller number.

New evidence in support of the “prudent pruning” possibility is presented in Figure 5.4, which shows results from Vanderbilt University Medical Center in Nashville, TN, USA, comparing speech reception scores obtained with conventional fittings of CIs (open bars) *versus* modified fittings with a subset of the previously utilized electrodes deactivated (gray bars). A computed tomography (CT) imaging and analysis technique was used to identify the electrodes that were relatively far away from the putative neural target for CIs, the spiral ganglion cells, and therefore likely to have higher thresholds for neural activation and greater spatial extents of excitation for supra-threshold stimuli. Those identified electrodes, or subsets of them, were deactivated. The technique is described in detail in an initial paper by Noble et al. (2013) and results from studies with implant patients are presented in a subsequent paper also by the Vanderbilt group (Noble et al., 2014).

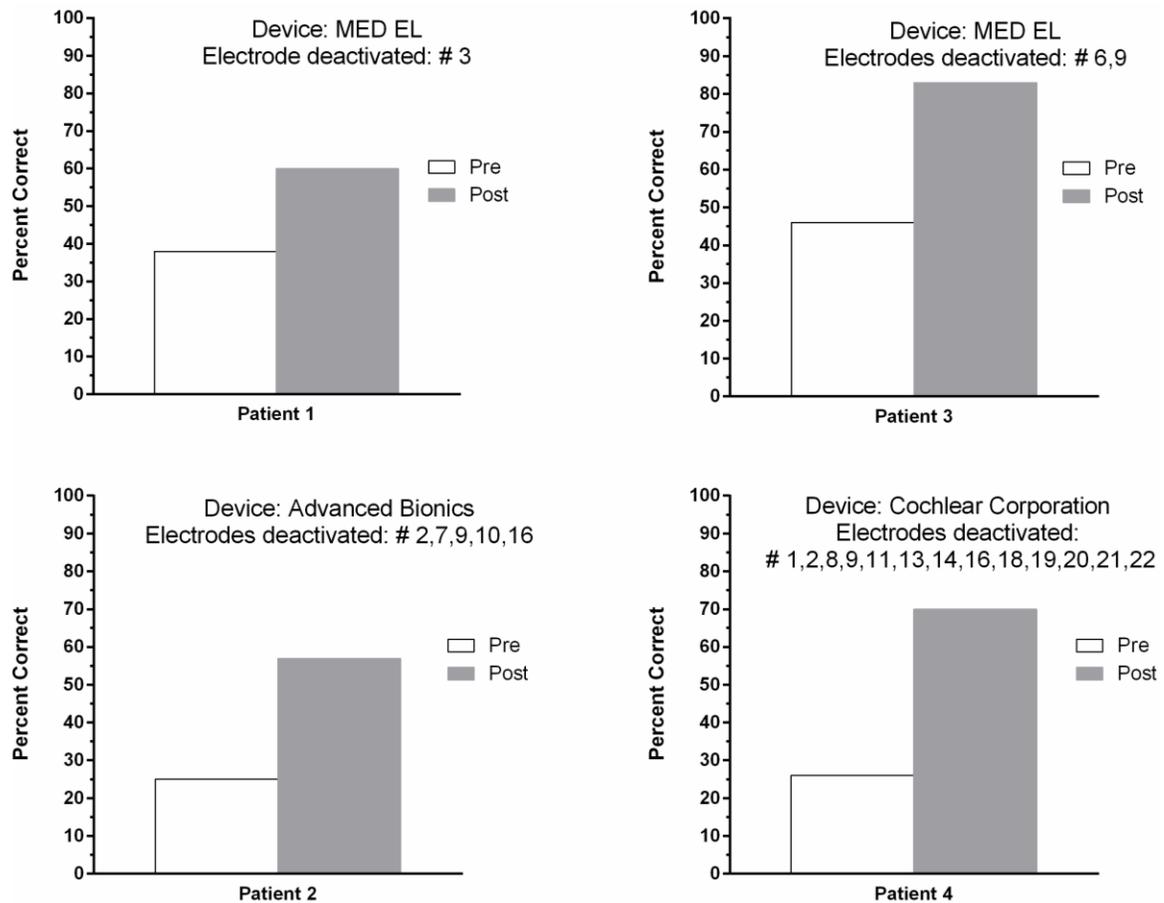


Figure 5.4: Percent correct scores for recognition of the Arizona Biomedical Institute (AzBio) sentences by users of unilateral cochlear implants (CIs). The sentences were presented in competition with noise at the speech-to-noise ratio of +10 dB. Scores are shown for conventional fittings of the CIs (pre) *versus* fittings in which electrodes were deactivated (post), for each of four subjects. The devices used by the subjects and the electrodes that were deactivated are indicated in the title lines for each panel. The subjects are identified by patient number, patients 1-4. (These data were kindly provided by René Gifford, Ph.D., of the Vanderbilt University Medical Center in Nashville, TN, USA, and are published in Wilson et al. (2015). The figure is reproduced from that publication with permission.)

Gains in speech reception from application of the technique can be large. For the four subjects in Figure 5.4, for instance, gains in the recognition of the Arizona

Biomedical (AzBio) sentences presented in competition with noise, at the speech-to-noise ratio (S/N) of +10 dB, ranged from 22 to 44 percentage points. Results vary across subjects and not all subjects have similarly large gains if any significant gain at all. However, gains like those shown in the figure are huge and clearly indicate the promise of the approach.

Alternatively, electrodes could be deactivated on the basis of direct measures of electrode interactions. The electrodes that produce the greatest interactions would be eliminated. Also, electrodes that are associated with relatively poor sensitivities to modulation of a pulse train carrier could be eliminated (Garadat et al., 2013), as the sensitivity to modulation is strongly correlated with speech reception scores (Fu, 2002). And most simply, electrodes could be eliminated to produce the maximum spatial separation among the retained electrodes, again to reduce interactions. For example, alternate electrodes in a 16-electrode array could be deactivated to produce the maximum spatial separation.

More than eight electrodes were retained for each of the subjects in Figure 5.4. Even better results might have been obtained if the numbers were further pruned to eight.

Future research might include the use of within-subject controls to evaluate the relative efficacies of the different techniques for selecting electrodes for deactivation. For example, the CT imaging technique, direct measures of electrode interactions, measures

of modulation sensitivity, and selection to maximize the spatial separation among the retained electrodes could all be compared (in randomized orders of presentations) in tests with the same subjects. In that way, the best technique(s) might be identified.

A further relaxation in the criteria for implant candidacy would make CIs available to many more persons who could benefit from them. In addition, the newly included persons would have more residual hearing than any of the present CI users and present candidates for CIs. The average scores would increase, through the demonstrated benefits of combined EAS, which also include better reception of sounds more complex than speech. Even a slight relaxation in the criteria would increase the number of candidates substantially. Possibly, for example, persons who now suffer from the debilitating effects of presbycusis may become candidates for a CI and the benefits of combined EAS.

Evidence in support of broadened candidacy is presented in Figure 5.5, which shows results from a retrospective chart study of 159 persons with residual hearing who were implanted at the International Center of Hearing and Speech in Kajetany (near Warsaw), Poland, from mid December 2002 to late June 2007 (Wilson, 2012). The amount of residual hearing for each of the subjects was characterized by her or his audiogram for the better hearing ear. Two measures were used: the PTA for 125, 250, and 500 Hz, and the threshold for 500 Hz only. The categories included relatively good, moderate,

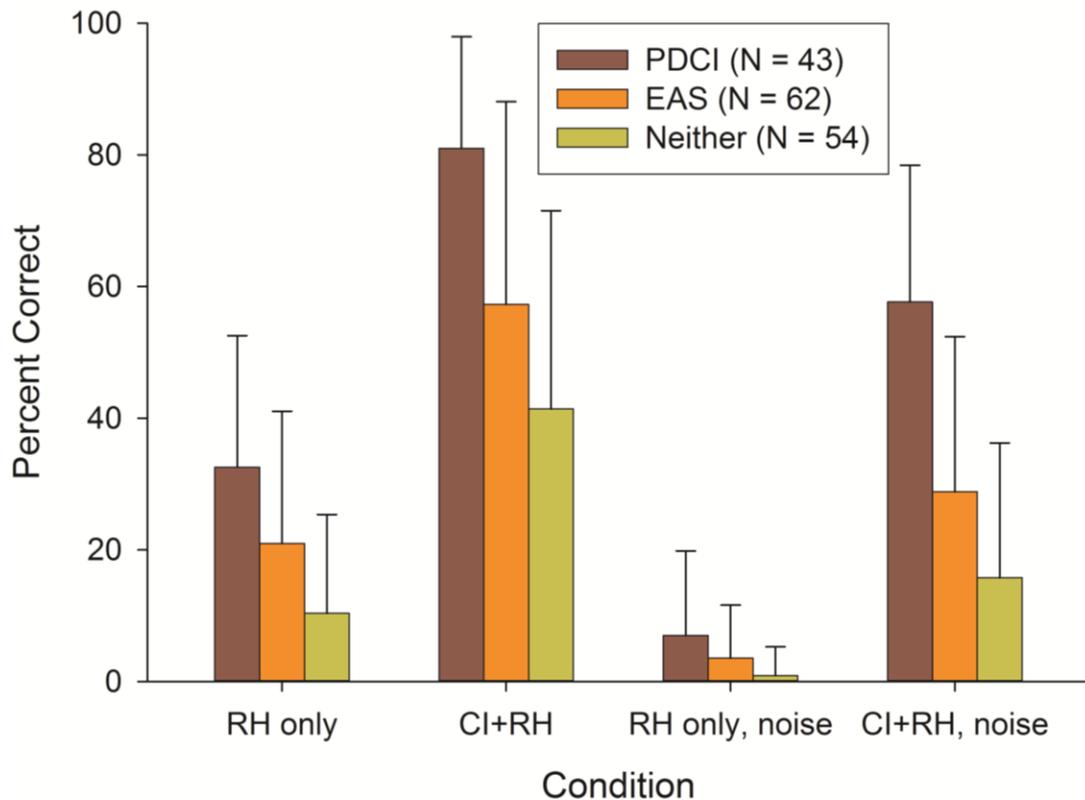


Figure 5.5: Means and standard deviations of percent correct scores for the recognition of the Pruszewicz monosyllabic words (in Polish) by users of unilateral cochlear implants (CIs) who were implanted at the International Center of Hearing and Speech in Kajetany, Poland, from mid December 2002 through most of June 2007. All 159 subjects had residual hearing (usually at low frequencies only) in one or both ears. The words were presented in quiet and in noise, the latter at the speech-to-noise ratio of +10 dB. Results are shown for acoustic stimulation using the residual hearing only (RH only and RH only, noise) and for electric plus acoustic stimulation using the CI plus the residual hearing (CI+RH and CI+RH, noise). The results for subjects with relatively good residual hearing are shown with brown bars; results for subjects with moderate residual hearing are shown with the orange bars; and results for subjects with relatively poor residual hearing are shown with the olive-colored bars. These categories of residual hearing are described further in the text. (The figure is adapted from Wilson, 2012, and is reproduced here with permission.)

and poor levels of residual hearing and are labeled in the figure as “PDCI,” “EAS,” and “Neither,” respectively. Prospective patients in the categories might be regarded as candidates for a “partial deafness cochlear implantation” (PDCI) procedure, for combined EAS, or for neither procedure, again on the basis of each person’s residual hearing. Persons in the PDCI category had thresholds at 500 Hz that were equal to or better than 55 dB HL *or* a PTA equal to or better than 45 dB; persons in the EAS category had thresholds at 500 Hz in the range from 80 to 56 dB HL *or* PTAs in the range from 70 to 46 dB HL; and persons in the “Neither” category had thresholds at 500 Hz that were worse than 80 dB HL *and* PTAs that were worse than 70 dB HL. All of the subjects used their residual hearing in conjunction with the CI in their daily lives.

The figure shows the means and standard deviations of the scores for the recognition of Polish monosyllabic words presented in quiet and in noise, the latter at the S/N of +10 dB. The conditions included tests with the residual hearing only (RH only) and with the CI plus the residual hearing (CI+RH). The acoustic stimuli were delivered to either or both ears, depending on which choice produced the best recognition of the monosyllabic words in quiet for each subject using her or his residual hearing only, with amplification as appropriate.

The addition of the CI produced large and highly significant improvements in speech reception in all cases. The improvements for the subjects with relatively high levels of residual hearing (the PDCI subjects) were just as great as the improvements for

the other subjects, with lower levels of residual hearing. That was a surprise, as the conventional wisdom at the time was that patients with such good residual hearing might be harmed by cochlear implantation and that there must be a point of diminishing returns at which the residual hearing is so good that it can't be augmented substantially with the addition of a CI. In contrast, the data show that enormous benefits are conferred by the CI even for the PDCI subjects. In addition, the highest scores in the study were obtained by the PDCI subjects in each of the experimental conditions. The data presented in Figure 5.5, along with other similar data (Gifford et al., 2010), strongly support a further relaxation in the criteria for implant candidacy and indeed the point of diminishing returns has yet to be identified.

And last but not least, the brain centric approach to designs and applications of CIs and related treatments may be especially helpful to patients presently at the low end of the performance spectrum (Wilson et al., 2011). Indeed, accumulating evidence is indicating that a large portion of the remaining variability in outcomes with CIs and the related treatments may be due to differences in the function of the hearing brain among the recipients. If so, then a better match between what the prosthesis provides and what the compromised brain can process may improve performance for the relatively small proportion of patients who are still struggling. Help for them would of course be another breakthrough.

5.7 Concluding Remarks

The modern CI is a triumph of engineering, otology, and neuroscience, among other disciplines. It is now widely regarded as one of the great advances in medicine and in technology. Most users today converse routinely with their cell and landline phones.

Performance with unilateral CIs has remained relatively stable since the early 1990s, when new and highly effective sound processing strategies were first introduced into widespread clinical applications.

In the early 2000s, adjunctive stimulation – either with bilateral CIs or combined EAS – produced further and highly significant gains in speech reception. In addition, bilateral CIs could reinstate sound localization abilities and combined EAS greatly improved reception of sounds more complex than speech.

However, not all candidates for CIs have access to bilateral CIs or enough residual hearing for effective use of combined EAS. In addition, room still exists for improvements even with the adjunctive stimulation treatments.

Additional steps forward might be achieved in any of multiple ways, including broadened indications that would allow many more people to benefit from combined EAS.

Appendix A: Acknowledgements Section from Wilson and Dorman (2012a)*

* The acknowledgements section in this appendix is presented with the permission of the publisher.

Acknowledgements Section from Wilson and Dorman (2012a)

An exceptionally large number of organizations and highly talented and dedicated investigators contributed to the research described in this book. In addition, the research would not have been possible without the generous contributions of time by the many cochlear implant users who participated in the studies.

The research was supported primarily by the National Institutes of Health (NIH), through its Neural Prosthesis Program (NPP). The first project began in September 1983 and the final of the seven contiguous projects ended in March 2006. Funding for our particular projects within the NPP was provided by the National Institute of Neurological Disorders and Stroke (NINDS) for the first two projects and by the National Institute on Deafness and Other Communication Disorders (NIDCD) for the remaining projects. Funding by the NIDCD began on May 1, 1989.

In addition, a study involving subjects fitted with an experimental version of the Nucleus cochlear implant device was jointly supported by the NIH and Cochlear Americas Corp. This study began in the spring of 1994.

Travel expenses for visiting subjects and guest scientists also were generously covered by the MED-EL GmbH for studies involving: (1) recipients of bilateral MED-EL implants; (2) users of combined electric and acoustic stimulation of the auditory system; (3) users of the newly introduced MED-EL PULSAR implant system; and (4) a subject implanted on one side for amelioration of intractable tinnitus and who had nearly normal hearing on the other side. MED-EL additionally provided important technical assistance in these studies.

Most of the work was conducted at the Research Triangle Institute (RTI) in the Research Triangle Park in North Carolina. RTI is a large, not-for-profit research institute that was created in 1958 by the three largest research universities in the area, Duke University, North Carolina State University, and the University of North Carolina at Chapel Hill. The present staff at the RTI includes more than 2,800 people at multiple locations in the United States and in other countries. The RTI is also known as RTI International, a trade name for RTI.

In addition, a substantial fraction of the research was conducted at the Duke University Medical Center in Durham, North Carolina. The great majority of patient

studies were conducted there until the fall of 1995, when two new laboratories were built at the RTI. Use of the laboratory at Duke was tapered down to zero over the ensuing two years and, ultimately, all studies were conducted in the RTI laboratories.

At the outset of our work in 1983, and up until mid-1985, studies with research subjects were conducted at the University of California at San Francisco (UCSF). The projects required collaboration with a tertiary care center that was active in the clinical application of cochlear implants. When the projects began, the only such centers in the United States were at UCSF, Stanford University in Palo Alto, California, and the House Ear Clinic in Los Angeles, California. UCSF graciously agreed to be our collaborating clinical center.

A cochlear implant program was created at Duke in early 1985. Soon thereafter, the laboratory was created at Duke for cochlear implant studies, and space and funding for the laboratory were generously provided by David C. Sabiston Jr., MD, who was the Chair of the Department of Surgery. Once the laboratory was operational, most studies were transferred from UCSF to Duke with enthusiastic technical support by—and ongoing collaboration with—UCSF.

The members of the RTI teams over the years included the people listed in Chapter 1, under the subheading “Composition of the RTI Teams.” Each of the members contributed strongly to the overall effort.

A hallmark of the projects was collaboration with many investigators, universities, and companies worldwide. Lists of the collaborating investigators and their affiliations at the times of their participation in the RTI studies are presented in Appendix A. Among the investigators, special acknowledgements are due to Michael M. Merzenich, PhD, who welcomed us into his program at UCSF at the beginning of our work when we had little to offer in return, and Joseph C. Farmer Jr., MD, who asked us to conduct patient studies at Duke and supported our efforts with the highest enthusiasm thereafter.

Spectacular support also was provided by the management at the RTI. All requests for equipment were approved, and ample space and other resources were provided throughout the course of the projects. Special thanks are due to George R. Herbert, who was RTI’s president during the early years of the projects; Grace C. Boddie, who was a vice president and the chief counsel for the Institute during the same period; and F.

Thomas Wooten, PhD, who was the vice president of the Electronics and Systems Division within the RTI from 1983 to 1989 and became RTI's president in 1989 when Mr. Herbert retired. All of these and many other great people at the RTI supported the projects strongly.

Of course, we could not have done anything without our research subjects. We were blessed with some of the best, and we were continually amazed by their engagement in the studies and by their generosity in spending time with us.

We were blessed as well to be a part of the NPP. The heads of that program, F. Terry Hambrecht, MD, and, later, William J. Heetderks, MD, PhD, fostered a collaborative spirit among the participants in the program. For example, a Neural Prosthesis Workshop was held each year at NIH to review the progress of the many projects within the NPP and for the investigators to interact and share ideas. The cross-pollination of ideas was impressive, and advice was freely given and received. Everyone and each of the projects benefitted, and these benefits were made possible by the positive tone set by Terry and Bill.

Terry and Bill also were the project monitors for our projects. Terry and then Terry and Bill made regular site visits to our laboratories to review progress, plans, and problems that had been encountered. In addition, they read our progress reports carefully and communicated with us frequently about the work and especially about new ideas.

The site visits were both intense and rewarding. Terry and Bill never failed to offer the most insightful suggestions imaginable, including suggestions for solving problems, for new hypotheses, and for refined or new research directions. The guidance so selflessly provided by these two brilliant and dedicated leaders of the NPP was vital to our successes.

This book was made possible with the generous and highly able assistance of Susanne Stoops, Jeannie H. Cox, Callen Shutters, Dewey T. Lawson, and Stefan M. Brill. We are especially indebted to Susanne for her many efforts in helping to produce the book, including her expert transformation of the selected sections from NIH progress reports into the manuscripts for Chapters 2 through 21.

In addition, we are deeply indebted to the spectacular team at Plural for their sterling and highly professional efforts. The team members we worked with included Caitlin Thompson Mahon, Angie S. Singh, Kim White, Judy Meyer, Mandy Licata, Casey Stach, Stephanie Meissner, and Sandy Doyle. We are sad to announce that Sandy is now deceased; she helped us greatly with the graphics aspects of the book. Among the many contributions by the Plural team, Caitlin's editorial and production work stands out. She is the best of the best.

The concept for this book was suggested by Professor Michael F. Dorman many years ago. Although I thought the concept was wonderful, I kept delaying the project due to the press of ongoing activities and obligations. He persisted, however, and even offered to write the book with me. We finally began working on the book in earnest in the winter of 2011. I will forever be grateful to Michael for the concept, and for his perseverance, cheerful encouragement, and many key contributions to the writing. Indeed, those contributions and his guiding hand produced a book that is very much better than any book I could have written on my own.

Our RTI teams were privileged to have had the grand opportunity to pursue the work described herein. We were helped mightily every step of the way.

Blake Wilson, July 2011

There are only a few times in a career in science when you get goose bumps. One of mine came when one of my patients, Max Kennedy, was being tested at RTI with a version of a continuous interleaved sampling (CIS) processor. I was watching Dewey Lawson input Max's responses to the monitor program and Max's responses keep coming up "correct." Near the end of the test, everyone in the room was staring at the monitor wondering if Max was going to get 100 percent correct on a difficult test of consonant identification. He came close, and at the end of the test, Max sat back, slapped the table in front of him, and said loudly, "Hot damn, I want to take this one home with me." I am indebted to Blake, Dewey, Charlie, and Marian for the goose bumps.

Michael Dorman, August 2011

Appendix B: Appendix A from Wilson and Dorman (2012a)*

* The appendix from Wilson and Dorman is presented here with the permission of the publisher.

Appendix A from Wilson and Dorman (2012a), Partners in Research

As noted in the Acknowledgments, the team at the Research Triangle Institute (RTI) was greatly augmented and enriched by participation in joint studies by many investigators from other organizations worldwide. The principal collaborations were with investigators at the University of California at San Francisco (UCSF) and the Duke University Medical Center (DUMC). We received spectacular help, advice, and partnership from Michael M. Merzenich, Dorcas K. Kessler, Patricia A. Leake, Stephen J. Rebscher, Robert A. Schindler, Robert V. Shannon, Lindsay Vurek, Mark W. White, David Wilkinson, and others from UCSF, and we received the same from Joseph C. Farmer, Jr., Nell B. Cant, John H. (Pete) Casseday, Leslie M. Collins, Warren M. Grill, William R. Hudson, Patrick D. Kenan, John T. McElveen, Jr., Patricia A. Roush, Debara L. Tucci, Bruce A. Weber, Robert D. Wolford (in the early years, before he joined the RTI team), and many others from DUMC. In addition, the RTI team conducted studies at UCSF up until mid-1985 and at DUMC from mid-1985 through the fall of 1995. Laboratory facilities were generously provided by UCSF and DUMC, and the investigators at those universities worked closely with us in the studies.

A partial listing of the many other investigators who worked alongside us over the years includes Sigfrid D. Soli, first with the 3M Company in Minnesota and later with the House Ear Institute in Los Angeles; Michael F. Dorman of Arizona State University; Philip Loizou, first with Arizona State University, then with the University of Arkansas at Little Rock, and then with the University of Texas at Dallas; James W. Heller and Ronald E. West of Cochlear Americas Corp.; James F. Patrick of Cochlear Ltd. in Lane Cove, Australia; Jacques François of the Ecole d'Ingenieurs de Geneve in Geneva, Switzerland; Wolfgang K. Gstoettner, Jan Kiefer, Thomas Pfennigdorff, Jochen Tillein, Christoph A. von Ilberg of the J. W. Goethe Universität in Frankfurt, Germany; Stefan (Marcel) Pok, first with the J. W. Goethe Universität and later with the Medical University of Vienna in Vienna, Austria; Robert V. Shannon and John Wygonski of the House Ear Institute; Albert A. Maltan, first with the House Ear Institute, then with the MED-EL GmbH of Innsbruck, Austria, and then with the Advanced Bionics Corp. in Valencia, CA, USA; Artur Lorens of the International Center of Hearing and Speech in Kajetany, Poland; Joachim M. Müller and Franz Schön of the Julius Maximilians Universität in Würzburg, Germany; Josef M. Miller and Bryan E. Pfingst of the Kresge Hearing Research Institute at the University of Michigan; Martin P. O'Driscoll of the

Manchester Royal Infirmary in Manchester, England; Peter Nopp of the MED-EL GmbH; Raymond Mederake of the MED-EL subsidiary in Starnberg, Germany; Colette Böex-Spano and Donald K. Eddington of the Massachusetts Eye & Ear Infirmary in Boston, MA, USA; William M. Rabinowitz of the Massachusetts Institute of Technology; Susan B. Waltzman of New York University; Sung June Kim of Seoul National University in Seoul, South Korea; Laurel J. Dent of Stanford University; David Calvert, Stephen Hutchison, and Gary Keibel of the Storz Instrument Company in St. Louis, MO, USA; Gerald E. Loeb, first as a guest researcher at the UCSF (on leave from the NIH), then with Queen's University in Kingston, Ontario, Canada, then with the Advanced Bionics Corp. (as its consulting Chief Scientist), and then with the University of California at Los Angeles; Oliver F. Adunka, first with the J. W. Goethe Universität and then with the UNC; Carol Higgins (now Carol Pillsbury) and Harold C. Pillsbury of the UNC; Marco Pelizzone of the Hôpital Cantonal Universitaire Geneva, in Geneva, Switzerland; Stefan Brill (before he became a member of the RTI team), Erwin S. Hochmair, Otto Peter, and Clemens M. Zierhofer of the University of Innsbruck in Innsbruck, Austria; Paul J. Abbas, Carolyn J. Brown, Bruce J. Gantz, Mary W. Lowder, Aaron J. Parkinson, Jay T. Rubinstein, and Richard S. Tyler of the University of Iowa; Korine Dankowski of the University of Utah; Christoph Arnoldner and Wolf-Dieter Baumgartner of the Medical University of Vienna in Vienna, Austria; Enrique A. Lopez-Poveda, first with the University of Castile—La Mancha and then with the University of Salamanca in Spain; and Margaret W. Skinner of Washington University in St. Louis, MO, USA. The affiliations for some of these people have changed (or changed further) since their active participation in the studies at RTI and Duke.

We also benefited from visits by many world leaders in the field of cochlear implants and related fields. A few among these visitors were Hugh J. McDermott from the University of Melbourne in Melbourne, Australia; Ingeborg J. Hochmair from the MED-EL GmbH; Erwin S. Hochmair from the University of Innsbruck (before his participation in studies at the RTI and DUMC); Deborah Ballantyne from the Università Degli Studi di Roma "La Sapienza" (Department of Otolaryngology) in Rome, Italy; Margaret (Margo) W. Skinner and A. Maynard Engebretson of Washington University (before Margo's participation in studies at RTI and Duke); Thomas Lenarz and Rolf D. Battmer from the Medizinische Hochschule Hannover in Hannover, Germany; Paul Carter from Cochlear Ltd. (while on leave at Cochlear Americas); Charles A. Miller from the University of Iowa; Matthew Bakke and Yifang Xu from Gallaudet University;

Russell L. Snyder from UCSF; Kevin H. Franck from The Children's Hospital of Philadelphia in Philadelphia, PA, USA; Christopher W. Turner also from the University of Iowa; Craig A. Buchman from the UNC; and Peter S. Roland from the University of Texas Southwestern Medical Center. The discussions with these wonderful visitors were highly enlightening and in some cases suggested new questions for us to ask in our research.

Appendix C: Overview Chapter (Chapter 1) from Wilson and Dorman (2012a)*

* The chapter in this appendix is presented with the permission of the publisher. The references for this appendix are presented in the book.

1. Introduction

As recently as the early 1980s, the success of cochlear implants (CIs) was very much in doubt. Indeed, it seemed that the more a researcher knew about auditory neurophysiology or speech acoustics, the more confident he was that implants could not provide a high (or even useful) level of speech understanding. Fortunately, pioneers in the implant field persisted in the face of doubt and, at times, intense criticism, and provided the foundation for the extremely successful CI devices that are available today.

Three large steps were needed to produce the present-day CIs: (1) the pioneering step to implant the first patients and to develop devices that were safe and had a life span of many years; (2) the development of devices that provided multiple sites of stimulation in the cochlea to take advantage of the tonotopic organization of the auditory system; and (3) the development of highly effective processing strategies that utilized the multiple sites of stimulation and supported for the first time high levels of speech recognition for most users of CIs. Findings from the landmark “Bilger study” in 1977 (Bilger et al., 1977)—and from the two consensus development conferences on cochlear implants held at the National Institutes of Health (NIH) in 1988 and 1995 (National Institutes of Health, 1988, 1995)—indicate the status of CIs at each of these steps. Principal conclusions from the Bilger study and the two consensus statements are presented in Table C.1. As noted there, especially large gains in performance were obtained in step 3.

Teams at the Research Triangle Institute (RTI) in North Carolina, USA, along with their many collaborating investigators from other research organizations worldwide, contributed significantly to step 3. This book describes the program of research at the RTI and the collaborating organizations, and presents key results selected from nearly 23 years of research.

2. The RTI Projects and their Membership in the Neural Prosthesis Program

As noted in the Acknowledgments, the research was supported primarily by the NIH, beginning in September 1983 and continuing through March 2006. In all, seven projects were supported. Each project had the title “Speech processors for auditory prostheses,” but a wide range of studies and activities was included in the projects that

Table C.1. Major Indicators of Progress in the Development of Cochlear Implants

Persons or Event	Year	Comment or Outcome
Bilger et al.	1977	“Although the subjects could not understand speech through their prostheses, they did score significantly higher on tests of lipreading and recognition of environmental sounds with their prostheses activated than without them.” (This was a NIH-funded study of all 13 implant patients in the United States at the time.)
First NIH Consensus Statement	1988	Suggested that multichannel implants were more likely to be effective than single-channel implants, and indicated that about 1 in 20 patients could carry out a normal conversation without lipreading. (The world population of implant recipients was about 3,000 in 1988.)
Second NIH Consensus Statement	1995	“A majority of those individuals with the latest speech processors for their implants will score above 80% correct on high-context sentences, even without visual cues.” (The number of implant recipients approximated 12,000 in 1995, and the number exceeded 220,000 in late 2010.)

went well beyond the design and testing of novel speech processors. A list of the projects with their terms and NIH numbers is presented in Table C.2.

The projects were a part of the Neural Prosthesis Program (NPP) at the NIH, which supported work in the many different areas relating to neural prostheses, for example, reambulation of paralyzed limbs or extremities; restoration of bladder control for quadriplegics; restoration of sensory inputs to the brain including auditory, visual, and vestibular inputs; brain-machine interfaces; packaging of implanted electronics; insulation for the nonactive parts of stimulating electrodes; alternative electrode designs for various neural prostheses; alternative stimulus designs; and safety of electrical stimulation.

Our area was restoration of auditory inputs to the brain, and our projects were accompanied by others in that same area. The projects at the RTI spanned the entire

Table C.2. The Series of “Speech Processors” Projects at the Research Triangle Institute

Project	NIH Number	Term
1	N01-NS-3-2356	26 September 1983 through 25 September 1985
2	N01-NS-5-2396	26 September 1985 through 30 April 1989
3	N01-DC-9-2401	1 May 1989 through 31 July 1992
4	N01-DC-2-2401	1 August 1992 through 31 July 1995
5	N01-DC-5-2103	1 August 1995 through 29 September 1998
6	N01-DC-8-2105	30 September 1998 through 31 March 2002
7	N01-DC-2-1002	1 April 2002 through 31 March 2006

period from 1983 to 2006, and each of the other projects relating to auditory prostheses spanned shorter periods within those years. At the outset, our projects were the only projects directed primarily at better speech processor designs. In later years, either two or three projects on this topic were supported at any one time up until 2006 when the projects ended and the NPP had been reorganized into smaller units across multiple institutes at the NIH. (The reorganization occurred in 2004 and followed Bill Heetderks’ decision in late 2002 to resign from his position as the Head of the NPP, so that he could accept an offer to become the Director of Extramural Programs at the newly created National Institute on Biomedical Imaging and Bioengineering; the NPP ceased to exist as a single entity with the reorganization.) These other “speech processors” projects were conducted at Stanford University in Palo Alto, CA; the University of Melbourne in Melbourne, Australia; the House Ear Institute in Los Angeles, CA; and the Massachusetts Eye and Ear Infirmary (MEEI) in Boston, MA.

Among the companion projects, we had an especially close and productive relationship with the team and projects at the MEEI. We developed portable speech processors together, and Don Eddington and Bill Rabinowitz of the MEEI team made important contributions to the development at the RTI (and Duke University Medical Center) of an especially effective and enduring processing strategy for CIs: the continuous interleaved sampling (CIS) strategy. This partnership leveraged the NIH support of the projects in Boston and North Carolina, in that we could accomplish more together than separately.

2.1 QPRs—Four a Year for Over Twenty Years

Projects within the NPP were supported through the contracts mechanism, which was in accord with an integrated and coordinated program to develop better neural prostheses. Requirements of the contracts included presentations by the project teams at the annual Neural Prosthesis Workshop at the NIH; a detailed report of progress and problems encountered during each quarter for each of the projects; and a final report for each of the projects. The quarterly progress reports (QPRs) included a section on plans for the next quarter for all quarters except the final quarter, and the final reports (FRs) included a section on recommendations for future research. The progress reports provided a comprehensive record of activities and achievements for each of the projects.

In all, 91 reports were produced during the seven projects at the RTI. The authors and principal topic(s) for each of the reports are presented in Appendix B, which includes a separate table for each of the seven projects.

2.2 A Very Costly Decision

Soon after the outset of the NIH projects, the RTI team at the time recommended a policy to its management for the handling of intellectual property (IP). The recommended policy was to donate all results from the NIH-sponsored research on CIs at the RTI to the public domain. The thought was that, with the inventions and other IP in the public domain, all valuable discoveries would be applied by most or all of the major manufacturers of CIs and thereby help the greatest possible number of deaf and severely hearing-impaired people.

George R. Herbert, President of the RTI, and Grace C. Boddie, General Counsel, approved the policy after careful consideration of its implications, including the relinquishing of the Institute's rights to the IP as specified by the Bayh-Dole act, which was enacted by the United States Congress in 1980. The act specified that organizations conducting research under Federal grants or contracts would have the right to retain and pursue IP resulting from the research, so long as the Government had a nonexclusive license to utilize the IP for its own purposes. The decision to forgo potential royalties from patents and exclusive licensing agreements proved to be important in that it greatly facilitated incorporation of discoveries from the RTI projects

into commercially-available CI systems at the earliest possible times. In retrospect, the negative economic consequences of the decision to approve the policy were enormous (in the 10s of millions of dollars), both to the organization and to the individual inventors. However, the policy did what it was supposed to do, and the outcomes were most gratifying to the RTI teams and management.

2.3 Composition of the RTI Teams

Members of the RTI teams over the years included Stefan M. Brill, Lianne A. Cartee, Jeannie H. Cox, Dee Dee Davis, Charles C. Finley, Kathrinn Fitzpatrick, Dewey T. Lawson, Reinhold Schatzer, Xiaoan Sun, Christopher van den Honert, Sandra Waters, Blake S. Wilson, Robert D. Wolford, and Mariangeli Zerbi. Kathrinn Fitzpatrick, Sandra Waters, Dee Dee Davis, and Jeannie H. Cox each served as the Administrative Assistant (AA) for the projects at different times in the program, and the remaining individuals served as investigators. (Jeannie Cox also assisted in patient studies in her later years in the program.) The projects were directed by Blake Wilson until he was appointed as one of the first four Senior Fellows at the RTI in late 2002. After that, Dewey Lawson became the Principal Investigator for the remainder of the final project in the series of the seven “speech processors” projects at the RTI.

A chart showing the times of service for most members of the teams is presented in Figure C.1. As noted in the Acknowledgments section, the RTI teams were assisted by many other investigators from many other research institutions worldwide, including institutions in Australia, Austria, Canada, Germany, Poland, South Korea, Spain, Switzerland, the United Kingdom, and the United States.

3. Organization of This Book

In the remaining chapters of this book, we present the most important sections from the most important progress reports, in part to provide a convenient access in one place to the key studies and their results. Many journal articles and book chapters also were produced as part of the projects, but they were generally brief and limited to particular studies and therefore do not provide the detail or the coverage of the progress reports. In addition, the journal articles and book chapters may be obtained easily from libraries and the web, whereas the progress reports are not as widely available.

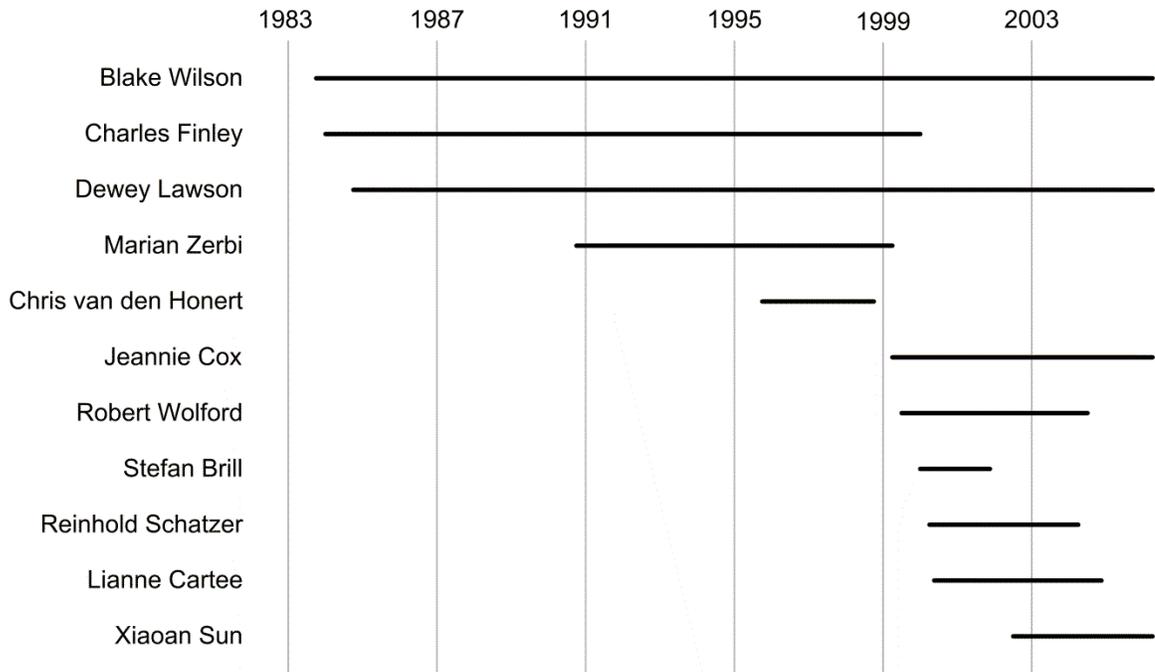


Figure C.1. Composition of the RTI teams from 1983 to 2006. In addition to the members shown, Kathrinn Fitzpatrick, Sandra Waters, and Dee Dee Davis each served as the Administrative Assistant for the projects at different times from 1983 to 1999.

Another reason to present material from the progress reports is that the reports convey the essence of the projects from start to finish. The journal articles fail to do that because they describe single studies only, as just mentioned, and the book chapters fail to do that because they generally integrate results from across many laboratories and areas of research to provide a tutorial for their readers. The journal articles and book chapters are cited at the appropriate places throughout the book, but the emphasis here is on the progress reports.

Following this overview chapter, the book is organized into major parts according to the principal areas of research in the RTI projects, including design and evaluation of novel processing strategies; electrical stimulation on both sides with bilateral CIs; combined electric and acoustic stimulation of the auditory system; and representations of temporal information with CIs. Multiple chapters are included in each part, and each chapter is a selected section from a progress report. In addition, each part

includes a brief introduction to indicate its contents and to point to other relevant reports and findings that could not be included in the book. The references originally cited in the selected sections from the selected progress reports are now presented in the single list of references at the end of this book. Also, some of the figures have been redrafted to provide high-resolution images. Otherwise, no changes have been made in the included source material other than formatting changes in the text for a uniform style and correction of typographical and other minor errors.

In the remainder of the present chapter, we: (1) describe the role of the RTI projects in the broader context of the development of CIs; (2) indicate how we selected the sections from the NIH progress reports for inclusion in the book; and (3) offer some concluding remarks.

4. RTI's Role in the Development of Cochlear Implants

In 1983, when the first project at RTI was underway, the first of the three steps listed near the beginning of this chapter had been taken and progress was being made in taking the second step. Dr. William F. House and a few other pioneers had implanted the first patients, and Dr. House in particular had developed single-channel devices that could be safely and usefully applied over many years. In addition, groups in the United States, Australia, and Europe had developed multielectrode arrays that could be safely inserted at surgery in the scala tympani of the cochlea and that could excite different sectors (or tonotopic regions) of the auditory nerve depending on which intracochlear electrode, or which closely spaced pair of intracochlear electrodes, was activated. However, high levels of speech recognition using hearing alone was still rare and even as late as 1988 only about one in 20 patients using any of the better multi-site and multichannel implants could carry out a normal conversation without lip-reading (National Institutes of Health, 1988; see Table C.1). The implant systems in 1983 were mainly useful as an adjunct to lip-reading and for an awareness of environmental sounds. In the rare cases, a patient could understand high-context sentences with her or his restored hearing alone. Those best performances were far below what was to come later with some further refinements in multisite stimulation and with the completion of step 3. In addition, the completion of step 3 allowed most patients to attain high levels of sentence recognition with hearing alone, as opposed to the small fraction of patients in 1988.

4.1 Step 3 and the CIS Strategy

The largest contribution from the RTI projects was in the completion of step 3, as mentioned previously. In particular, multiple new ways to represent speech and other sounds with CIs were created in the projects, and these new ways supported high levels of sentence recognition using hearing alone for the great majority of implant users. Perhaps the best known discovery came in 1989 and was first called the “supersampler” strategy and then soon thereafter the CIS strategy (Wilson et al., 1989).

Results from the initial studies with the CIS processor were reported in *Nature* in 1991 (Wilson et al., 1991a). This paper soon became the most highly cited publication on studies with CI patients and remains as the most highly cited publication on the topic today. As of July 2011, the paper had been cited in 476 other peer-reviewed publications (Web of Knowledge, 2011).

CIS was a combination of new and prior elements, including: (1) a full representation of energies in frequency bands spanning the spectrum of speech and other sounds; (2) no further analysis of, or “feature extraction” from, this or other information, to allow the brain of the user to make the decisions about what was important or not important in the incoming stream of information; (3) nonsimultaneous stimulation with charge-balanced biphasic pulses across the electrodes in a multielectrode implant, to eliminate the component of electrode or “channel” interactions due to direct summation of overlapping electric fields from the electrodes for simultaneously presented stimuli; (4) stimulation at relatively high rates at each of the electrodes, to allow representations of fundamental frequencies for periodic sounds such as voiced speech and of distinctions between periodic versus aperiodic sounds such as unvoiced speech (again, without explicit extraction of these “features”); (5) use of cutoff frequencies in the energy (or “envelope”) detectors for each of the bandpass filters that would include the fundamental frequency variations in the outputs of the detectors (cutoff frequencies in the range of 200 to 400 Hz); (6) use of current sources rather than the relatively uncontrolled voltage sources that had been used in some prior implant systems; and (7) a relatively high number of activated electrodes (at least four but generally higher and not limited in number). No assumptions about sounds in the environment, or in particular how speech is produced or perceived, were made in the way CIS was constructed. This approach allowed the brain of the user to become a far more active and important part of perception with CIs.

It is worth noting that the gains in performance produced with CIS are sometimes attributed to the non-simultaneous stimulation across electrodes. However, the gains were produced with the discovery of a unique combination of many elements, not just non-simultaneous stimulation, which had been used before (see, e.g., Doyle et al., 1964) but not in conjunction with the other elements. The breakthrough was in the combination and in exactly how the parts were put together.

4.2 Step 3 and “*n-of-m*” or Channel-Picking Strategies

During the late 1980s and early 1990s, the RTI teams and their collaborating investigators created multiple other ways to represent speech and other sounds with multisite and multichannel implants. These ways included the *n-of-m* approach that was subsequently incorporated in a line of processing strategies developed for implant devices manufactured by Nucleus Ltd. and later by Cochlear Pty. Ltd., of Lane Cove, Australia. (Nucleus was the parent company for Cochlear.) The *n-of-m* approach is a variation of CIS in which the envelope signals for the different bandpass channels are “scanned” prior to each frame of stimulation across the intracochlear electrodes, to identify the signals with the *n*-highest amplitudes from among a total of *m* processing channels (and associated intracochlear electrodes). Stimulus pulses are delivered only to the electrodes that correspond to the channels with those highest amplitudes. (The *n-of-m* approach actually was created before CIS; describing the *n-of-m* approach as a variation of CIS is a retrospective description.)

This channel selection or “spectral peak picking” scheme is designed in part to reduce the density of stimulation while still representing the most important aspects of the acoustic environment. The deletion of low-amplitude channels (and associated stimuli) for each frame of stimulation may reduce the overall level of masking or interference across electrode and excitation regions in the cochlea. To the extent that the omitted channels do not contain significant information, such “unmasking” may improve the perception of the input signal by the patient. In addition, for positive signal-to-noise ratios, selection of the channels with the greatest amplitudes in each frame may emphasize the primary speech (or other) signal with respect to the noise.

The *n-of-m* approach was first described for relatively low rates of stimulation in a QPR in 1986 (Wilson et al., 1986; also see Wilson et al., 1987, 1988a). The approach was the basis for the “spectral maxima sound processor” (SMSP) developed in Melbourne,

Australia, in the early 1990s (McDermott et al., 1992; McDermott & Vandali, 1997) and later applied in slightly modified form as the “spectral peak” (SPEAK) strategy, which was used as a part of the Nucleus and Cochlear CI systems for many years thereafter. The patent for the SMSP (McDermott & Vandali, 1997) cites Wilson et al. (1987, 1988a) as the “prior art,” and primarily specifies desirable values for the parameters n and m .

Soon after the creation of CIS, the RTI team at the time suggested that the relatively high rates of stimulation and other attributes of CIS might be beneficial for the n -of- m approach as well (Lawson et al., 1995; Wilson et al., 1995a, 1995b). This suggestion led to a large project at the RTI that was jointly supported by the NIH, Cochlear Pty. Ltd., and the Duke University Medical Center. An important aim of the study was to evaluate the suggestion, and the resulting data affirmed it fully (e.g., Lawson et al., 1996).

Some years later, Cochlear Pty. Ltd. introduced the “advanced combination encoder” (ACE) strategy, which used the n -of- m approach in conjunction with the relatively high rates of stimulation and other attributes of CIS. This strategy quickly became the default processing option for the Cochlear devices and remains as the default option today.

The “high rate” n -of- m strategy, as described and evaluated by the RTI team, also is used as a processing option in a series of CI systems manufactured by MED-EL GmbH of Innsbruck, Austria. The option is called the n -of- m strategy in those systems.

4.3 Step 3 and the Virtual-Channel Strategy

The RTI team also created a way to utilize virtual pitches in a multichannel processor context (e.g., Wilson et al., 1992, 1994). In that approach, pairs of adjacent intracochlear electrodes were stimulated simultaneously to produce pitches that were intermediate to the pitches produced with stimulation of either electrode in the pair alone. Each pair in the electrode array was stimulated after stimulation of the prior pair, maintaining nonsimultaneity of stimulation across the pairs (and regions of stimulation in the cochlea). Other aspects of CIS were retained as well, and these processors were called “virtual channel interleaved sampling (VCIS) processors.”

The production of intermediate pitches with simultaneous stimulation of two electrodes had been described before, first by Simmons et al. in 1965 for electrodes

implanted directly within the auditory nerve and then by Townshend et al. in 1987 for electrodes implanted in the scala tympani (Simmons et al., 1965; Townshend et al., 1987). The RTI group was the first to describe the use of intermediate pitches in a multichannel context and among multiple pairs of electrodes. The VCIS approach was later used in a processing strategy developed by the Advanced Bionics Corp. (ABC) of Valencia, CA, USA (e.g., Trautwein, 2006). The strategy in the ABC devices is called the “Hi-Resolution 120” or HiRes 120 strategy.

In the early development of VCIS processors, the RTI team showed that with appropriate current biasing a pitch percept could be created that was: (1) lower than the pitch percept produced by stimulation of the most apical electrode in the array or (2) higher than the pitch produced by stimulation of the most basal electrode. Signal processors were created and tested that used both between-electrode VCIS channels and a supra-apical virtual channel, which produced the lowest pitch (Dorman et al., 1996; Wilson et al., 1992). A similar concept, that is, a virtual channel with lower pitch than the most apical electrode, is now embodied in the “phantom electrode” system from ABC (Saoji & Litvak, 2010).

4.4 Step 3 and the Fine Structure Processing Strategy

The RTI team, in the early 1990s, created a way to represent the “fine structure” or “fine timing” information in channels with low center frequencies by presenting stimulus pulses at the times of detected peaks or zero crossings in the bandpass filter outputs for the channels (e.g., Wilson et al., 1990a). This approach was called a “peak picker/CIS” strategy, and all channels except the 1-3 channels with the lowest center frequencies presented CIS stimuli.

The peak picker/CIS approach was later refined by the MED-EL GmbH and utilized in its “fine structure processing” (FSP) strategies (e.g., Hochmair et al., 2006).

The processing strategies in current widespread use are shown in Table C.3. As was the hope of the RTI teams, utilization of discoveries from the NIH projects has been excellent. All of the systems manufactured by the three largest implant companies use a version of the CIS strategy. These versions include the “CIS,” “CIS+,” “High Definition CIS” (HDCIS), and “Hi-Resolution” (HiRes) strategies, as named by the manufacturers.

Table C.3. Processing Strategies in Current Widespread Use*

Manufacturer	CIS	CIS+	HDCIS	<i>n-of-m</i>	FSP	ACE	SPEAK	HiRes	HiRes 120
MED-EL GmbH	•	•	•	•	•				
Cochlear Ltd.	•					•	•		
Advanced Bionics Corp.	•							•	•

*Manufacturers are shown in the left column and the processing strategies used in their implant systems are shown in the remaining columns. The full names of the strategies are presented in the text.

In addition, (1) the MED-EL and Cochlear systems use various implementations of the *n-of-m* approach, including the listed *n-of-m*, ACE, and SPEAK strategies; (2) the MED-EL systems use the concept of the peak picker/CIS approach in the FSP strategy; and (3) the AB systems use an implementation of the VCIS approach in their HiRes 120 strategy.

Each of these strategies and others are described in much greater detail in two chapters by Wilson and Dorman, the first on “The design of cochlear implants” (Wilson & Dorman, 2009) and the second on “Signal processing strategies for cochlear implants” (Wilson & Dorman, 2012). The first of these chapters also presents information about other aspects of the design, e.g., design considerations for the electrode array, implanted receiver/stimulator, and transcutaneous transmission link. The second of the chapters is more sharply focused on processing strategies and provides more up-to-date information on that topic. Additional relevant reviews include ones by Loizou (2006), Wilson (2004, 2006), and Zeng et al. (2008).

As of late 2010, more than 220,000 deaf or severely-hearing-impaired persons had received CIs, either in one or both ears for each person. The cumulative number of

implants over time is shown in Figure C.2 (adapted and updated from Wilson & Dorman, 2008a). The rapid growth in the number beginning in the early 1990s corresponds to the introductions into standard clinical practice of new and highly effective processing strategies during the early 1990s and afterwards.

4.5 Developments in Other Domains

Besides CIS and the other processing strategies mentioned previously, the RTI teams and their collaborating investigators produced or helped to enable advances in many other areas including but not limited to: (1) building of tools for research on CIs such as highly flexible and real-time processing systems; (2) design and application of some of the first portable processors for CIs that were based on digital signal processing and could support high numbers of processing channels and stimulus sites; (3) development of additional processing strategies for unilateral implants, for example, the “closer mimicking” strategies described in Schatzer et al. (2003) and Wilson et al. (2003, 2006, 2010); (4) evaluation and further development of bilateral CIs and processing strategies for them; (5) evaluation and further development of combined electric and acoustic stimulation of the auditory system for persons with at least some residual hearing at low frequencies; (6) development and application of mathematical models of the electrically stimulated cochlea; (7) recording and interpretation of intracochlear evoked potentials in response to a wide range of electrical stimuli; (8) elucidation of temporal patterns of neural responses in CI patients; (9) evaluation of possible relationships between the temporal patterns and pitch percepts for the same patients; (10) development of processing strategies for the Auditory Brainstem Implant or ABI; (11) psychophysical measures of responses to many different types of electrical stimuli; and (12) design of inexpensive but nonetheless highly effective CI systems primarily for use in low- and mid-income countries.

4.6 Technology Transfer

An important aspect of the work at the RTI was a program of active technology transfer to accelerate or otherwise facilitate the incorporation of inventions and other new concepts or findings into commercially available implant systems. (This program was in addition to the policy on IP described previously; both the program and the policy were designed to facilitate the incorporation of advances into commercially-available systems.) We believe this active transfer was far more effective than the

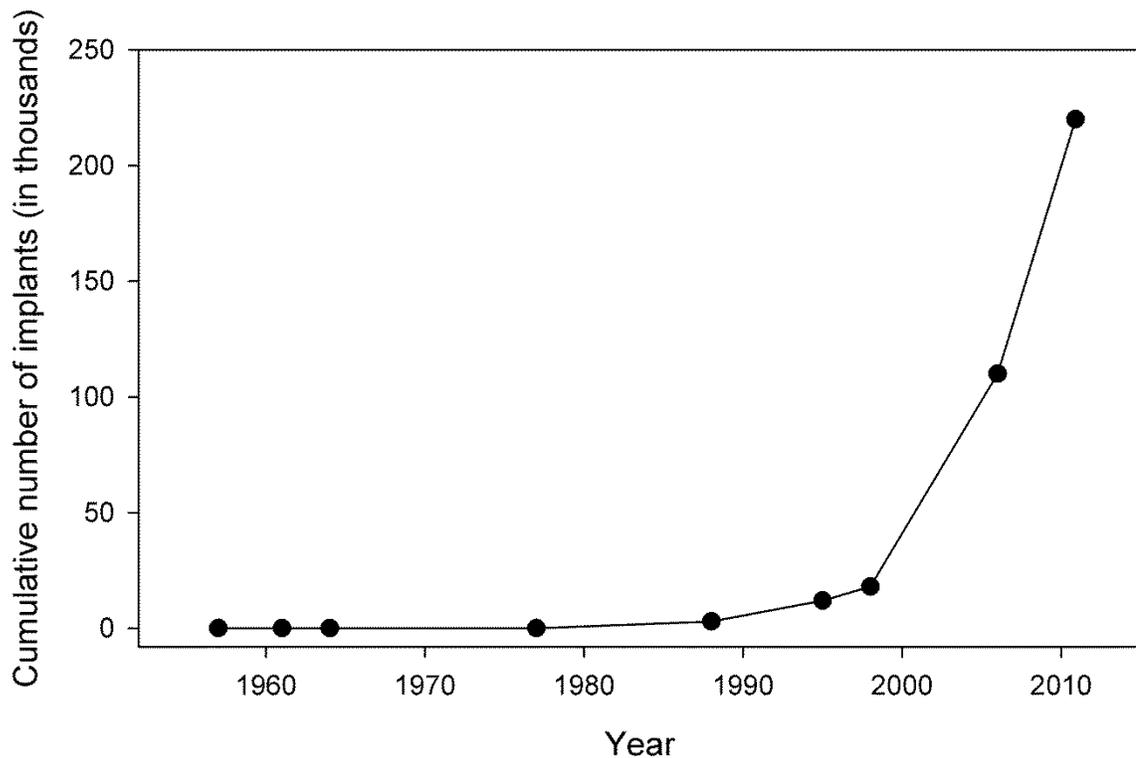


Figure C.2. Cumulative number of cochlear implants across years. Events marked by the dots include: (1) the first implant operation by Drs. Andre Djourno and Charles Eyriès in 1957; (2) the first two implants by Dr. William F. House in 1961; (3) the first implant by Dr. F. Blair Simmons in 1964; (4) the “Bilger report” in 1977; (5) the first NIH Consensus Conference on Cochlear Implants in 1988; (6) the second NIH Consensus Conference in 1995; (7) the National Academy of Sciences report (Finn et al.) in 1998; (8) an estimate of the cumulative number published in the middle of 2006; and (9) an estimate of the number published in late 2010. Multichannel devices began to supplant single-channel devices in the early 1980s, and highly effective processing strategies were first introduced into widespread clinical use in the early 1990s, as described in the text. These large steps forward fueled the increasing acceptance and applications of cochlear implants. (Adapted with permission from Wilson, B. S., & Dorman, M. F. (2008a). *Interfacing sensors with the nervous system: Lessons from the development and success of the cochlear implant. IEEE Sensors Journal*, 8, 131–147. Copyright 2008 IEEE.)

alternative passive approach of simply presenting some of the necessary information in publications and the progress reports. We did present the information in those ways, but

we also made ourselves available to answer questions and to work directly with the design teams at the manufacturers to move research results into products that people could use. This additional effort was most unusual at the time and in retrospect was an early example of what now is called “translational research” or “translational medicine.” The teamwork promoted by the effort was beneficial to all concerned.

Of course, the active technology transfer was only a small fraction of the overall effort needed to produce new or substantially modified CI devices. For that, the companies deserve the greatest credit by far.

4.7 Contributions by Others

Many teams worldwide contributed significantly to the CI systems we have today. The RTI contributions are important, but they are only a part of the story. The fascinating history of CIs is recounted in Eisen (2006, 2009), Finn et al. (1998), Hannaway (1996), Levitt (2008), Niparko and Wilson (2000), Seitz (2002), and Wilson and Dorman (2008b).

One thread that runs through the histories is the remarkable courage and perseverance of the pioneers in laying the foundations for the present devices. Another thread is that no one person or group is primarily responsible for the development of the CI. Many contributions from many sources were needed. For example, different groups contributed most strongly to each of the three major steps listed near the beginning of this chapter.

5. Selections from the NIH Progress Reports

Extraordinarily difficult decisions were made in selecting the sections from the NIH progress reports for inclusion in this book. At the outset, we made the easy decision to exclude sections that had been published as journal articles or book chapters, for the reasons mentioned previously. However, that decision did not produce enough of a reduction for a book-length exposition of the projects. We therefore decided to sharpen the focus for the book by excluding all sections from the remaining sections on tool building; portable processors; development of models of the electrically stimulated cochlea; and parametric and longitudinal studies with CIS and other processors. This second (and much more difficult) decision winnowed the list considerably, but did not

shorten it enough. Thus, as a final step we selected what we thought to be the most important sections from among the sections still in the list. The ultimate selections included 20 sections from 18 of the 91 reports.

Guides to the excluded material are presented in Appendices C and D. Appendix C lists the journal articles and book chapters that were published during the projects and also as a result of the projects afterwards. Appendix D presents the contents of the RTI progress reports sorted by topic, as opposed to the sorting by project and chronological order in Appendix B. Reference to Appendix 4 would allow one to identify all reports on any of the many topics, areas, and activities included in the projects.

All of the NIH progress reports are in the public domain and all can be requested from the NIH. In addition, the reports are posted at <http://www.rti.org/capr/caprqprrs.html>, which is a daughter page within the website for the prior Center for Auditory Prosthesis Research at the RTI. This website has been maintained since the closing of the Center in 2008 and may continue to be maintained for the foreseeable future.

In the remainder of this book, the QPRs are referenced by their project number and report number in the format QPR X:Y, where X is the project number (1 through 7; see Table C.2) and Y is the report number. Similarly, the FRs are referenced by their project number, in the format FR X. The references include: (1) citations to the reports within the text for each chapter, and (2) identification of the report from which the material is drawn for each chapter, in the title and running heading for the chapter.

6. Not a Miracle, Just Hard Work

In an interview in 1998, a reporter suggested to our long-time research patient Michael Pierschalla (SR2 in the QPRs) that it must seem like a miracle that his hearing had been restored. Michael, remembering the thousands of hours he spent in the laboratory, said quietly, "It is no miracle at all. It is the result of long, long hours of very hard work by researchers around the world." The members of the RTI teams are proud to have been part of that effort and we are grateful to the sponsors, research subjects, administrators, collaborating investigators, and colleagues at companies who made our work possible. The work was exhilarating and among the greatest adventures of our lives.

Appendix D: Book Review by Prof. Mario Svirsky (Svirsky, 2014)*

* The review in this appendix is presented with the permission of the publisher.

Better Hearing with Cochlear Implants: Studies at the Research Triangle Institute

Mario Svirsky, Ph.D.

Noel L. Cohen Professor of Hearing Science; Professor of Otolaryngology (School of Medicine) and Neural Science, and Vice-Chairman for Research, Department of Otolaryngology, NYU Langone Medical Center, 550 First Avenue, NBV-5E5, New York, NY 10010, USA

Cochlear implants remain the only example to date of an electronic device successfully replacing a human sensory end organ, and they represent one of the major medical advances of the twentieth century. This has been recently recognized by the Lasker Foundation by giving the prestigious Lasker-DeBaakey Clinical Medical Research Award to Blake Wilson, Graeme Clark, and Ingeborg Hochmair, “for the development of the modern cochlear implant—a device that restores hearing and speech to individuals with total or nearly complete deafness.” The Lasker Awards are second only to the Nobel Prize in Physiology or Medicine for honoring advances in medicine and medical science. Indeed, fully a third of the Lasker winners go on to win the Nobel Prize at a later time.

One of the Lasker awardees, Blake Wilson, and Michael Dorman (who is another pioneer and major contributor to the development of cochlear implant technology) describe the body of research and development work done at Research Triangle Institute (RTI) between 1983 and 2006. This work was largely funded by a series of contracts from the National Institute of Health’s Neural Prostheses Program. One important characteristic of the Neural Prostheses Program was that a quarterly progress report (QPR) was required. These QPRs (which can still be found on the Web site http://www.nidcd.nih.gov/funding/programs/npp/pages/neuralprostheses_archive_reports.aspx) were for many years one of the best-kept secrets in the cochlear implant field. (Full disclosure: I was an investigator in a similar contract awarded to Massachusetts Institute of Technology (MIT) in 1992, with Don Eddington as Principal Investigator). The QPRs were not, by any means, the only source of information about RTI cochlear implant research. After all, Appendix C of the present book lists 65 publications that resulted from RTI projects. Many of these publications were highly influential. A

description of the first results obtained with the continuous interleaved sampling (CIS) stimulation strategy, that was published in *Nature* in 1991, remains to this day the most highly cited publication in the cochlear implant field. Nevertheless, QPRs from the RTI research group were highly sought after for over two decades by eager investigators who wanted to quickly find out what this elite team was working on. Information could be obtained in a much more timely fashion by reading the QPRs than if one had to wait for the whole peer review and publication process to complete, and the information itself was frequently much more detailed and richer in the QPR than in the peer-reviewed publications. Readers of the QPRs were aware that the reports had not been subjected to the same level of scrutiny as a publication in an archival journal would have been, but they appreciated the trade-off of being able to access the data much more quickly. In other words, the material in the QPRs was useful in a way that was complementary to that of peer-reviewed publications. Perhaps the main problem was that, because of its very nature, the data in the reports were simply organized in a chronological fashion, quarter by quarter, and it was not easy to access all the information about a given topic without having prior knowledge of which specific report one should peruse.

The publication of *Better Hearing with Cochlear Implants* goes a long way toward filling this void. Information is carefully organized according to theme and topic. The first part is about design and evaluation of novel processing strategies, and it includes information about the initial development of the CIS speech-processing strategy, its comparison with other strategies, the evaluation of other promising strategies, and a series of studies done with relatively poor performers. There is also a chapter about studies done with auditory brainstem implant users, and three chapters that explore the concept of “virtual channels.” Chapter 12 is dedicated to the design of an inexpensive but effective cochlear implant system. The last chapter in this part describes studies done with a cochlear implant that used a 22-electrode percutaneous array, an interesting device that allows much greater flexibility in stimulation parameters than the clinically available systems, which must rely on transcutaneous stimulation. Part two covers bilateral cochlear implant studies and focuses on the study of sensitivity to interaural timing differences as well as pitch ranking across the two electrode arrays. The third part examines combined electric and acoustic stimulation of the auditory system, with one chapter dedicated to psychophysical studies and another related to speech perception. The fourth and final part presents studies of the representation of temporal

information with cochlear implants and the ways in which such representation might be improved by appropriate adjustments in the stimulation strategy. As will become clear to the reader, the RTI group pioneered many of the approaches described in the book. The book is engaging, clear, and very well written. It is obvious that a substantial amount of reflection and effort went into preparing the book, this was not at all a simple but massive “cut-and-paste” exercise from the QPRs. The authors present much information from the QPRs, but they also provide appropriate historical and technical context. An extremely useful resource to those readers who want to follow up by reading the original QPRs can be found in Appendix D, which lists QPR contents sorted by topic.

Besides the technical information, readers will find the book interesting as an important contribution to the study of cochlear implant research history. Much information along these lines is contained in the Acknowledgments section, in the overview provided in Chapter 1, as well as in many of the other chapters that deal predominantly with technical information. I highly recommend this book to any reader with a personal or professional interest in cochlear implants, either from a historical perspective or a strictly technical perspective.

Appendix E: Invited talks by Blake Wilson after January 7, 2015

Lecture as a Guest of Honor

Wilson BS: How to close the gap? 4th Munich^{LMU} Hearing Implant Symposium 2015: *Hearing Implants Around the World*, Ludwig-Maximilians-Universität München, Munich, Germany, December 10-13, 2015. (This lecture also is listed as one of the keynote speeches in the Program for the Symposium.)

Duke Engineering 75th Anniversary Lecture

Wilson BS: The development of the modern cochlear implant. Duke University, Durham, NC, USA, March 5, 2015.

Graham Fraser Memorial Lecture

Wilson BS: Possible ways forward for cochlear implants and building on the grand legacy of Graham Fraser, M.D. Lecture presented in conjunction with the *Annual Meeting of the British Cochlear Implant Group*, Bristol, UK, March 19-20, 2015. (The Graham Fraser Memorial Lectures celebrate his life and achievements and are the most prestigious lectures in the fields of cochlear implants and remediation of severe losses in hearing. More information about the lectures is presented at <http://www.grahamfraserfoundation.org.uk/memlects.htm>.)

RTI Distinguished Lecture

Wilson BS: Toward better representations of sound with cochlear implants. *RTI International Distinguished Lecture Series*, Research Triangle Foundation, Research Triangle Park, NC, USA, April 14, 2015. (This talk was the inaugural lecture in the series.)

Distinguished BME Lecture

Wilson BS: The development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. University of California at Irvine, Irvine, CA, USA, April 22, 2016.

C. Paul and Beth K. Stocker Lecture

Wilson BS: Getting a decent (but sparse) signal to the brain for users of cochlear implants. Ohio University, Athens, OH, USA, April 12, 2016. (This lecture was one in a series by winners of the Russ Prize and was supported by the Fritz J. and Dolores H. Russ College of Engineering and Technology and the Robe Leadership Institute at Ohio University.)

Inauguration Speech for the Institute for Auditory Neuroscience at the University of Göttingen

Wilson BS: Auditory neuroscience: The prosthetic's perspective. One of three lectures to inaugurate the Institute for Auditory Neuroscience at the University of Göttingen, Göttingen, Germany, March 21, 2015. (The other two speakers were Tobias Moser, M.D., Director of the new Institute, and Benedikt Grothe, Ph.D., Chair of the Division of Neurobiology and Dean of the Faculty of Biology, Ludwig-Maximilians-Universität München, Munich, Germany.)

Grand Rounds Presentation

Wilson BS: The development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. Surgical Grand Rounds, Department of Otolaryngology – Head & Neck Surgery, Northwestern University Medical Center, Evanston, IL, USA, April 16, 2015.

Keynote Speeches

Wilson BS: Possibilities for narrowing the remaining gaps between prosthetic and normal hearing. *10th Asia Pacific Symposium on Cochlear Implants and Related Sciences*, Beijing, China, April 30 through May 3, 2015. (This speech was the opening plenary address for the conference.)

Wilson BS: Remaining challenges for cochlear implants. *Perth Auditory Implant Workshop*, University of Western Australia, Perth, Australia, October 28-31, 2015. (This speech was the opening lecture for the conference.)

Additional Invited Presentations

Wilson BS, Pätzold J: Cochlear implants, music, and the hearing brain. Invited lecture for Duke University course NEUROSCI 290-01/MUSIC 290-01, "Music and the Brain," February 5, 2015.

- Wilson BS: Possible ways forward for hearing prostheses. Medizinische Hochschule Hannover, Hannover, Germany, March 23, 2015.
- Gantz B (moderator), Hochmair I, Wilson BS, Dowell R, Zeng F-G: Round Table Discussion on “Recent challenges in cochlear implantation.” *10th Asia Pacific Symposium on Cochlear Implants and Related Sciences*, Beijing, China, April 30 through May 3, 2015.
- Wilson BS (moderator), Büchner A, Landsberger D, Yuen K, Zeng F-G: Round Table Discussion on “New directions in sound coding and pre-processing strategies.” *10th Asia Pacific Symposium on Cochlear Implants and Related Sciences*, Beijing, China, April 30 through May 3, 2015.
- Wilson BS: Combined EAS – One of Prof. von Ilberg’s many gifts to humanity. *Symposium in Honor of Prof. Dr. Christoph von Ilberg on the Occasion of his 80th Birthday*, J. W. Goethe Universität, Frankfurt, Germany, May 8, 2015.
- Wilson BS: Acceptance remarks on the occasion of receiving an honorary doctorate in medicine from the University of Salamanca. University of Salamanca, Salamanca, Spain, May 11, 2015. (The remarks are posted at [http://saladeprensa.usal.es/webusal/files/Discurso%20Blake%20S.%20Wilson%20-%20Honoris%20Causa%20Blake%20S.%20Wilson%20\(ingl%C3%A9s\).pdf](http://saladeprensa.usal.es/webusal/files/Discurso%20Blake%20S.%20Wilson%20-%20Honoris%20Causa%20Blake%20S.%20Wilson%20(ingl%C3%A9s).pdf).)
- Wilson BS: The punctuation mark in an equilibrium state: modern signal processing. Special session on cochlear implants sponsored by the Committees on Psychological and Physiological Acoustics, Biomedical Acoustics, Speech Communication, and Signal Processing in Acoustics, *Annual Spring Meeting of the Acoustical Society of America*, Pittsburgh, PA, USA, May 18-22, 2015.
- Wilson BS: Possibilities for narrowing the remaining gaps between prosthetic and normal hearing. University of Texas at Dallas, Richardson, TX, USA, May 26, 2015.
- Lopez-Poveda EA, Eustaquio-Martin A, Stohl JS, Wolford RD, Schatzer R, Wilson BS: Mimicking the unmasking benefits of the contralateral medial olivocochlear reflex with cochlear implants. *2015 Conference on Implantable Auditory Prostheses*, Tahoe City, CA, USA, July 12-17, 2015.
- Cerf VG (moderator), Pisoni DB, Wilson BS, Zeng F-G: Closing Plenary Session on “Hearing restoration and neuroscience: how hearing affects thought and how the brain perceives sound.” *CI 2015 Conference – American Cochlear Implant Alliance*, Washington DC, USA, October 15-17, 2015.

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Biography

Blake S. Wilson is a Co-Director (with Co-Director Debara L. Tucci, M.D., M.S., M.B.A., F.A.C.S.) of the Duke Hearing Center and has six other appointments at Duke, including Consulting Professor in the Department of Biomedical Engineering and Adjunct Professor in the Departments of Surgery and Electrical and Computer Engineering. He also is the Chief Strategy Advisor for MED-EL Medical Electronics GmbH in Innsbruck, Austria. He has been involved in the development of the cochlear implant (CI) for more than three decades, and is the inventor of many of the signal processing strategies used with the present-day CIs. One of his papers, in the journal *Nature*, is the most highly cited publication by far in the specific field of CIs. He or he and his teams or colleagues have been recognized with a high number of awards and honors, most notably the 2015 Russ Prize for “engineering cochlear implants that allow the deaf to hear” (to Wilson, Erwin S. Hochmair, Ingeborg J. Hochmair, Graeme M. Clark, and Michael M. Merzenich); the 2013 Lasker~DeBakey Clinical Medical Research Award for “the development of the modern cochlear implant – a device that bestows hearing to individuals with profound deafness” (to Graeme Clark, Ingeborg Hochmair, and Wilson); the 2007 Distinguished Alumnus Award from the Pratt School of Engineering at Duke; the American Otological Society’s President’s Citation in 1997 for “Major contributions to the restoration of hearing in profoundly deaf persons” (to Wilson, Charles C. Finley, Dewey T. Lawson, and Mariangeli Zerbi); and the 1996

Discover Award for Technological Innovation in the category of “sound” (to Wilson). Wilson is a Life Fellow of the IEEE, has been the Guest of Honor at 13 international conferences, the Chairman for two other international conferences, the Co-Chairman for three more international conferences, and a keynote or an invited speaker at more than 180 additional conferences. In addition, he has given 13 named lectures to date, including the *Hopkins Medicine Distinguished Speaker Lecture*; the *Flexner Discovery Lecture*; and the *Duke Engineering 75th Anniversary Lecture*. His degrees include higher doctorates in science and in engineering, from the University of Warwick in the UK and the University of Technology, Sydney, in Australia, respectively, and two honorary doctorates in medicine, from Uppsala University in Sweden and the University of Salamanca in Spain.

Further information about Wilson and his career to date is presented in the lists on the following pages 174-210, which include lists of present positions; past plus present positions; degrees; major awards and honors; selected professional activities and additional awards and honors; peer-reviewed publications; books; published papers in conference proceedings; magazine articles; lectures as a Guest of Honor; named lectures; grand rounds presentations; keynote speeches; additional invited presentations; chaired conferences; and chaired sessions within conferences. Considerably more information is presented in his full CV, such as lists of patents, major reports, funded projects, and other talks.

Because the included lists reflect a decades-long career in research, this biography is longer than the usual one or two pages for biographies in Ph.D. dissertations.

Current Positions

Co-Director (with Debara L. Tucci, M.D., M.S., M.B.A., F.A.C.S.), Duke Hearing Center, Duke University Medical Center (DUMC), Durham, NC 27710, USA
Adjunct Professor, Department of Surgery, Division of Otolaryngology – Head & Neck Surgery, DUMC
Adjunct Professor, Department of Electrical & Computer Engineering, Duke University, Durham, NC 27708, USA
Consulting Professor, Department of Biomedical Engineering, Duke University, *Scholar in Residence*, Pratt School of Engineering, Duke University
Investigator and Member of the Faculty Network, Duke Institute for Brain Sciences, Duke University
Affiliated Faculty, Duke Global Health Institute, Duke University
Honorary Professor, School of Engineering, University of Warwick, Coventry CV4 8UW, UK
Adjunct Professor, School of Behavioral and Brain Sciences, The University of Texas at Dallas (UTD), Richardson, TX 75080, USA
Adjunct Professor, Erik Jonsson School of Engineering and Computer Science, Departments of Bioengineering and Electrical Engineering, UTD
Chief Strategy Advisor, MED-EL Medical Electronics GmbH, A-6020 Innsbruck, Austria
Director, MED-EL Laboratory for Basic Research Research Triangle Park, NC 27709, USA

Positions and Experience

1974 to 2007: Several positions at the Research Triangle Institute (now RTI International) in the Research Triangle Park (RTP), NC, USA, including Research Engineer (1974-78); Senior Research Engineer (1978-83); Senior Research Scientist (1979-83); Head, Neuroscience Program (1983-94); Director, Center for Auditory Prosthesis Research (1994-2002); and Senior Fellow (2002-07). (Wilson created the Neuroscience Program and the Center for Auditory Prosthesis Research at the RTI with assistance and permissions from others, and he served as the first director for both the Program and the Center. He retired from RTI in 2007 after 33 years of continuous service there.)

2006 to 2010: The Overseas Expert, Marie Curie Project for the Remediation of Hearing Loss, five centers in Europe and with the International Center of Hearing and Speech in Kajetany (near Warsaw), Poland, serving as the lead center. (The Marie Curie projects have one term only.)

1984 to date: Adjunct appointments in the Department of Surgery, Duke University Medical Center (DUMC), Durham, NC, USA, including Assistant Professor (1984-94); Associate Professor (1994-2002); and full Professor (2002 to date).

2007 to date: Chief Strategy Advisor, Med El GmbH, Innsbruck, Austria. (This is a half-time consulting position.)

2008 to date: Co-Director (with Co-Director Debara L. Tucci, M.D.), Duke Hearing Center, DUMC. (Drs. Farmer, Tucci, Wilson, and Corless created the Duke Hearing Center with assistance and permissions from many others.)

2008 to date: Investigator, Duke Institute for Brain Sciences, Duke University, Durham, NC, USA.

2009 to date: Adjunct Professor, Department of Electrical and Computer Engineering, Duke University.

2011 to date: Director, MED-EL Laboratory for Basic Research, RTP, NC, USA.

2012 to date: Honorary Professor, School of Engineering, University of Warwick, Coventry, UK.
2012 to August 2015: Adjunct Professor, Department of Biomedical Engineering, Duke University.
2013 to date: Scholar in Residence, Pratt School of Engineering, Duke University. (Wilson is the first Scholar in Residence for the Pratt School and the position was created for him.)
2013 to date: Member of the Faculty Network, Duke Institute for Brain Sciences, Duke University, Durham, NC, USA.
2013 to date: Member of the Affiliated Faculty, Duke Global Health Institute, Duke University, Durham, NC, USA.
2015 to date: Adjunct Professor, School of Behavioral and Brain Sciences, The University of Texas at Dallas (UT Dallas), Richardson, TX, USA.
2015 to date: Adjunct Professor, Erik Jonsson School of Engineering and Computer Science, Departments of Bioengineering and Electrical Engineering, UT Dallas
2015 to date: Consulting Professor, Department of Biomedical Engineering, Duke University

Experience in these positions includes direction, as Principal Investigator, of 26 projects (13 for the NIH). Among the projects is a series of seven contiguous projects to develop speech processors for auditory prostheses (1983-2006: NIH N01-NS-3-2356, N01-NS-5-2396, N01-DC-9-2401, N01-DC-2-2401, N01-DC-5-2103, N01-DC-8-2105, and N01-DC-2-1002).

The experience also includes supervision of, or participation in, many other projects in the fields of neural prostheses and remediation of hearing loss.

The positions include more than 30 years of continuous service to both the RTI and Duke University.

Degrees

B.S.E.E., Duke University, Durham, NC, USA
D.Sc., University of Warwick, Coventry, UK
D.Eng., University of Technology, Sydney, Sydney, Australia
Dr.med.*hc*, Uppsala University, Uppsala, Sweden
Dr.med.*hc*, University of Salamanca, Salamanca, Spain

Major Awards and Honors

Guest of Honor (along with Andrej Kral, M.D., Ph.D.), 2nd *Global Otology Research Forum*, Las Palmas de Gran Canaria, Spain, November 29 through December 2, 2017.
Guest of Honor, 149th *Annual Meeting of the American Otological Society*, Chicago, IL, USA, May 18-22, 2016.
Guest of Honor, 4th *Munich^{LMU} Hearing Implant Symposium 2015: Hearing Implants Around the World*, Ludwig-Maximilians-Universität München, Munich, Germany, December 10-13, 2015.
The Gold Medal of Honor from the Paul Sabatier University in Toulouse, France, June 18, 2015. (Separate medals were conferred by the President of the University to Wilson, Graeme M. Clark, M.D., Ph.D., Ingeborg J. Hochmair, Ph.D., and Claude-Henri Chouard, M.D., in recognition of their contributions to the field of cochlear implants.)

The Fritz J. and Dolores H. Russ Prize shared with Graeme M. Clark, M.D., Ph.D., Erwin S. Hochmair, Ph.D., Ingeborg J. Hochmair, Ph.D., and Michael M. Merzenich, Ph.D., “for engineering cochlear implants that allow the deaf to hear,” January 7, 2015. (The Russ Prize is the top honor worldwide in bioengineering and is one of three Prizes awarded by the United States’ National Academy of Engineering that are collectively known as the “Nobel Prizes of Engineering.” The Russ Prize is awarded biennially and the other two Prizes are awarded annually; only 15 persons have received the Russ Prize since the inception of the awards program in 2001. Further details about the Russ Prize are presented at <http://www.nae.edu/Projects/Awards/RussPrize.aspx>.)

Honorary doctorate in medicine from the University of Salamanca in Salamanca, Spain, recommended by the University Council on November 27, 2014; approved by the University Doctors Assembly on December 4, 2014; and conferred at a special ceremony in Salamanca on May 11, 2015.

Appointment as a Life Fellow of the IEEE, November 24, 2014. (The Fellow appointment is the highest honor bestowed by the IEEE and less than 0.1 percent of the voting members are elevated to the Fellow grade each year.)

Honorary doctorate in medicine from Uppsala University in Uppsala, Sweden, approved by the Faculty Senate in September 2014 and conferred at the winter conferment ceremony in Uppsala on January 30, 2015.

Inaugural inductee – along with Robert J. Lefkowitz, M.D. and winner of the 2012 Nobel Prize in Chemistry, and Mary-Dell Chilton, Ph.D. and winner of the 2013 World Food Prize – into the Bull City Hall of Fame, March 27, 2014. (Durham, North Carolina, USA, also is known as the “Bull City” and “The City of Medicine.” It is the home of Duke University, the Duke University Health System, North Carolina Central University, and the Durham Performing Arts Center. Durham is a vibrant city with a diverse population of about 240,000.)

Recipient of one of the first three commendations from the *American Cochlear Implant Alliance*, “in recognition of the lifetime contributions of 2013 Lasker Award winner Dr. Blake S. Wilson in serving those with hearing loss through his remarkable contributions to the science of cochlear implantation,” October 24, 2013. (The other two recipients of the first commendations were Ingeborg J. Hochmair, Ph.D., and Graeme M. Clark, M.D., Ph.D., also “for lifetime contributions ... to the science of cochlear implantation.”)

Appointment as the first Scholar in Residence for the Pratt School of Engineering at Duke University, September 13, 2013. (This appointment was created for Wilson, was approved by the President of the University, and has a five-year term that is renewable.)

The 2013 Lasker-DeBakey Clinical Medical Research Award, shared with Graeme M. Clark, M.D., and Ingeborg J. Hochmair, Ph.D., “for the development of the modern cochlear implant – a device that bestows hearing to individuals with profound deafness,” September 9, 2013. (The Lasker Awards are among the most respected science prizes in the world and are second only to the Nobel Prize in Physiology or Medicine for recognizing advances in medicine and medical science; indeed, fully a third of the winners of a Lasker Award go on to win the Nobel Prize at a later time. The Lasker Awards are popularly known as “America’s Nobels.” Only about 250 persons have received a Lasker Award since the inception of the awards program in 1945. Please see <http://www.laskerfoundation.org/> for further details about the Lasker Foundation and its awards.)

Co-Chair, with Co-Chair Christoph von Ilberg, M.D., of the *Presbycusis Research Meeting*, Munich, Germany, January 12-14, 2012.

Guest of Honor (along with Jan Helms, M.D.), *Munich Hearing Implant Symposium: Reaching New Heights*, Ludwig-Maximilians-Universität München, Munich, Germany, December 8-10, 2011.

Guest of Honor, *Ninth European Symposium on Paediatric Cochlear Implantation*, Warsaw, Poland, May 14-17, 2009. (This Symposium is among the largest conferences in the field of cochlear implants; more than 1,700 delegates attended the symposium in Warsaw, which was an all-time high for these symposia.)

One of Wilson's inventions was named as one of the four greatest inventions or discoveries in the 50-year history of the Research Triangle Park (RTP), as announced in the *Triangle Business Journal*, February 27, 2009. (The RTP is the largest research park in the USA and includes more than 170 research organizations whose aggregate number of full-time employees exceeds 42,000. The other three inventions or discoveries were the UPC barcode, invented at IBM; the anti-cancer drug Taxol, discovered and developed at the Research Triangle Institute; and the anti-viral drug AZT used to treat HIV-AIDS, invented at GlaxoSmithKline.)

Invitation to give the Neel Distinguished Research Lecture at the *Annual Meeting of the American Academy of Otolaryngology, Head & Neck Surgery*, Chicago, IL, USA, September 21-24, 2008. (The two-part lecture for this year was given with Richard T. Miyamoto, M.D., Chair of Otolaryngology – Head & Neck Surgery at the Indiana University School of Medicine; the attendance for the *Annual Meeting* approximated 8,500. The prior Neel Lecture was given in 2007 by Elias Zerhouni, M.D., the Director of the NIH.)

Invitations to give 12 other named lectures to date, a Hopkins Medicine Distinguished Speaker Lecture, the Duke Engineering 75th Anniversary Lecture, the Graham Fraser Memorial Lecture, and one of the Flexner Discovery Lectures.

Invitation to write the lead article for the special issue of the journal *Hearing Research on Frontiers of Auditory Prosthesis Research: Implications for Clinical Practice*. (The special issue was published in September 2008 and included 18 articles.)

Guest of Honor, *Friedberger Cochlear Implant Symposium*, Bad Nauheim, Germany, June 28-30, 2007.

2007 recipient of the Distinguished Alumnus Award, Pratt School of Engineering, Duke University, April 21, 2007.

Guest of Honor, *Sixth Wullstein Symposium 2006: New Developments in Hearing Technology*, Würzburg, Germany, December 7-10, 2006.

Chair, with Co-Chair Michael F. Dorman, Ph.D., of the *Hearing Preservation Workshop V*, Research Triangle Park, NC, USA, October 13-15, 2006.

Guest of Honor, *Workshop on the Present Status and Future Directions of Cochlear Implants*, Nano Bioelectronics & Systems Research Center, Seoul National University, Seoul, Korea, August 25, 2006.

Guest of Honor, *Meeting of the Clinical Otologic Research Team (CORT)*, Cal-Creek Ranch, near Santa Fe, NM, USA, August 8-12, 2006. (The CORT includes leading otologists in the United States.)

Named as an honorary member of the CORT, August 2006.

Special Guest of Honor, *Ninth International Conference on Cochlear Implants and Related Sciences*, 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 of cochlear implants; the Vienna Conference was attended by more than 1,600 delegates from more than 70 countries.)

Guest of Honor, Naval Science & Technological Laboratory, Visakhapatnam, India, March 27-28, 2006.

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

Guest of Honor and 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.

Guest of Honor, Annual Nalli Family Day, The Hospital for Sick Children, University of Toronto, Toronto, Canada, February 17, 2005.

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

Co-Chair, with Chair Peter S. Roland, M.D., of the *Third Hearing Preservation Workshop*, Dallas, TX, USA, October 15-16, 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, USA, 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.

Co-Chair, with Chair Richard T. Miyamoto, M.D., of the *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, USA, November 8-10, 2002.

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

Appointment as one of the first four Senior Fellows for RTI International, September 2002. (RTI International is a large not-for-profit research institute with a staff of more than 2,800 at locations in the United States, Africa, Europe, the United Arab Emirates, Indonesia, and El Salvador; one of the principal charges of the Fellows is to serve as advisors to the RTI President in setting the scientific directions for the organization.)

Guest of Honor, *Wullstein Symposium (2nd Conference on Bilateral Cochlear Implantation and Bilateral Signal Processing, 6th International Cochlear Implant Workshop and 2nd Auditory Brainstem Implant (ABI) Workshop)*, Würzburg, Germany, April 26-30, 2001.

Guest of Honor, *5th International Cochlear Implant Workshop and 1st Auditory Brainstem Implant (ABI) Workshop*, Würzburg, Germany, June 30 to July 4, 1999.

Recipient of the Presidential Citation for "Major contributions to the restoration of hearing in profoundly deaf persons," on the occasion of the 130th Annual Meeting of the American Otological Society, Scottsdale, AZ, USA, May 10-11, 1997. (This Citation was to Wilson, Dewey T. Lawson, Charles C. Finley, and Mariangeli Zerbi, who were the principal members of the team at the Research Triangle Institute at the time.)

Invitation to write a Guest Editorial in celebration of the 30th anniversary of the *British Journal of Audiology* (1997).

Winner of the 1996 Discover Award for Technological Innovation in the category of "sound."

Guest of Honor, *International Workshop on Cochlear Implants*, Vienna, Austria, October 24-25, 1996.

Elected General Chair of the *1991 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, June 2-7, 1991.

Selected Professional Activities and Additional Awards and Honors

- Inventor of many of the speech processing strategies used with present-day cochlear implant systems.
- Listed in Who's Who in the World, Who's Who in America, Who's Who in Science and Engineering, Who's Who in Finance and Industry, 2000 Outstanding People of the 20th Century (IBC, Cambridge), Strathmore's Who's Who. (Each of these listings has been in place for more than a decade.)
- Recipient of three Professional Development Awards from the Research Triangle Institute (1977, 1983 and 1988; the award in 1977 was one of the three awards granted in the first year of the program).
- Recipient of the Physician Award from the Duke University Hospital, Durham, NC, USA, April 20, 2015.
- The Overseas Expert for a large training and research project, "Remediation of Hearing Loss," at the Institute of Hearing and Speech, in Kajetany-Warsaw, Poland (2006-2010; this project was supported by the European Commission).
- Consultant to the President of India, His Excellency Dr. A.P.J. Kalam, on remediation of hearing loss in that country (March 2006).
- Principal outside reviewer for an effort to develop an indigenous cochlear implant system for manufacture and widespread application in India (2005-2007).
- Visiting Professor, University of Technology, Sydney, October 2011.
- Visiting Professor, University of Illinois, Urbana-Champaign, IL, February 2007.
- Visiting Professor, University of Toronto, February 2005.
- Election to Sigma Xi, the scientific honorary society, October 29, 2004.
- Member of the International Scientific Advisory Board for the International Center of Hearing and Speech, Kajetany (near Warsaw), Poland (2003-present).
- Consultant and principal outside reviewer for an effort at Seoul National University to develop a low cost but nonetheless highly effective cochlear implant system for use in developing countries (2002-).
- Founder with Dr. Joseph C. Farmer, Jr., and others of the Cochlear Implant Program at Duke (1984).
- Member of the core committee (of four) to develop a comprehensive Hearing Center at Duke (2003-2008).
- Member of the Outreach Faculty for the Engineering Research Center (ERC) for Wireless Integrated Microsystems, at the University of Michigan (2000-present). (The Center is supported as one of approximately 20 ERCs by the NSF; one key goal of the Center at the University of Michigan is to develop a fully implantable auditory prosthesis.)
- Member of the External Scientific Advisory Committee for the W.M. Keck Foundation Neural Prosthesis Research Center, located in Boston, MA (1999-2003).
- Member of the oversight committees for Program Project Grants on cochlear implants at the Kresge Hearing Research Institute, University of Michigan (1987-1995), and at the University of Iowa (1994-1995).
- Co-Investigator for two projects in the Program Project Grant on cochlear implants at the University of Iowa (1995-2000; the projects included the Audiology and Electrophysiology projects within the PPG, with Richard Tyler serving as the PI for the Audiology project and Paul Abbas serving as the PI for the Electrophysiology project).

Co-investigator for a Duke Institute for Brain Sciences (DIBS) incubator award on “Feasibility studies of the inferior colliculus as a prosthetic site” (2009-2010; the other investigators include Nell Cant, Warren Grill, Jennifer Groh, and Debara Tucci).

Member of the Science Advisory Council for the House Ear Institute, Los Angeles, CA (1990).

Member of a team of five North American experts invited by the Chinese government to assist in the specification and development of an inexpensive yet effective cochlear implant system for widespread use in that country (1993).

Reviewer of grant and contract applications for the NIH, NSF, DVA, MRC (Canada), MRC (UK), Swiss National Science Foundation, Austrian Science Fund, Action on Hearing Loss (UK), and the Wellcome Trust (UK), including service as the Chair of a review committee for the NIH.

Member of site visit teams to evaluate program project and single grant applications in the areas of cochlear prostheses (for the NIH), hearing aids (NIH), and biological effects of non-ionizing radiation (DVA).

Invited guest scientist at the Coleman Memorial Laboratory, University of California at San Francisco (various times in the years 1983-1986).

Member of the NIDCD/DVA Advisory Committee on Hearing Aid Research and Development (1993-1996).

Member of the Subcommittee on Microwave and Laser Exposure, North Carolina Radiation Protection Commission (1981-1986)

Chair of sessions or focus groups at 34 international conferences since 1987.

Invited speaker for the NIH Consensus Development Conference on Cochlear Implants, May 2-4, 1988; member of the planning committee for the 1995 NIH Consensus Development Conference on Cochlear Implants in Adults and Children; and invited speaker at that Conference, May 15-17, 1995.

Keynote, Guest of Honor (GOH), or named Distinguished Speaker at 49 international conferences and at three national conferences (in the UK, South Korea, and the USA). (The GOH and some of the named speeches also are noted in the preceding section on “Major Awards and Honors.”)

Invited speaker at more than 160 other national and international conferences.

Faculty member for many continuing-education courses on cochlear implants.

Consultant for the past 3+ decades for many NIH projects on cochlear implants and related topics.

Senior Member of the IEEE and the IEEE Engineering in Medicine and Biology Society (Wilson was promoted from the Member grade to the Senior Member grade in April 2006).

Member of the Acoustical Society of America, American Association for the Advancement of Science, the New York Academy of Sciences, the Association for Research in Otolaryngology, and Sigma Xi.

Member of Steering Committees for the biennial *Conference on Implantable Auditory Prostheses* for the years 1987, 1989, 1993, 1995, 1997, 1999, 2001, 2003 and 2005.

Member of the Planning Committee for the *Vth International Cochlear Implant Conference*, New York, NY, 1997.

Member of the Steering Committee for the *VIII International Cochlear Implant Conference*, Indianapolis, IN, May 10-13, 2004.

Member of the Faculty Board for the *7th European Symposium on Paediatric Cochlear Implantation*, Geneva, Switzerland, May 2-5, 2004.

Member of the Faculty Board for more than 100 other conferences on cochlear implants and related topics.

Organizer (with Professors Rainer Klinke, Ph.D, and Rainer Hartmann, Ph.D.) of a special one-day symposium on *Future Directions for the Further Development of Cochlear Implants*, Frankfurt, Germany, October 15, 2003.

Co-Organizer (with Prof. Henryk Skarżyński, M.D., Ph.D.) of the *Fourth Hearing Preservation Workshop*, Warsaw-Kajetany, Poland, October 2005.

Co-Organizer (with Donald K. Eddington, Ph.D.) of a special retreat on *Future Directions for Cochlear Implants*, Boston, MA, March 17-19, 2006.

Co-Organizer (with Peter S. Roland, M.D.) of a special meeting on *The Future of Cochlear Implants: Roles of the Brain in Implant Outcomes and Design*, Dallas, TX, August 17, 2007.

Organizer (with Debara Tucci, M.D.) of the Grand Opening of the Duke Hearing Center, with a keynote speech by Prof. Michael M. Merzenich of the University of California at San Francisco, Durham, NC, January 29, 2009.

Organizer (with Dale Purves, M.D.) of a special Roundtable in honor of Prof. Michael M. Merzenich, on *A 'Top-Down' or 'Cognitive Neuroscience' Approach to Cochlear Implant Designs*, Durham, NC, January 30, 2009.

Organizer (with David Fitzpatrick, Ph.D., Elizabeth Johnson, Ph.D., and Debara Tucci, M.D.) of a Duke Institute for Brain Sciences (DIBS) “Transcending the Boundaries” Workshop on *Listening with the Brain: New Approaches to Optimizing the Effectiveness of Cochlear Prosthetics*, Durham, NC, February 26-27, 2010.

Organizer (with Eva Karltorp, M.D., and Josef Miller, Ph.D.) of a Special Symposium on “The Listening Brain” at the *11th International Conference on Cochlear Implants and Other Auditory Implantable Technologies*, held in Stockholm, Sweden, June 30 through July 3, 2010.

Organizer (with Emily Tobey, Ph.D., and Peter Roland, M.D.) of a Workshop on *Brain Centric Considerations for Cochlear Implantation*, held in Dallas, TX, August 27, 2012.

Co-Organizer (with Jane Opie, Ph.D., Christoph von Ilberg, M.D., and René Gifford, Ph.D.) of a Conference on *Hearing Implants for Older Adults*, held in New York City, January 16-18, 2014.

Member of the Duke Cornerstone Society, recognizing 30+ years of continuous financial support for the University.

Peer-Reviewed Publications

1. Wright D, Hebrank JH, Wilson BS: Pinna reflections as cues for localization. *J Acoust Soc Am* 56: 957-962, 1974.
2. Wilson BS, Scott SM: Hemodynamic design considerations for an improved artery shunt prosthesis. In DJ Schneck (Ed.), *Bio-Fluid Mechanics*, VPI Press, Blacksburg, VA, 1978, pp. 93-98.
3. Scott SM, Wilson BS: The mechanical design of vascular prostheses. In P Puel, H Boccalon and A Enjalbert (Eds.), *Hemodynamics of the Limbs*, Institut National de la Sante et de la Recherche Medicale, Paris, 1979, pp. 251-259.
4. Wilson BS, Zook JM, Joines WT, Casseday JH: Alterations in activity at auditory nuclei of the rat induced by exposure to microwave radiation: Autoradiographic evidence using [¹⁴C]-2-deoxy-D-glucose. *Brain Res* 187: 291- 306, 1980.
5. Joines WT, Wilson BS: Field-induced forces at dielectric interfaces as a possible mechanism of rf hearing effects. *Bull Math Biol* 43: 401-413, 1981.
6. Kobler JB, Wilson BS, Henson OW Jr., Bishop AL: Echo intensity compensation by echolocating bats. *Hear Res* 20: 99-108, 1985.

7. Wilson BS, Joines WT: Mechanisms and physiologic significance of microwave action on the auditory system. *J Bioelect* 4: 495-525, 1985.
8. Henson OW Jr., Bishop A, Keating A, Kobler J, Henson M, Wilson B, Hansen R: Biosonar imaging of insects by *Pteronotus p. parnellii*, the Mustached bat. *National Geographic Res* 3: 82-101, 1987.
9. Wilson BS, Finley CC, Farmer JC Jr., Lawson DT, Weber BA, Wolford RD, Kenan PD, White MW, Merzenich MM, Schindler RA: Comparative studies of speech processing strategies for cochlear implants. *Laryngoscope* 98: 1069-1077, 1988.
10. Wilson BS, Schindler RA, Finley CC, Kessler DK, Lawson DT, Wolford RD: Present status and future enhancements of the UCSF cochlear prosthesis. In P Banfai (Ed.), *Cochlear Implants: Current Situation*, Rudolf Bermann GmbH, Erkelenz, Germany, 1988, pp. 395-427.
11. Wilson BS (moderator), Dent LJ, Dillier N, Eddington DK, Hochmair-Desoyer IJ, Pfingst BE, Patrick J, Sürth W, Walliker J: Round table discussion on speech coding. In P Banfai (Ed.), *Cochlear Implants: Current Situation*, Rudolf Bermann GmbH, Erkelenz, Germany, 1988, pp. 693-704.
12. Wilson BS, Finley CC, Lawson DT, Wolford RD: Speech processors for cochlear prostheses. *Proc IEEE* 76: 1143-1154, 1988.
13. Kohut RI, Carney AE, Eviatar L, Green DM, Hind JE, Hinojosa R, Levitt H, Miller KD, Mills JH, Rockette HE, Rybak LP, Schwartz IR, Stark RE, Thompson SJ, Bilger RC, Boothroyd A, Cohen NL, Eddington DK, Gantz BJ, Hambrecht FT, Jerger J, Knutson JF, Lansing CR, Linthicum FH Jr, Mecklenburg DJ, Miller JM, Miyamoto RT, Osberger MJ, Rabinowitz WM, Rosen S, Ruben RJ, Shannon RV, Simmons FB, Somers MN, Tong YC, van den Honert C, Wilson BS, Elkins E, Bernstein MJ, Black FO, Clark SM, Duncan P, Elliott JM, Hill JG, Jakubczak LF, Kavanagh, JF, Naunton RF, Shakhshiri ZA, Yin L, Young ED: Cochlear implants. *NIH Consens Statement* 7(2): 1-25, 1988. (This Statement also was published in the *Arch Otolaryngol Head Neck Surg* 115: 31-36, 1989, and in the *Int J Technol Assess Health Care* 5: 288-297, 1989.)
14. Finley CC, Wilson BS, White MW: Models of neural responsiveness to electrical stimulation. In JM Miller and FA Spelman (Eds.), *Cochlear Implants: Models of the Electrically Stimulated Ear*, Springer-Verlag, 1990, pp. 55-96.
15. Wilson BS, Finley CC, Lawson DT: Representations of speech features with cochlear implants. In JM Miller and FA Spelman (Eds.), *Cochlear Implants: Models of the Electrically Stimulated Ear*, Springer-Verlag, 1990, pp. 339-376.
16. Wilson BS, Lawson DT, Finley CC, Wolford RD: Coding strategies for multichannel cochlear prostheses. *Am J Otol* 12 (Suppl. 1): 56-61, 1991.
17. Wilson BS, Finley CC, Lawson DT, Wolford RD, Eddington DK, Rabinowitz WM: Better speech recognition with cochlear implants. *Nature* 352: 236-238, 1991. (This paper is the most highly cited publication in the specific field of cochlear implants and has been since the end of 1999. At present, it has more than 560 citations according to the Web of Science.)
18. Wilson BS: Signal processing. In R Tyler (Ed.), *Cochlear Implants: Audiological Foundations*, Singular Publishing Group, San Diego, CA, 1993, pp. 35-85.
19. Wilson BS, Lawson DT, Finley CC, Wolford RD: Importance of patient and processor variables in determining outcomes with cochlear implants. *J Speech Hear Res* 36: 373-379, 1993.
20. Lawson DT, Wilson BS, Finley CC: New processing strategies for multichannel cochlear prostheses. *Prog Brain Res* 97: 313-321, 1993.

21. Wilson BS, Finley CC, Lawson DT, Wolford RD, Zerbi M: Design and evaluation of a continuous interleaved sampling (CIS) processing strategy for multichannel cochlear implants. *J Rehab Res Devel* 30: 110-116, 1993.
22. Wilson BS, Lawson DT, Zerbi M, Finley CC: Recent developments with the CIS strategies. In IJ Hochmair-Desoyer and ES Hochmair (Eds.), *Advances in Cochlear Implants*, Verlag Manz, Vienna, 1994, pp. 103-112.
23. Wilson BS, Lawson DT, Zerbi M, Finley CC, Wolford RD: New processing strategies in cochlear implantation. *Am J Otol* 16: 669-675, 1995.
24. Wilson BS, Lawson DT, Zerbi M: Advances in coding strategies for cochlear implants. *Adv Otolaryngol Head Neck Surg* 9: 105-129, 1995.
25. Gates GA, Daly K, Dichtel WJ, Dooling RJ, Gulya AJ, Hall JW, Jerger SW, Jones JE, Mayer MH, Pierschalla M, Ross LF, Schwartz RG, Weinstein BE, Young ED, Abbas PJ, Blamey P, Brackmann DE, Brimacombe JA, Chute PM, Cohen NL, Dorman MF, Eddington DK, Gantz BJ, Heller JW, Ketten DR, Knutson JF, Leake PA, McDermott HJ, Miyamoto RT, Moog JS, Osberger MJ, Shannon RV, Skinner MW, Summerfield Q, Tobey EA, Wilson BS, Zwolan TA, Donahue AH, Allen MP, Beck LB, Bray EA, Cooper JA, Ferguson JH, Flack MN, Hall WH, Hambrecht FT, Krasnegor N, Monjan AA, Naunton RF: Cochlear implants in adults and children. *NIH Consens Statement* 13(2): 1-30, 1995. (The Statement also was published in the *JAMA* 274: 1955-1961, 1995.)
26. Wilson BS: Thirty years of the *British Journal of Audiology*: Guest Editorial: The future of cochlear implants. *Brit J Audiol* 31: 205-225, 1997.
27. Lawson DT, Wilson BS, Finley CC, Zerbi M, Cartee LA, Roush PA, Farmer JC Jr., Tucci DL: Cochlear implant studies at Research Triangle Institute and Duke University Medical Center. *Scand Audiol* 26 (Suppl. 46): 50-64, 1997.
28. Wilson BS, Finley CC, Lawson DT, Zerbi M: Temporal representations with cochlear implants. *Am J Otol* 18: S30-34, 1997.
29. Wilson BS, Rebscher S, Zeng F-G, Shannon RV, Loeb GE, Lawson DT, Zerbi M: Design for an inexpensive but effective cochlear implant. *Otolaryngol Head Neck Surg* 118: 235-241, 1998.
30. Lawson DT, Wilson BS, Zerbi M, van den Honert C, Finley CC, Farmer JC Jr., McElveen JT, Roush PA: Bilateral cochlear implants controlled by a single speech processor. *Am J Otol* 19: 758-761, 1998.
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Editorial

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Lectures as a Guest of Honor

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10. Wilson BS: Cochlear implants: A remarkable past and a brilliant future. *Ninth International Cochlear Implant Conference*, Vienna, Austria, June 14-17, 2006.
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12. Wilson BS: My vision for a cochlear implant in five years. *Sixth Wullstein Symposium 2006: New Developments in Hearing Technology*, Würzburg, Germany, December 7-10, 2006.
13. Wilson BS: Acceptance of the Distinguished Alumnus Award. *Annual Awards Banquet and Ceremony*, Pratt School of Engineering, Durham, NC, USA, April 21, 2007.
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15. Wilson BS: Partial deafness cochlear implantation (PDCI) and electro-acoustic stimulation (EAS). *9th European Symposium on Paediatric Cochlear Implantation*, Warsaw, Poland, May 14-17, 2009. (This lecture also is listed as one of the four keynote speeches in the Program for the Symposium.)
16. Wilson BS: Two opportunities for the further development and broader application of cochlear implants. *Munich Hearing Implant Symposium: Reaching New Heights*, Ludwig-Maximilians-Universität München, Munich, Germany, December 8-10, 2011. (This lecture also is listed as one of the four keynote speeches in the Program for the Symposium.)
17. Wilson BS: How to close the gap? *4th Munich^{LMU} Hearing Implant Symposium 2015: Hearing Implants Around the World*, Ludwig-Maximilians-Universität München, Munich, Germany, December 10-13, 2015. (This lecture also is listed as one of the keynote speeches in the Program for the Symposium.)

Nalli Family Distinguished Lecture

1. 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.

Neel Distinguished Research Lectureship

1. Wilson BS, Miyamoto RT: How basic science has influenced the design of cochlear implants? *112th Annual Meeting of the American Academy of Otolaryngology, Head and Neck Surgery*, Chicago, IL, USA, September 21-24, 2008. (This meeting was attended by more than 8,500 physicians and other professionals; the Neel Distinguished Research Lectureship is among the highest honors conferred by the *American Academy*. The prior lecture in the series was by Elias Zerhouni, M.D., the then Director of the United States' National Institutes of Health.)

Chandra Sekhar Lecture

1. Wilson BS: Thinking about the hearing brain in designs and applications of cochlear implants. The *Chandra Sekhar Lecture*, New York University School of Medicine, NYU Langone Medical Center, New York, NY, USA, April 10, 2013. (The Chandra Sekhar lectures honor Dr. Hosakere K. Chandra Sekhar for his work in temporal bone histology and for his contributions to education and clinical care during his distinguished career at the NYU School of Medicine, which began in 1971. The lectures are supported by a fund established by his family upon his retirement in 2008; the present lecture by Wilson was the second in the series of lectures.)

Hopkins Medicine Distinguished Speaker Lecture

1. Wilson BS: Do you hear what I hear? – Cochlear implants & the past, present, and future of prosthetic hearing. Johns Hopkins University School of Medicine, Baltimore, MD, USA, February 4, 2014. (The following is a description of the Distinguished Speakers Series: “The Distinguished Speaker Series was established by a group of medical students at Johns Hopkins to inform and inspire medical scientists, clinicians, public health leaders, and students through scholarly exchange with the world’s foremost visionaries and thinkers. Our inaugural event brought together seven recipients of the MacArthur “Genius Grant” for a lively dialogue on the ways in which creative minds engage the public. Since then, we have hosted Lasker Award recipient Dr. Anthony S. Fauci, noted bioethicist Dr. Charles Bosk, and Dr. Françoise Barré-Sinoussi, recipient of the Nobel Prize in Physiology or Medicine and co-discoverer of HIV. Our most recent events featured Dr. K. Anders Ericsson, cognitive psychologist and expert on expertism, Dr. Robert Langer, head of the largest biomedical engineering laboratory in the world, and five exceptional faculty at Johns Hopkins presenting their personal and professional journeys in medicine.”)

Vanderbilt University Medical Center Flexner Discovery Lecture

1. Wilson BS: The development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. Vanderbilt University Medical Center, Nashville, TN, USA, March 13, 2014. (The following is a description of the Flexner Discovery Lectures: “The Flexner Discovery Lecture Series features the world’s most eminent scientists, who speak on the highest-impact research and policy issues in science and medicine today. Prior speakers have included multiple Nobel Laureates and members of the United States’ Institute of Medicine.”)

2014 Lasker Lecture

1. Wilson BS: Toward better representations of sound with cochlear implants. Keck School of Medicine, University of Southern California, Los Angeles, CA, USA, April 10, 2014.

Göttingen Sensory Lecture

1. Wilson BS: Brain centric approaches to designs and applications of cochlear implants. Georg-August-Universität Göttingen, Göttingen, Germany, June 24, 2014. (The Lecture was jointly supported by the collaborative sensory research grant on Cellular Mechanisms of Sensory Processing and the Bernstein Center for Computational Neuroscience.)

Duke Engineering 75th Anniversary Lecture

1. Wilson BS: The development of the modern cochlear implant. Duke University, Durham, NC, USA, March 5, 2015.

Graham Fraser Memorial Lecture

1. Wilson BS: Possible ways forward for cochlear implants and building on the grand legacy of Graham Fraser, M.D. Lecture presented in conjunction with the *Annual Meeting of the British Cochlear Implant Group*, Bristol, UK, March 19-20, 2015. (The Graham Fraser Memorial Lectures celebrate his life and achievements and are the most prestigious lectures in the fields of cochlear implants and remediation of severe losses in hearing. More information about the lectures is presented at <http://www.grahamfraserfoundation.org.uk/memlects.htm>.)

RTI Distinguished Lecture

1. Wilson BS: Toward better representations of sound with cochlear implants. *RTI International Distinguished Lecture Series*, Research Triangle Foundation, Research Triangle Park, NC, USA, April 14, 2015. (This talk was the inaugural lecture in the series.)

Distinguished BME Lecture

1. Wilson BS: The development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. University of California at Irvine, Irvine, CA, USA, April 22, 2016.

C. Paul and Beth K. Stocker Lecture

1. Wilson BS: Getting a decent (but sparse) signal to the brain for users of cochlear implants. Ohio University, Athens, OH, USA, April 12, 2016. (This lecture was one in a series by winners of the Russ Prize and was supported by the Fritz J. and Dolores H. Russ College of Engineering and Technology and the Robe Leadership Institute at Ohio University.)

Honored 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, USA, May 10-13, 2004.

Dean's Leadership in Innovation Seminar

1. Wilson BS: Cochlear implants: A remarkable past and a brilliant future. Faculty of Engineering and Information Technology, University of Technology, Sydney, Sydney, Australia, October 27, 2011.

Distinguished Guest Address

1. Wilson BS: A designer's perspective of cochlear implants. *Fourth Workshop on Transcanal Techniques for Cochlear Implants*, New Delhi, India, February 4-5, 2012.

Invited Address for the President's Symposium within the 2012 Meeting of the ARO

1. Wilson BS, Dorman MF, Woldorff MG, Tucci DL: A "top down" or "cognitive neuroscience" approach to cochlear implant designs and fittings. Presidential Symposium on *Listening with the Brain: Cochlear Implants and Central Auditory System Plasticity*, 35th Midwinter Meeting, Association for Research in Otolaryngology, San Diego, CA, USA, February 25-29, 2012.

Inaugural Plenary Addresses

1. Wilson BS: Cochlear implants: Matching the prosthesis to the brain and facilitating desired plastic changes in brain function. *2nd Congress of Spanish-America on Cochlear Implants and Related Sciences*, Cartagena, Columbia, December 1-3, 2010.
2. Wilson BS: The significance of the 2013 Lasker~DeBakey Clinical Medical Research Award to the field of cochlear implants and for fulfilling the mission of the American Cochlear Implant Alliance. *CI 2013 Conference – American Cochlear Implant Alliance*, Washington DC, USA, October 24-26, 2013.

Presentation to the Duke University Board of Trustees

1. Wilson BS: The 2013 Lasker~DeBakey Award and the first substantial restoration of a human sense using a medical intervention. Duke University, Durham, NC, USA, December 6, 2013.

Distinguished Speaker Address

1. Wilson BS: Progress and remaining problems in the development of the cochlear implant. *Future of Hearing Symposium*, sponsored by the Cluster of Excellence "Hearing4all," Oldenburg, Germany, November 6-7, 2014.

Inauguration Speech for the Institute for Auditory Neuroscience at the University of Göttingen

1. Wilson BS: Auditory neuroscience: The prosthetic's perspective. One of three lectures to inaugurate the Institute for Auditory Neuroscience at the University of Göttingen, Göttingen, Germany, March 21, 2015. (The other two speakers were Tobias Moser, M.D., Director of the new Institute, and Benedikt Grothe, Ph.D., Chair of the Division of Neurobiology and Dean of the Faculty of Biology, Ludwig-Maximilians-Universität München, Munich, Germany.)

Grand Rounds Presentations

1. Farmer JC Jr., Kenan PD, Wilson BS: Cochlear implants. Surgical Grand Rounds, Duke University Medical Center, Durham, NC, USA, November, 1985.
2. Farmer JC Jr., Javel E, McElveen JT Jr., Wilson BS: Advances in cochlear implants. Surgical Grand Rounds, Duke University Medical Center, Durham, NC, USA, December 13, 1989.
3. Wilson BS: Advances in cochlear implant research. Grand Rounds presentation, Department of Otolaryngology, University of Toronto, Toronto, Canada, February 18, 2005.
4. Wilson BS: The development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. Surgical Grand Rounds, Duke University Medical Center, Durham, NC, USA, March 5, 2014.
5. Wilson BS: Thinking about the hearing brain in designs and applications of cochlear implants. Grand Rounds presentation, Department of Otolaryngology – Head & Neck Surgery and Department of Hearing and Speech Sciences, Vanderbilt University Medical Center, Nashville, TN, USA, March 14, 2014.
6. Wilson BS: The development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. Surgical Grand Rounds, Department of Otolaryngology – Head & Neck Surgery, Northwestern University Medical Center, Evanston, IL, USA, April 16, 2015.

Keynote Speeches

1. Wilson BS: Suggestions for the future development of cochlear implants. *Third European Symposium on Paediatric Cochlear Implantation*, Hannover, Germany, June 6-8, 1996. (This presentation was the penultimate summary lecture for the Symposium, preceding the concluding lecture by Professor Lenarz, General Chair.)
2. Wilson BS: New directions in implant design. *4th European Symposium on Paediatric Cochlear Implantation*, 's-Hertogenbosch, The Netherlands, June 14-17, 1998.
3. 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.
4. Wilson BS: Future directions for cochlear implants. *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.
5. 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. (This was the single keynote speech for this conference.)

6. Wilson BS: Present results and future possibilities for bilateral cochlear implants. *Sixth International Meeting on Bilateral Cochlear Implants and Binaural Signal Processing*, Bern, Switzerland, March 29-30, 2007.
7. Wilson BS: Cochlear implants. *International Workshop on Advances in Audiology*, Salamanca, Spain, May 25-26, 2007.
8. Wilson BS: The past, present, and future of cochlear implants. *Nemours Cochlear Implant Symposium*, Wilmington, Delaware, USA, October 12-13, 2009. (This was the single keynote speech for this conference.)
9. Wilson BS: The listening brain: Roles of the “auditory brain” in outcomes and designs for cochlear implants. *Perth Auditory Implant Workshop*, University of Western Australia, Perth, Australia, October 28-30, 2010.
10. Wilson BS: Cochlear implants: A remarkable past and a brilliant future. *Conference on Hearing Implants: A Remarkable Past and a Brilliant Future*, Frankfurt am Main, Germany, December 9-11, 2010.
11. Wilson BS: Cochlear implantation: A remarkable past and a brilliant future. *10th European Symposium on Paediatric Cochlear Implantation*, Athens, Greece, May 12-15, 2011.
12. Wilson BS: Cochlear implants: Matching the prosthesis to the brain and facilitating desired plastic changes in brain function. *12th International Conference on Cochlear Implants and Other Implantable Auditory Technologies*, Baltimore, MD, USA, May 3-5, 2012.
13. Wilson BS: Present and future of cochlear implants. *VI International Meeting on Advances in Audiology*, Salamanca, Spain, June 7-9, 2012.
14. Wilson BS: The four large steps forward that led to the present-day cochlear implants. *Perth Auditory Implant Workshop*, Perth, Australia, November 8-10, 2012.
15. Wilson BS: Future possibilities for combined electric and acoustic stimulation. *3rd Munich Hearing Implant Symposium: Comprehensive Hearing Implant Solutions*, Ludwig-Maximilians-Universität München, Munich, Germany, December 12-15, 2013.
16. Wilson BS: Toward better representations of sound with cochlear implants. Special session honoring the development of the modern cochlear implant and the winners of the 2013 Lasker-DeBakey Clinical Medical Research Award, *13th International Conference on Cochlear Implants and Other Implantable Auditory Prostheses*, Munich, Germany, June 18-21, 2014.
17. Wilson BS: Evolution of electrical stimulation in the cochlea; single to multichannel to deep insertion to EAS – A historical perspective. *Conference on the APEX of the Cochlea – From Neuroanatomy to Electrical Stimulation*, Chapel Hill, NC, USA, September 4-7, 2014.
18. Wilson BS: Possibilities for narrowing the remaining gaps between prosthetic and normal hearing. *10th Asia Pacific Symposium on Cochlear Implants and Related Sciences*, Beijing, China, April 30 through May 3, 2015. (This presentation was the opening plenary address for the conference.)
19. Wilson BS: Remaining challenges for cochlear implants. *Perth Auditory Implant Workshop*, University of Western Australia, Perth, Australia, October 28-31, 2015.

Banquet Address

1. Wilson BS: How my education in engineering at Duke helped me to contribute to the development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. *Annual Workshop for the Graduate Program in Electrical and Computer Engineering*, Pratt School of Engineering, Duke University, Durham, NC, USA, January 23, 2014.

Additional Invited Presentations

1. Wilson BS: Speech processors for auditory prostheses. *14th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1983.
2. Wilson BS: Speech processors for auditory prostheses. *15th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1984.
3. Wilson BS: Coding strategies for multichannel auditory prostheses. *Gordon Research Conference on Implantable Auditory Prostheses*, Tilton, NH, USA, August 19-23, 1985.
4. Finley CC, Wilson BS: An integrated field-neuron model of intracochlear stimulation. *Gordon Research Conference on Implantable Auditory Prostheses*, Tilton, NH, USA, August 19-23, 1985.
5. Finley CC, Wilson BS: A simple finite-difference model of the field patterns produced by bipolar electrodes of the UCSF array. *IEEE Bioengineering Conference*, September 27-30, 1985.
6. Wilson BS, Finley CC: Speech processors for auditory prostheses. *IEEE Bioengineering Conference* (special session on “Signal Processing for the Hearing Impaired”), September 27-30, 1985.
7. Finley CC, Wilson BS: Models of neural stimulation for electrically-evoked hearing. *Annual Conference on Engineering in Medicine and Biology*, September 30 through October 2, 1985.
8. Wilson BS: Speech processors for auditory prostheses. *16th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1985.
9. Wilson BS: Comparison of strategies for coding speech with multichannel auditory prostheses. *Conference on Speech Recognition with Cochlear Implants*, New York University, New York, NY, USA, April 17-19, 1986.
10. Wilson BS: Coding strategies for cochlear implants. Kresge Hearing Research Institute, University of Michigan, Ann Arbor, MI, USA, May 22, 1986.
11. Wilson BS: Ensemble models of neural discharge patterns evoked by intracochlear electrical stimulation. *International Union of Physiological Scientists (IUPS) Satellite Symposium on Advances in Auditory Neuroscience*, San Francisco, CA, USA, July 8-11, 1986.
12. Wilson BS: Processing strategies for cochlear implants. *Annual Meeting of the American College of Otolaryngologists*, San Antonio, TX, USA, September 18-19, 1986.
13. Kenan PD, Farmer JC Jr., Weber BA, Wilson BS: Cochlear implants. *Annual Meeting of the Mecklenburg County Otolaryngology, Head and Neck Surgery Society*, Charlotte, NC, fall, 1986.
14. Wilson BS: Speech processors for auditory prostheses. *17th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1986.
15. Wilson BS: Cochlear implants. *First North Carolina Workshop on Bioelectronics* (session on “Auditory Signal Processing”), Quail Roost, NC, USA, October 24-26, 1986.

16. Wilson BS: The RTI/Duke cochlear implant program. Executive committee of the Research Triangle Institute (RTI) Board of Governors, June 17, 1987.
17. Farmer JC Jr., Wilson BS: Cochlear implantation for the profoundly deaf. Department of Physiology, Duke University Medical Center, June 18, 1987.
18. Wilson BS: Factors in coding speech for auditory prostheses. *Gordon Research Conference on Implantable Auditory Prostheses*. New London, NH, USA, June 29 through July 3, 1987.
19. Schindler RA, Wilson BS: Present status and future enhancements of the UCSF/RTI/Duke cochlear implant. *International Cochlear Implant Symposium 1987*, Düren, Germany, September 7-11, 1987.
20. Wilson BS: Speech processors for auditory prostheses. *18th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1987.
21. Wilson BS: Review of RTI research on coding strategies for cochlear prostheses. 3M Company, St. Paul, MN, USA, November 12, 1987.
22. Wilson BS, Finley CC, White MW, Lawson DT: Comparisons of processing strategies for multichannel auditory prostheses. *Ninth Annual Conference on Engineering in Medicine and Biology* (special session on cochlear implants), Boston, MA, USA, November 13-16, 1987.
23. White MW, Finley CC, Wilson BS: Electrical stimulation model of the auditory nerve: Stochastic response characteristics. *Ninth Annual Conference on Engineering in Medicine and Biology* (special session on cochlear implants), Boston, MA, USA, November 13-16, 1987.
24. Finley CC, Wilson BS, White MW: A finite-element model of bipolar field patterns in the electrically stimulated cochlea – A two dimensional approximation. *Ninth Annual Conference on Engineering in Medicine and Biology* (special session on cochlear implants), Boston, MA, USA, November 13-16, 1987.
25. Finley CC, Wilson BS, White MW: Models of afferent neurons in the electrically stimulated ear. *Ninth Annual Conference on Engineering in Medicine and Biology* (special session on cochlear implants), Boston, MA, USA, November 13-16, 1987.
26. Wilson BS: Various coding schemes used. *Cochlear Implant Consensus Development Conference*, National Institutes of Health, Bethesda, MD, USA, May 2-4, 1988.
27. Wilson BS: Comparison of encoding schemes. *25th Anniversary Symposium of the Kresge Hearing Research Institute*, Ann Arbor, MI, USA, October 3-5, 1988.
28. Wilson BS: Speech processors for auditory prostheses. *19th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1988.
29. Soli SD, Wilson BS: Within-subject comparisons of analog and pulsatile speech processors for cochlear implants. *Annual Meeting of the Acoustical Society of America* (special session on “Speech Processing Aids for the Handicapped”), Honolulu, Hawaii, USA, November 14-18, 1988. (Abstract published in *J Acoust Soc Am* 84: S41, 1988)
30. Wilson BS: Within-patient evaluation of speech processors. *Engineering Foundation Conference on Implantable Auditory Prostheses*, Potosi, MO, USA, July 30 through August 4, 1989.
31. Wilson BS: Comparison of analog and pulsatile coding strategies for multichannel cochlear prostheses. University of Iowa, Iowa City, IA, USA, August 28, 1989.
32. Wilson BS: Speech processors for auditory prostheses. *20th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1989.
33. Wilson BS: Processing strategies for cochlear implants. *Third Symposium on Cochlear Implants in Children*, Indianapolis, IN, USA, January 26 and 27, 1990.

34. Wilson BS: Recent advances in the design of cochlear prostheses. Richards Medical, Memphis, TN, USA, February 5, 1990.
35. Wilson BS: Design of cochlear prostheses. *AAAS Meeting* (special session on "Cochlear Implants in Children"), New Orleans, LA, USA, February 15-20, 1990.
36. Shannon RV (moderator), Wilson BS, Eddington DK, Walliker J, Pfungst BE, Patrick JF, Rosen S (panelists): Round table discussion on "Future directions in Speech Processing." *Second International Cochlear Implant Symposium*, Iowa City, IA, USA, June 4-8, 1990.
37. Wilson BS: Speech processors for auditory prostheses. *21st Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1990.
38. Wilson BS: Strategies for representing speech with cochlear implants. *Meeting of the Acoustical Society of America* (special session on "Speech Perception and Hearing Handicap"), Baltimore, MD, USA, April 29 to May 3, 1991. (Abstract published in *J Acoust Soc Am* 89, Suppl. 1, p. 1957, 1991)
39. Wilson BS: New levels of speech recognition with cochlear implants. *1991 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, June 2-7, 1991.
40. Wilson BS, Lawson DT, Finley CC: A new processing strategy for multichannel cochlear prostheses. *International Symposium on Natural and Artificial Nervous Control of Hearing and Balance*, Rheinfelden, Switzerland, September 4-8, 1991. (Lecture presented by Lawson)
41. Wilson BS: A new coding strategy for cochlear implants. *Annual Meeting of the American Neurotology Society*, Kansas City, MO, USA, September 21, 1991.
42. Wilson BS: Speech processors for auditory prostheses. *22nd Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October, 1991.
43. Wilson BS: Processing strategies for multichannel cochlear implants. *Fourth Symposium on Cochlear Implants in Children*, Kansas City, MO, USA, February 14 and 15, 1992.
44. Wilson BS: Speech processing for auditory prostheses. Lecture for the course on "Current Status of Multichannel Cochlear Implants," *96th Meeting of the American Academy of Otolaryngology -- Head & Neck Surgery*, Washington DC, USA, September 13, 1992.
45. Wilson BS: Processing strategies for multichannel cochlear implants. *First European Symposium on Paediatric Cochlear Implantation*, Nottingham, England, September 24-27, 1992.
46. Wilson BS: Panelist, round table on Programming. *First European Symposium on Paediatric Cochlear Implantation*, Nottingham, England, September 24-27, 1992.
47. Wilson BS: Speech processors for auditory prostheses. *23rd Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 13-15, 1992.
48. Wilson BS: Representations of envelope information with CIS and VCIS processors. *Mini Symposium on Envelope Representations with Cochlear Implants*, House Ear Institute, Los Angeles, CA, USA, February 25-28, 1993.
49. Wilson BS: Optimizing performance with new processing strategies. *1993 Cherry Blossom Conference: Current and New Applications in Hearing and Equilibrium*, American Academy of Otolaryngology -- Head & Neck Surgery, Washington DC, USA, April 2, 1993.
50. Wilson BS: Recent developments with the CIS strategies. *Third International Cochlear Implant Conference*, Innsbruck, Austria, April 4-7, 1993.
51. Wilson BS, Lawson DT, Zerbi M, Finley CC: CIS and "virtual channel" CIS (VCIS) processors. *1993 Conference on Implantable Auditory Prostheses*, Smithfield, RI, USA, July 11-15, 1993.

52. Wilson BS, Lawson DT, Zerbi M, Finley CC, Wolford RD: New processing strategies in cochlear implantation. *Annual Meeting of the American Neurotology Society* (special session on "Basic Science Update"), Minneapolis, MN, USA, October 1, 1993.
53. Wilson BS: Speech processors for auditory prostheses. *24th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 13-15, 1993.
54. Wilson BS: Introduction to speech processor design and testing. *1993 Zhengzhou International Symposium on Electrical Cochlear Hearing and Linguistics*, Zhengzhou, China, October 23-26, 1993.
55. Wilson BS: New processing strategies for cochlear prostheses. *1993 Zhengzhou International Symposium on Electrical Cochlear Hearing and Linguistics*, Zhengzhou, China, October 23-26, 1993.
56. Wilson BS: Further studies with CIS and related processors. *1993 Zhengzhou International Symposium on Electrical Cochlear Hearing and Linguistics*, Zhengzhou, China, October 23-26, 1993.
57. Wilson BS: Review of speech processor studies. University of Iowa, Department of Otolaryngology – Head & Neck Surgery, Iowa City, IA, USA, January 18, 1994.
58. Wilson BS: Progress in speech processor design. *Fifth Symposium on Cochlear Implants in Children*, New York, NY, USA, February 4, 1994.
59. Wilson BS: Review of speech processor studies. Indiana University School of Medicine, Department of Otolaryngology -- Head & Neck Surgery, Indianapolis, IN, USA, March 9, 1994.
60. Wilson BS: Progress in the development of speech processors for cochlear prostheses. *127th Meeting of the Acoustical Society of America* (special session on "Electro-Auditory Prostheses"), Cambridge, MA, USA, June 8, 1994. (Abstract published in *J Acoust Soc Am* 95: 2905, 1994.)
61. Wilson BS: Cochlear modeling studies. *25th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 18-21, 1994.
62. Wilson BS: Speech processors for auditory prostheses. *25th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 18-21, 1994.
63. Wilson BS, Lawson DT, Zerbi M, Finley CC: New developments in speech processors. Lecture for the "Workshop on Auditory Prosthetics," *18th Midwinter Meeting of the Association for Research in Otolaryngology*, St. Petersburg, FL, USA, February 5-9, 1995. (Abstract published in *ARO Abstracts*, p. 97, 1995.)
64. Wilson BS: Future directions in speech processing. *CIS Workshop* (sponsored by Med El GmbH and held in conjunction with the *IIIrd International Congress on Cochlear Implant*), Paris, France, April 26, 1995.
65. Wilson BS: Continuous Interleaved Sampling and related strategies. *NIH Consensus Development Conference on Cochlear Implants in Adults and Children*, May 15-17, 1995.
66. Wilson BS: Temporal representations with cochlear implants. *1995 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, August 20-24, 1995.
67. Wilson BS: Speech processors for auditory prostheses. *26th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 18-20, 1995.
68. Wilson BS: Strategies for representing speech information with cochlear implants. *6th Symposium on Cochlear Implants in Children*, Miami Beach, FL, USA, February 2-3, 1996.
69. Wilson BS, Finley CC, Lawson DT, Zerbi M: Temporal representations with cochlear implants. *Third European Symposium on Paediatric Cochlear Implantation*, Hannover, Germany, June 6-8, 1996.

70. Wilson BS: Progress in the development of speech processing strategies for cochlear implants. University of Iowa, Department of Otolaryngology – Head and Neck Surgery, Iowa City, IA, USA, July 29, 1996.
71. Wilson BS, Lawson DT: Speech processors for auditory prostheses. *27th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 16-18, 1996.
72. Wilson BS: Possibilities for the further development of speech processor designs. *Fifth International Cochlear Implant Conference*, New York, NY, USA, May 1-3, 1997.
73. Lawson DT, Wilson BS, Zerbi M, Roush PA, van den Honert C, Finley CC, Tucci DL, Farmer JC Jr.: Within patient comparisons among processing strategies for cochlear implants. *130th Annual Meeting of the American Otological Society*, Scottsdale, AZ, USA, May 10-11, 1997. (Lecture presented by Wilson)
74. Lawson DT, Wilson BS, Zerbi M, van den Honert C, Finley CC, Farmer JC Jr., McElveen JT, Roush PA: Bilateral cochlear implants controlled by a single speech processor. *130th Annual Meeting of the American Otological Society*, Scottsdale, AZ, USA, May 10-11, 1997.
75. Wilson BS: Design of speech processors for cochlear prostheses. Johns Hopkins University, Department of Biomedical Engineering, May 30, 1997.
76. Wilson BS, Finley CC, Zerbi M, Lawson DT, van den Honert C: Representations of temporal information in responses of the human auditory nerve to electrical stimuli. *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, August 17-21, 1997.
77. Finley CC, Wilson BS, van den Honert C: Fields and EP responses to electrical stimulation: Spatial distributions, electrode interactions and regional differences along the tonotopic axis. *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, August 17-21, 1997.
78. Lawson DT, Wilson BS, Zerbi M, Finley CC: Design differences and parametric adjustments among CIS and related processors. *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, August 17-21, 1997.
79. Wilson BS: Speech processors for auditory prostheses. *28th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 15-17, 1997.
80. Wilson BS: Review of studies at RTI with recipients of bilateral cochlear implants. University of Iowa, Department of Otolaryngology, Head & Neck Surgery, Iowa City, IA, USA, January 27, 1998.
81. Wilson BS, Pierschalla M: Development of cochlear prostheses. *NIH Bioengineering Symposium on "Building the Future of Biology and Medicine,"* National Institutes of Health, Bethesda, MD, USA, February 27 and 28, 1998. (This was one of five invited poster presentations to represent bioengineering research supported by the NIDCD.)
82. Wilson BS: Possibilities for improving the performance of cochlear prostheses. University of Innsbruck, Innsbruck, Austria, June 18, 1998.
83. Wilson BS: Speech processors for auditory prostheses. *29th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 28-20, 1998.
84. 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, USA, August 29 through September 3, 1999.

85. 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, USA, August 29 through September 3, 1999.
86. 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, USA, August 29 through September 3, 1999. (Wilson presented the talk for Lawson, who could not attend the conference due to illness.)
87. Wilson BS: Speech processors for auditory prostheses. *30th Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 12-14, 1999.
88. Wilson BS: Psychophysical measures and speech understanding in bilaterally implanted patients. *Bilateral Research Meeting*, Frankfurt, Germany, December 3, 1999. (This meeting was sponsored by Med El GmbH.)
89. Wilson BS: New directions in cochlear implants. *6th International Cochlear Implant Conference*, Miami Beach, FL, USA, February 3-5, 2000.
90. Wilson BS, Lawson DT, Brill SM, Wolford RD, Schatzer R: Binaural cochlear implants. *Conference on Binaural Hearing, Hearing Loss, Hearing Aids, & Cochlear Implants*, Iowa City, IA, USA, June 22-24, 2000.
91. 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, USA, June 22-24, 2000.
92. Wilson BS, Lawson DT, Brill SM, Wolford RD, Schatzer R: Speech processors for auditory prostheses. *31st Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 25-7, 2000.
93. Lawson DT, Wilson BS, Wolford RD, Brill SM, 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.
94. Lawson DT, Wilson BS, Wolford RD, Brill SM, 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.
95. Lawson DT, Wilson BS, Wolford RD, Brill SM, 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.
96. Wilson BS, Lawson DT, Wolford R, Brill SM, 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.
97. 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* 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*.)

98. Lawson DT, Brill SM, Wolford RD, Wilson BS, Schatzer R: Speech processors for binaural stimulation. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, August 19-24, 2001.
99. 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, USA, August 19-24, 2001.
100. Wilson BS, Lawson DT, et al.: Speech processors for auditory prostheses. *32nd Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 17-19, 2001.
101. 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.)
102. 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.
103. Wilson BS: Speech processors for auditory prostheses. *33rd Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, USA, October 16-18, 2002.
104. Wilson BS: Evaluation of combined EAS in studies at the Research Triangle Institute. *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, USA, November 8-10, 2002.
105. 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.
106. Wilson BS: 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.
107. Wilson BS: 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.
108. Wilson BS: Recent and future cochlear implant stimulation strategies. Conference celebrating *25 Years of Cochlear Implants in Vienna*, Vienna, Austria, June 19, 2003.
109. 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, USA, August 17-22, 2003.
110. 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, USA, August 17-22, 2003.
111. 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, USA, October 21-3, 2003. (Presented by Dewey Lawson and Reinhold Schatzer)
112. Wilson BS: Future developments of CI. *II Meeting Consensus on Auditory Implants*, Valencia, Spain, February 19-21, 2004.

113. 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.
114. 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, USA, May 10-13, 2004. (Honorary Speaker presentation)
115. Wilson BS: Update on EAS studies at the Research Triangle Institute. *Hearing Preservation Workshop III*, Dallas, TX, USA, October 15-16, 2004.
116. Wilson BS: The auditory prosthesis as a paradigm for successful neural interfaces. *Neural Interfaces Workshop*, National Institutes of Health, Bethesda, MD, USA, November 15-17, 2004.
117. 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)
118. Wilson BS: Moderator's overview and introduction, session on Signal Processing and Speech in Noise. *2005 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, July 30 to August 4, 2005.
119. Wilson BS, Müller JM, Wolford RD, Lawson DT: Signal processing for binaural devices. *International Binaural Symposium 2005*, Manchester, UK, October 29-31, 2005.
120. Wilson BS: The auditory prosthesis as a paradigm for successful neural interfaces. *Ninth Annual Meeting of the North American Neuromodulation Society*, Washington DC, USA, November 10-12, 2005.
121. Gstöttner W (Moderator), Wilson B, Lorens A, Kiefer J, Gantz B, James C, Baumgartner W-D: Roundtable on Electric Acoustic Stimulation. *Ninth International Cochlear Implant Conference*, Vienna, Austria, June 14-17, 2006.
122. Wilson BS: Cochlear implants: A remarkable past and a brilliant future. *World Congress on Medical Physics and Biomedical Engineering 2006*, Seoul, Korea, August 27 through September 1, 2006.
123. Wilson BS: Cochlear implants: A remarkable past and a brilliant future. University lecture sponsored by the Hearing and Speech Research Laboratory and the Departments of Cognitive Neuroscience, Bioengineering, and Otolaryngology, Head and Neck Surgery, University of California at Irvine, Irvine, CA, USA, November 8, 2006.
124. Wilson BS, Dorman MF: A new "top down" or "cognitive neuroscience" approach to cochlear implant design. The National Academics and Keck Futures Initiative on *Smart Prosthetics: Exploring Assistive Devices for the Body and Mind*, Arnold & Mabel Beckman Center, Irvine, CA, USA, November 9-11, 2006. (invited poster presentation)
125. Wilson BS: The surprising performance of present-day cochlear implants. *Symposium in Honor of Prof. Dr. Jan Helm's 70th Birthday*, Würzburg, Germany, March 3, 2007.
126. Wilson BS: The surprising performance of present-day cochlear implants. *Special Guest Address*, International Centre of Hearing and Speech, Warsaw-Kajetany, Poland, April 26, 2007.
127. Wilson BS: Cochlear implants from past to present. *Symposium in Celebration of 15 Years of Cochlear Implants in Poland*, International Centre of Hearing and Speech, Warsaw-Kajetany, Poland, July 13, 2007.

128. Wilson BS: A new “top down” or “cognitive neuroscience” approach to the design of cochlear implants. Special meeting on *The Future of Cochlear Implants: Roles of the Brain in Implant Outcomes and Design*, Dallas, TX, USA, August 17, 2007.
129. Lorens A, Wilson BS, Piotrowska A, Skarzynski H: The surprising benefits of cochlear implantation for persons with high levels of residual hearing. *7th Wullstein Symposium*, Würzburg, Germany, December 4-7, 2008. (Presented by Wilson by invitation.)
130. Wilson BS: Cochlear implants: Design aspects. Invited lecture for Duke University course BME 265 on Neural Prosthetic Systems, Pratt School of Engineering, March 19, 2009.
131. Wilson BS: The past, present, and future of cochlear implants. Invited lecture for the Hearing and Chemical Senses Program, Kresge Hearing Research Institute, University of Michigan, April 29, 2009.
132. von Ilberg Ch, Lorens A (moderators), Uziel A, Podskarbi-Fayette R, Lenarz T, Baumgartner W-D, Wilson B, Kiefer J, Batman C, Bebear JP: Round Table on Treatment of Partial Deafness. *9th European Symposium on Paediatric Cochlear Implantation*, Warsaw, Poland, May 14-17, 2009.
133. Wilson BS: Partial deafness cochlear implantation (PDCI) and electro-acoustic stimulation (EAS). *Hearing Preservation Workshop VIII*, Vienna, Austria, October 15-18, 2009.
134. Wilson BS: Signal processing and binaural integration of cochlear implant and normal contralateral hearing. *8th Wullstein Symposium: Treatment of Unilateral Deafness*, Würzburg, Germany, December 11-12, 2009.
135. Müller J (moderator), Kleine Punte A, Hagan R, Brill S, Walger M, Wilson B, Aschendorff A, McKinnon B: Concluding discussion and consensus statement on treatment of unilateral deafness. *8th Wullstein Symposium: Treatment of Unilateral Deafness*, Würzburg, Germany, December 11-12, 2009.
136. Wilson BS: A “top-down” or “cognitive neuroscience” approach to cochlear implant designs. Duke Institute for Brain Sciences workshop on *Listening with the Brain: New Approaches to Optimizing the Effectiveness of Cochlear Prosthetics*, Duke University, Durham, NC, USA, February 26-27, 2010.
137. Wilson BS: Worldwide developments and availabilities of low-cost cochlear implants. *Coalition for Global Hearing Health Conference*, American Academy of Otolaryngology – Head and Neck Surgery Foundation, Alexandria, VA, USA, June 14-15, 2010.
138. Tucci DL, Wilson BS: Global priorities for hearing loss. *Coalition for Global Hearing Health Conference*, American Academy of Otolaryngology – Head and Neck Surgery Foundation, Alexandria, VA, USA, June 14-15, 2010.
139. Rask-Andersen H (President), Baumgartner W-D, Colletti V, Gantz B, Giovannini M, Lenarz Th, Martini A, Olgun L, Ramsden R, Shannon R, Vischer M, Wilson B: Round Table conference on “Future Developments of Auditory Implants.” *ABI 2010 – State of the Art Symposium on Auditory Brainstem Implants*, Uppsala, Sweden, June 29, 2010.
140. Wilson BS: Processing strategies for central auditory prostheses. Presented in the Round Table session on “Future Developments of Auditory Implants.” *ABI 2010 – State of the Art Symposium on Auditory Brainstem Implants*, Uppsala, Sweden, June 29, 2010.
141. Wilson BS: Introduction to the Special Symposium on “The Listening Brain.” *11th International Conference on Cochlear Implants and Other Auditory Implantable Technologies*, Stockholm, Sweden, June 30 through July 3, 2010.
142. Wilson BS: The listening brain. Medizinische Hochschule Hannover, Hannover, Germany, July 8, 2010.

143. Wilson BS: Cochlear implants: Matching the prosthesis to the brain and facilitating desired plastic changes in brain function. *Symposium on Brain Machine Interfaces – Implications for Science, Clinical Practice and Society*, Ystad Saltsjöbad, Sweden, August 26-29, 2010. (This Symposium was supported by the Nobel Foundation among others.)
144. Wilson BS: Cochlear implants for the restoration of hearing. Invited lecture for Duke University course BME 265 on Neural Prosthetic Systems, Pratt School of Engineering, October 14, 2010.
145. Wilson BS: The surprising benefits of cochlear implantation for persons with high levels of residual hearing. *2nd Congress of Spanish-America on Cochlear Implants and Related Sciences*, Cartagena, Columbia, December 1-3, 2010.
146. Baumgartner W-D, Wilson BS: Vienna experience of electrical acoustic surgery. *2nd Congress of Spanish-America on Cochlear Implants and Related Sciences*, Cartagena, Columbia, December 1-3, 2010.
147. Wilson BS (moderator), Baumgartner W-D, Labadie R, Manrique M, Özgirgin N: Round Table on “Future trends in implantation.” *2nd Congress of Spanish-America on Cochlear Implants and Related Sciences*, Cartagena, Columbia, December 1-3, 2010.
148. Rajan G, Kleine Punte A, Schatzer R, Wie OB, Wilson BS, McKinnon B, Streitberger C: Round Table on “Cochlear implants in unilateral deafness.” *Conference on Hearing Implants: A Remarkable Past and a Brilliant Future*, Frankfurt am Main, Germany, December 9-11, 2010.
149. Schatzer R, Wilson BS, Lopez-Poveda E, Wolford RD, Zerbi M, Cox JH: A bio-inspired coding strategy for cochlear implants: Concept and results. *Conference on Hearing Implants: A Remarkable Past and a Brilliant Future*, Frankfurt am Main, Germany, December 9-11, 2010.
150. Wilson BS, Lorens A, Piotrowska, Skarzynski H: The surprising benefits of cochlear implantation for persons with high levels of residual hearing. *10th European Federation of Audiology Societies (EFAS) Congress*, Warsaw, Poland, June 22-25, 2011. (Presented by Artur Lorens in the special session on “International collaboration projects – 15th Anniversary of the Institute of Physiology and Pathology of Hearing.”)
151. Wilson BS: Cochlear implants: a remarkable past and a brilliant future. Seminar presentation at the University of Warwick, Coventry, UK, October 17, 2011.
152. Wilson BS: The surprising benefits of cochlear implantation for persons with high levels of residual hearing. *Presbycusis Research Meeting*, Munich, Germany, January 12-14, 2012.
153. Briand P, Buchman C, Caraway T, Gantz B, Hochmair I, Hodges A, Janssen J, Lenarz T, Luntz, M, Luxford W, Mueller J, Nedzelski J, Roehrienin G, van de Heyning P, Wilson B, Zwolan T (panelists and industry representatives): The future of cochlear implant care and technology. *12th International Conference on Cochlear Implants and Other Implantable Auditory Technologies*, Baltimore, MD, USA, May 3-5, 2012.
154. Wilson BS, Lorens A, Piotrowska, Skarzynski H: Evaluation of the relative benefits of cochlear implantation according to the level of residual hearing. *Scientific Congress in Celebration of the Grand Opening of the World Hearing Center*, Kajetany, Poland, May 10-11, 2012. (This talk was presented by Artur Lorens.)
155. Wilson BS: Cochlear implants: matching the prosthesis to the brain and facilitating desired plastic changes in brain function. One-day meeting on *Brain Centric Considerations for Cochlear Implantation*, Dallas, TX, USA, August 27, 2012.

156. Wilson BS: Design and engineering aspects of cochlear implants. Invited lecture for Duke University course BME 515 on Neural Prosthetic Systems, Pratt School of Engineering, October 30, 2012.
157. Wilson BS (moderator), Nicoletti M, Schatzer R, Visser D, Zirn S, Hemmert W, Nopp P, Stohl J: Round Table discussion on “Challenges in cochlear implants today.” *2nd Munich Hearing Implant Symposium: Hearing Implants Around the World*, Ludwig-Maximilians-Universität München, Munich, Germany, December 6-9, 2012.
158. Wilson BS: Brain centric approaches for the design, fitting, and application of cochlear implants. Guest Address at the *Annual Conference of the British Cochlear Implant Group*, on “The Hearing Brain,” Ayrshire, Scotland, March 21-22, 2013.
159. Wilson BS: Acceptance remarks. *Awards Luncheon for the 2013 Lasker Awards*, New York, NY, September 20, 2013. (This speech is posted at http://www.laskerfoundation.org/awards/2013_c_accept_wilson.htm.)
160. Wilson BS: Importance of the hearing brain in cochlear implant designs and outcomes. *Brain Plasticity and Cochlear Implant Use 2013 Workshop*, New York University School of Medicine, NYU Langone Medical Center, New York, NY, USA, September 23, 2013.
161. Wilson BS: Future possibilities for combined electric and acoustic stimulation. *Hearing Preservation Workshop XII*, Heidelberg, Germany, October 10-13, 2013.
162. Wilson BS: Getting a decent, but sparse, signal to the brain of cochlear implant patients. *Workshop on Neural Imaging: From the Cochlea to the Cortex*, Arizona State University, Tempe, AZ, USA, November 4, 2013.
163. Wilson BS: Importance of the hearing brain in cochlear implant designs and outcomes. Seminar presentation at the UCL Ear Institute, University College London, London, UK, December 10, 2013.
164. Wilson BS: The development of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. Seminar presentation at the Instituto de Neurociencias de Castilla y León, University of Salamanca, Salamanca, Spain, December 16, 2013.
165. Wilson BS: Evaluation of the relative benefits of cochlear implantation according to the level of residual hearing. *Conference on Hearing Implants for Older Adults*, New York, NY, USA, January 16-18, 2014.
166. Wilson BS: Cochlear implants: Matching the prosthesis to the brain and facilitating desired plastic changes in brain function. Seminar presentation for the Department of Biomedical Engineering and the Center for Hearing and Balance, Johns Hopkins University, Baltimore, MD, USA, February 5, 2014.
167. Wilson BS, Stohl JS: A simple but fast and useful model of the electrically stimulated auditory periphery. *Bernstein Sparks Workshop on Modeling and Signal Processing for Auditory Implants*, held in conjunction with the *13th International Conference on Cochlear Implants and Other Implantable Auditory Prostheses*, Munich, Germany, June 20, 2014.
168. Wilson BS: Cochlear implants – A remarkable past and a brilliant future. *Berufsverband cochlear implants & hearing implants – Compact, structured session & round table (*program only provided in German)*, held in conjunction with the *13th International Conference on Cochlear Implants and Other Implantable Auditory Prostheses*, Munich, Germany, June 21, 2014.
169. Wilson BS: Thinking about the hearing brain in designs and applications of cochlear implants. Ludwig Maximilians Universität, Munich, Germany, June 23, 2014.

170. Wilson BS: Cochlear implants: One of the great success stories in modern medicine. *Cochlear Implants and Deafness: Symposium in Honor of Ingeborg Hochmair-Desoyer*, Vienna, Austria, September 19, 2014. (The *Symposium* was a part of the celebration for the award of the 2014 Wittgenstein Preis to Dr. Hochmair-Desoyer.)
171. Wilson BS: Design and engineering aspects of cochlear implants. Invited lecture for Duke University course BME 515 on Neural Prosthetic Systems, Pratt School of Engineering, October 28, 2014.
172. Wilson BS, Pätzold J: Cochlear implants, music, and the hearing brain. Invited lecture for Duke University course NEUROSCI 290-01/MUSIC 290-01, "Music and the Brain," February 5, 2015.
173. Wilson BS: Possible ways forward for hearing prostheses. Medizinische Hochschule Hannover, Hannover, Germany, March 23, 2015.
174. Gantz B (moderator), Hochmair I, Wilson BS, Dowell R, Zeng F-G: Round Table Discussion on "Recent challenges in cochlear implantation." *10th Asia Pacific Symposium on Cochlear Implants and Related Sciences*, Beijing, China, April 30 through May 3, 2015.
175. Wilson BS (moderator), Büchner A, Landsberger D, Yuen K, Zeng F-G: Round Table Discussion on "New directions in sound coding and pre-processing strategies." *10th Asia Pacific Symposium on Cochlear Implants and Related Sciences*, Beijing, China, April 30 through May 3, 2015.
176. Wilson BS: Combined EAS – One of Prof. von Ilberg's many gifts to humanity. *Symposium in Honor of Prof. Dr. Christoph von Ilberg on the Occasion of his 80th Birthday*, J. W. Goethe Universität, Frankfurt, Germany, May 8, 2015.
177. Wilson BS: Acceptance remarks on the occasion of receiving an honorary doctorate in medicine from the University of Salamanca. University of Salamanca, Salamanca, Spain, May 11, 2015. (The remarks are posted at [http://saladeprensa.usal.es/webusal/files/Discurso%20Blake%20S.%20Wilson%20-%20Honoris%20Causa%20Blake%20S.%20Wilson%20\(ingl%C3%A9s\).pdf](http://saladeprensa.usal.es/webusal/files/Discurso%20Blake%20S.%20Wilson%20-%20Honoris%20Causa%20Blake%20S.%20Wilson%20(ingl%C3%A9s).pdf).)
178. Wilson BS: The punctuation mark in an equilibrium state: modern signal processing. Special session on cochlear implants sponsored by the Committees on Psychological and Physiological Acoustics, Biomedical Acoustics, Speech Communication, and Signal Processing in Acoustics, *Annual Spring Meeting of the Acoustical Society of America*, Pittsburgh, PA, USA, May 18-22, 2015.
179. Wilson BS: Possibilities for narrowing the remaining gaps between prosthetic and normal hearing. University of Texas at Dallas, Dallas, TX, USA, May 26, 2015.
180. Lopez-Poveda EA, Eustaquio-Martin A, Stohl JS, Wolford RD, Schatzer R, Wilson BS: Mimicking the unmasking benefits of the contralateral medial olivocochlear reflex with cochlear implants. *2015 Conference on Implantable Auditory Prostheses*, Tahoe City, CA, USA, July 12-17, 2015.
181. Cerf VG (moderator), Pisoni DB, Wilson BS, Zeng F-G: Special Synergy Session on "Hearing restoration and neuroscience: how hearing affects thought and how the brain perceives sound." *CI 2015 Conference – American Cochlear Implant Alliance*, Washington DC, USA, October 15-17, 2015.

Chaired Conferences

1. Wilson BS (Chair): *1991 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, June 2-7, 1991.

2. Wilson BS (Chair): *Mini Symposium on Cochlear Implants*, Research Triangle Park, NC, USA, February 7, 2000. (This symposium included three international speakers and one speaker from the RTI/Duke team.)
3. Miyamoto RT, Wilson BS (Co-Chairs): *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, USA, November 8-10, 2002.
4. Roland PS, Wilson BS (Co-Chairs): *Third Hearing Preservation Workshop*, Dallas, TX, USA, October 15-16, 2004.
5. Wilson BS, Dorman MF (Co-Chairs): *Hearing Preservation Workshop V*, Research Triangle Park, NC, USA, October 13-14, 2006.
6. von Ilberg C, Wilson BS (Co-Chairs): *Presbycusis Research Meeting*, Munich, Germany, January 12-14, 2012.

Chaired Track

1. Wilson BS, Kim SJ (Co-Chairs): Track on Neural Systems and Engineering, *World Congress on Medical Physics and Biomedical Engineering 2006*, Seoul, Korea, August 27 through September 1, 2006 (see <http://www.wc2006-seoul.org/index.htm>). Professor Kim is the Director of the Nano-Bioelectronics and Systems Research Center at Seoul National University in Seoul, Korea. The Neural Systems and Engineering track included seven sessions: (1) Neural Networks and Brain-Computer Interfaces; (2) Invited Talk I, on "Cochlear implants: A remarkable past and a brilliant future;" (3) Auditory Prosthesis; (4) Invited Talk II, on "The optic nerve visual prosthesis;" (5) Visual Prosthesis; (6) Neural Signal Processing; and (7) a poster session.

Chaired Sessions

1. Wilson BS (Chair): Session on "Cardiovascular Fluid Dynamics." *2nd Mid-Atlantic Conference on Bio-Fluid Mechanics*, Blacksburg, VA, USA, April, 1980.
2. Wilson BS (Discussion Leader): *Gordon Research Conference on Implantable Auditory Prostheses*, Tilton, NH, USA, August 19-23, 1985.
3. Wilson BS (Moderator), Dent LJ, Dillier N, Eddington DK, Hochmair-Desoyer IJ, Pfingst BE, Patrick J, Sürth W, Walliker J (Panelists): Round table discussion on speech coding. *International Cochlear Implant Symposium 1987*, Düren, Germany, September 7-11, 1987.
4. Wilson BS (Moderator): Session on "Speech Processing." *Second International Cochlear Implant Symposium*, Iowa City, IA, USA, June 4-8, 1990.
5. Wilson BS (Chair): Session on "Audiological Assessment and Device Programming." *First European Symposium on Paediatric Cochlear Implantation*, Nottingham, England, September 24-27, 1992.
6. Wilson BS, Dillier N (Co-Chairs): Session on "Speech Coding." *Third International Cochlear Implant Conference*, Innsbruck, Austria, April 4-7, 1993.
7. Wilson BS (Chair), Cazals Y, Dillier N, MacLeod P, McDermott H, Pelizzone M (Panelists): Round Table on "Sound Signal Processing." *IIIrd International Congress on Cochlear Implant*, Paris, France, April 27-29, 1995.
8. Wilson BS (Chair): Focus group on "Speech Processing." *1995 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, August 20-24, 1995.
9. Wilson BS (Chair): Session on "Basic Science and Technical Aspects." *Third European Symposium on Paediatric Cochlear Implantation*, Hannover, Germany, June 6-8, 1996.

10. Wilson BS (Discussion Leader), Böex-Spano C (Discussion Co-Leader), Svirsky M (Discussion Co-Leader): Focus group on “Issues in Speech Processor Design.” *1997 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, August 17-21, 1997.
11. 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, USA, November 8-10, 2002.
12. 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.
13. 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.
14. 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.)
15. Wilson BS (Chair): Session on "Clinical Issues." *Hearing Preservation Workshop II*, Frankfurt, Germany, October 17-18, 2003.
16. Wilson BS, Talavage TM (Co-Chairs): Session 2C. *Eighth International Cochlear Implant Conference*, Indianapolis, IN, USA, May 10-13, 2004.
17. Wilson BS (Chair): Session on "Neural Enhancement." *Hearing Preservation Workshop III*, Dallas, TX, USA, October 15-16, 2004.
18. Wilson BS (Moderator): Session on “Signal Processing and Speech in Noise.” *2005 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, USA, July 30 to August 4, 2005.
19. Wilson BS (Chair): Session on “Hearing Preservation, Partial Deafness Cochlear Implantation, and EAS.” *Hearing Preservation Workshop IV*, Warsaw-Kajetany, Poland, October 14-15, 2005.
20. Wilson BS (Chair): Session NP1: Auditory Prosthesis. *World Congress on Medical Physics and Biomedical Engineering 2006*, Seoul, Korea, August 27 through September 1, 2006.
21. Wilson BS (Co-Chair with R Schatzer): Session on “Speech Processing – Temporal Coding, Preprocessing, and New Designs.” *11th International Conference on Cochlear Implants in Children*, Charlotte, NC, USA, April 11-14, 2007.
22. Wilson BS (Co-Chair with R Schatzer): Session on “Speech Processing – Current Steering.” *11th International Conference on Cochlear Implants in Children*, Charlotte, NC, USA, April 11-14, 2007.
23. Wilson BS: Session on “Novel Stimulation and Signal Processing Strategies and Modeling.” *2007 Conference on Implantable Auditory Prostheses*, Lake Tahoe, NV, USA, July 15-20, 2007.
24. Wilson BS: Session on “Electric Acoustic Stimulation.” *Hearing Preservation Workshop VI*, Antwerp, Belgium, October 19-20, 2007.
25. Wilson BS (First Chair), Vermeire K: Session on “Coding Strategies 1.” *9th European Symposium on Paediatric Cochlear Implantation*, Warsaw, Poland, May 14-17, 2009.

26. Wilson BS (First Chair), von Ilberg Ch: Session on “Results of Electric Acoustic Stimulation.” *9th European Symposium on Paediatric Cochlear Implantation*, Warsaw, Poland, May 14-17, 2009.
27. Wilson BS: Afternoon session for Friday, February 26. Duke Institute for Brain Sciences workshop on *Listening with the Brain: New Approaches to Optimizing the Effectiveness of Cochlear Prosthetics*, Duke University, Durham, NC, USA, February 26-27, 2010.
28. Wouters J, Wilson BS: Second session on “Coding Strategies and Electrode Designs.” *11th International Conference on Cochlear Implants and Other Auditory Implantable Technologies*, Stockholm, Sweden, June 30 through July 3, 2010.
29. Wilson BS: Chairman for the invited lecture by Prof. Marco Pelizzone, “Beyond cochlear implants: vestibular and retinal implants. *10th European Symposium on Paediatric Cochlear Implantation*, Athens, Greece, May 12-15, 2011.
30. Coninx F, Lorens A, Wilson B, McPherson D: Special session on “International collaboration projects – 15th Anniversary of the Institute of Physiology and Pathology of Hearing,” *10th European Federation of Audiology Societies (EFAS) Congress*, Warsaw, Poland, June 22-25, 2011.
31. Wilson BS: Chairman of the session on “Outcomes Assessments,” *10th Hearing Preservation Workshop*, London, UK, October 13-16, 2011.
32. Wilson BS: Chairman of the session on “Physiological Assessment – from Periphery to Cortex,” *Hearing Preservation Workshop*, Toronto, Canada, October 18-20, 2012.
33. Wilson BS: Chairman of the session on “Outcome prediction and improvement,” *Hearing Preservation Workshop XII*, Heidelberg, Germany, October 10-13, 2013.
34. Wilson BS, Helms J: Chairpersons for the Round Table on “Cochlear implants: A remarkable past and a brilliant future – The past presidents panel,” *13th International Conference on Cochlear Implants and Other Implantable Auditory Prostheses*, Munich, Germany, June 19-21, 2014.
35. Visser D, Wilson BS: Chairpersons for the keynote session on “Binaural hearing,” *13th International Conference on Cochlear Implants and Other Implantable Auditory Prostheses*, Munich, Germany, June 19-21, 2014.
36. Wilson BS: Chairman of the session on “Perception and Performance in the APEX,” *Conference on the APEX of the Cochlea – From Neuroanatomy to Electrical Stimulation*, Chapel Hill, NC, USA, September 4-7, 2014.
37. Wilson BS, Dorman MF: Celebration of the modern cochlear implant and the first substantial restoration of a human sense using a medical intervention. Special sessions sponsored by the Committees on Psychological and Physiological Acoustics, Biomedical Acoustics, Speech Communication, and Signal Processing in Acoustics, *Annual Spring Meeting of the Acoustical Society of America*, Pittsburgh, PA, USA, May 18-22, 2015.
38. Wilson BS: Moderator for Session 3: “Outcome prediction and improvement,” *14th Hearing and Structure Preservation Workshop*, Nashville, TN, USA, October 8-11, 2015.
39. Wilson BS: Moderator for Session 6: “Assessment – From cortex to periphery,” *14th Hearing and Structure Preservation Workshop*, Nashville, TN, USA, October 8-11, 2015.