Published in final edited form as:

J Am Acad Audiol. 2012 June ; 23(6): 438–445. doi:10.3766/jaaa.23.6.6.

Cochlear Implantation Updates: The Dallas Cochlear Implant Program

Emily A. Tobey^{1,2}, Lana Britt¹, Ann Geers^{1,2}, Philip Loizou^{1,3}, Betty Loy^{2,4}, Peter Roland^{1,2}, Andrea Warner-Czyz^{1,2}, and Charles G. Wright^{1,2}

¹Dallas Cochlear Implant Program, Callier Advanced Hearing Research Center, University of Texas at Dallas, Dallas, TX

²Dallas Cochlear Implant Program, Department of Otolaryngology—Head and Neck Surgery, University of Texas Southwestern Medical Center

³Dallas Cochlear Implant Program, Department of Electrical Engineering, University of Texas at Dallas, Dallas, TX

⁴Dallas Cochlear Implant Program, Children's Medical Center of Dallas, Dallas, TX

Abstract

This report provides an overview of many research projects conducted by the Dallas Cochlear Implant Program, a joint enterprise between The University of Texas at Dallas, The University of Texas Southwestern Medical Center and Children's Medical Center. The studies extend our knowledge of factors influencing communication outcomes in users of cochlear implants. Multiple designs and statistical techniques are used in the studies described including both cross sectional and longitudinal analyses. Sample sizes vary across the studies and many of the samples represent large populations of children from North America. Multiple statistical techniques are used by the team to analyze outcomes. The team has provided critical information regarding electrode placement, signal processing, and communication outcomes in users of cochlear implants.

Keywords

Cochlear implants; pediatrics; adolescents; speech. Language; quality of life

INTRODUCTION

The Dallas Cochlear Implant Program (DCIP) represents a joint enterprise between The University of Texas at Dallas (UT Dallas), The University of Texas Southwestern Medical Center (UT Southwestern Medical Center) and Children's Medical Center. DCIP provides clinical services to both adult and pediatric cochlear implant recipients and their families through the Callier Center for Communication Disorders. In addition, the DCIP provides a focal synergy for several major research endeavors associated with laboratories located in the Callier Advanced Hearing Research Center and the Department of Electrical

Engineering of UT Dallas and the Departments of Otorhinolaryngology—Head and Neck Surgery and Radiology at UT Southwestern Medical Center. In the following paragraphs, we will highlight studies conducted in the laboratory and briefly present their results.

SCIENTIFIC THRUSTS

The DCIP focuses on several broad clinical research arenas to address important questions about cochlear implantation including questions about: (a) the anatomical consequences of the insertion of a CI electrode array; (b) how to individualize signal processing to maximize performance; (c) how early speech perception influences communication performance at later ages; (d) the impact early language production has on communication development and later language production; (e) what influences the constellation of communication outcomes over time; and (f) quality of life of individuals using CIs. CIs consist of internal components, an internal receiver and electrode array which is surgically inserted into the cochlea, and three external components, a microphone, speech processor, and transmitter coil. The microphone picks up sound and transfers it to the speech processor that has software which extracts important aspects of the signal, converts it to electrical pulses of varying current which are delivered to the electrode array via the transmitter coil. Speech perception performance in these individuals is characterized by a great deal of variation, ranging from individuals who simply detect the presence of a sound to individuals who talk easily on the telephone. Likewise, speech production skills may range from a highly intelligible individual easily understood by others to individuals who rely on sign language to be understood by others.

PRESERVATION: SURGICAL CONSIDERATIONS RELATED TO ANATOMY

Success of the CI device begins with placement of the electrode array within the cochlea. Traditionally, surgeons insert the electrode array through an opening drilled in the cochlear bony wall so that the array hugs the modiolar wall to maximize contact with the spiral ganglion cells (Roland et al., 2007a; Wright and Roland, 2011). Recent work by Drs. Peter Roland, Gary Wright, and colleagues in the Anatomy Laboratory of the Department of Otolaryngology--Head and Neck Surgery at the UT Southwestern Medical Center challenges conventional surgical techniques by examining the anatomical parts vulnerable to trauma during electrode insertion. Understanding the susceptibility of cochlear anatomy to trauma is important, particularly for the conservation of residual hearing in candidates seeking combined electrical and acoustic stimulation. In spite of advancements in surgical technique and electrode design, residual hearing is lost in 10–20% of cochlear implant patients – most likely due to mechanical trauma to various intracochlear structures (i.e., modiolus, basilar membrane, soft tissues of the lateral cochlear wall and blood vessels associated with scala tympani) (Berrettini et al., 2008; O’Leary et al., 1991).

The DCIP Anatomy Laboratory uses temporal bone studies, particularly temporal bone microdissection to explore the effects of surgical techniques on vulnerability of inner ear structures. In temporal bone microdissection, tissues of the membranous labyrinth are stained with osmium after which the otic capsule bone is drilled to a thin shell and then opened in a manner that permits direct observation of the three-dimensional anatomy of the cochlea. Microdissection allows exploration of cochlear anatomy and morphology in

response to surgical implantation. Blood vessels located near an electrode's path may be injured during implantation and such vascular injuries may compromise inner ear function and contribute to loss of residual hearing (Wright et al., 2008). A series of photomicrographs is posted on the Department's internet website demonstrating the relevant vascular anatomy (<http://www.utsouthwestern.edu/utsw/cda/dept28151/files/440124.html>) (Wright and Roland, 2011). With careful choice of surgical approach and electrode design, human temporal bones studies indicate a round window insertion offers a safe and feasible means for reducing insertion trauma, thereby preserving residual hearing in patients who retain useful low frequency hearing (Roland et al., 2007b). However, some larger electrode arrays in current use may not be suitable for round window insertion (Souter et al., 2011). A human temporal bone study explored the feasibility of electrode insertion via an alternative approach utilizing the middle turn of the cochlea (Isaacson et al., 2008). Better understanding of middle turn cochleostomy will help some patients, particularly those patients who suffered hearing loss due to meningitis. In these cases, the lower portion of the cochlea may be filled with bone and dense connective tissue making conventional implantation quite challenging.

New methods of computer-assisted x-ray imaging improve implant placement, postoperative evaluation, and implant programming. We recently collaborated with investigators at Vanderbilt University, who are developing novel techniques of computer assisted x-ray imaging of electrode arrays positioned inside the inner ears of living patients, to verify the accuracy and improve the quality of these new imaging techniques via a temporal bone study (Schuman et al., 2011). In an effort to identify ways to reduce surgical trauma during cochlear implantation, we currently are also working with an Italian developer of surgical equipment on a new bone drilling device that may eventually find application in cochlear implant surgery (Pawlowski et al., 2010).

SIGNAL PROCESSING ALGORITHMS FOR DIFFERENT LISTENING SCENARIOS

Despite the many advances made in the design of novel speech coding algorithms and electrode arrays, the CI fitting process often lags behind other important developments related to the design and functioning of the devices. The current fitting approaches used by most clinicians fall along the lines of "one-size-fits-all", in that it is assumed that the initial fitting in the clinic should work equally well in all listening environments. Other than the psychophysical mapping associated with establishing threshold (T) and comfort (M) levels, the speech coding algorithms and associated parameters (e.g., compression functions, filter spacing) are fixed and are not optimized in any way by either the patient or clinician for different listening situations (e.g., quiet, music, noise) (Wolfe and Schafer, 2010). In situations where patients wear a hearing aid (HA) in one ear and an implant in the other (bimodal users) or wear two implants (bilateral users), the fitting is done separately for each implant, rather than jointly. These issues limit severely our ability to tap into the full potential of existing CI devices which are currently not customized to individual users for different listening environments.

Ongoing studies led by Dr. Philip Loizou and his team in the Electrical Engineering Department at UT Dallas address the above limitations with the use of a portable research

speech processor that allows users to: (a) change the programming (MAP) parameters based on different outcome measures, (b) customize the MAP to different listening situations for maximum benefit, and (c) collect feedback and recordings of real acoustic signals for further analysis. Unilateral, bilateral and bimodal users are participating in double-blinded field trials to assess the benefit of a speech processor that can be easily customized by the users to fit their needs (Loizou and Kim, 2011). These studies are conducted in collaboration with Arizona State University (Dr. Michael Dorman) and University of Wisconsin-Madison (Dr. Ruth Litovsky).

A portable research processor, based on a Personal Digital Assistant (PDA) mobile device, was developed under an National Institute of Deafness and Other Communication Disorders contract (Lobo et al., 2007). This PDA processor allows researchers to program their own speech coding algorithm using a high-level programming language (C/C++) and give it to the patients to take home for field trials. The PDA processor was designed with research flexibility and has a number of features which are not available in commercial processors. These features allow the user to make changes (on the fly) to a select number of parameters (e.g., stimulation rate, compression) of speech coding algorithms. It also allows users to record real-world signals and brings the signals to the lab for further analysis. The PDA processor provides software flexibility to researchers in terms of programming and testing new algorithms quickly by allowing users to record/log comments and feedback regarding how their clinical or research MAPs work in the real world. In brief, the PDA processor allows the users to customize, and perhaps optimize the MAP parameters to their listening preferences. An Investigational Device Exemption (IDE) application has been submitted to Food and Drug Administration seeking approval of the PDA processor for research studies.

Many factors contribute to the difficulty of enhancing speech intelligibility for CI users. Some of these factors include the mathematical processing of the intended signal relative to the processing of background noise. It is important to accurately estimate and sample the background noise but such noise changes. Speech intelligibility improves in situations where the background noise remains stable, such as in a car, but is less successful when the background changes over time (Hu and Loizou, 2010a). Distortions also occur when the intended and estimated signals differ. If the differences are positive, the spectral difference denotes an attenuation distortion. If the spectral differences are negative, the difference denotes an amplification distortion (Loizou and Kim, 2011). Algorithms that improve overall speech quality (Hu and Loizou, 2010b) do not necessarily improve speech intelligibility (Loizou and Kim, 2011). Sophisticated modeling, in conjunction with the adaptable PDA platform, will help guide important changes to the mathematical considerations underlying the processing of signals for individuals who have difficulty hearing in background noise.

INFANT PROCESSING OF COCHLEAR IMPLANT SIGNALS

Acoustic simulations of cochlear implant signals provide a sophisticated research tool for assessing how the mathematically processed signals of CIs are perceived by typical hearing individuals. Simulation studies usually use adult listeners to estimate how well they perceive signals processed in different ways (Dorman et al., 1998; Dorman et al., 1997), although a

few studies have investigated teenagers and older children with typical hearing (Dorman et al., 2000; Eisenberg et al., 2000). The DCIP's Spectral Resolution in Infant Testing (SPRITE) study uses signal processing and visual habituation techniques to assess how infants with typical hearing discriminate spectrally degraded signals. Typically hearing preschool and school-aged children need more spectral information than adults to recognize simulated signals with reduced spectral content accurately (Dorman et al., 2000; Dorman et al., 1997; Eisenberg et al., 2002; Eisenberg et al., 2000; Shannon et al., 2004; Shannon et al., 1995). It is important to also assess how infants with typical hearing respond to the spectrally reduced signals associated with acoustic simulations children less than 18 months comprise nearly 25% of current CI recipients in the United States. Simulations allow an estimate of how much and what type of information a baby might need in order to improve their speech perception.

Dr. Andrea Warner-Czyz uses a visual habituation paradigm to assess vowel discrimination of CI-simulated, spectrally degraded signals in 6-month-old infants with typical hearing. Stimuli include spectrally distinct consonant-vowel syllables with vowels that differ on vowel height and front-back position; thus, providing a maximally distinct acoustic difference between stimuli. Vowel presentation occurred in one of three listening conditions: unprocessed speech, 32 spectral channels, or 16 spectral channels. The latter two conditions simulate a cochlear implant using spectral reduction techniques. Infants are habituated to one syllable then presented a series of test trials of both familiar and novel syllables. Difference in mean looking time to novel vs. familiar stimuli is calculated as a surrogate indicator of discrimination. Longer looking time during novel stimulus trials suggests discrimination of the speech contrast; No difference in looking times suggests no discrimination; and longer looking times during familiar stimulus trials implies the signal might be too complex to be processed completely.

Infants in each listening condition habituated to the initial stimulus in approximately the same number of trials. Six-month-old infants with typical hearing look longer during novel stimulus trials involving unprocessed speech or speech simulated with 32 spectral channels, but infants did not look longer for stimuli processed into 16 spectral channels. When viewed in terms of stimuli "complexity," these results indicate that 6-month-old infants may perceive the 32-channel stimuli as similar enough to unprocessed speech to produce a preference for the novel stimuli, but the 16-channel stimuli require additional processing time to overcome the further spectral reductions in the signal. Thus, typical hearing infants need more spectral information than pre-school and school-aged children to process and accurately discriminate some speech contrasts. These data further suggest young babies with sensorineural hearing losses who use CIs may need more spectral information than current CI processors provide in order to be equivalently accurate as older children.

INFLEUENCE OF AGE AT IMPLANTATION ON SPEECH AND LANGUAGE

Early performance and intervention appears to have substantial, long-term impact on children using cochlear implants. One of the difficulties in carefully examining the impact of early intervention of cochlear implants on communication performance, however, is the need to separate out contributions due to age of implantation versus duration of experience

using an implant (Geers et al., 2011; Nicholas and Geers, 2007; Nicholas and Geers, 2008). Children implanted earlier also have longer exposure of processed sound during proposed critical or sensitive periods. Several large studies are on-going examining these issues.

Ann Geers, Emily Tobey and their colleague, Johanna Nicholas at Washington University Medical Center, evaluate language, sound production and speech intelligibility in CI children at three specific chronologic ages (3.5, 4.5 and 8.5 years) in four cohorts of children implanted between 6 and 12 months, 12-to-18 months, 18-to-24 months, and 24-to-30 months. The design of this study permitted separate examination of the effects of age at implant and duration of implant experience on language outcome. Children were administered a test battery at 3.5 and 4.5 years of age that included language sampling, parent ratings and formal language testing (Geers et al., 2007; Nicholas and Geers, 2007; Nicholas and Geers, 2008). Preliminary findings revealed a substantial age-of-implantation effect existed, evidenced by higher accuracy in children implanted at the youngest ages relative to children implanted at later ages. While language scores increased with each month of cochlear implant experience regardless of age implanted, there was an added benefit to spoken language of receiving an equivalent amount of implant experience at a very young age (12-to-18 months) compared with even a few months later (24–30 months). Children implanted at younger ages demonstrate a greater change over time within a year than children implanted at later ages. Better aided hearing levels prior to cochlear implantation were associated with better language outcomes and removing variance due to pre-implant hearing served to enhance the effect of implant age on language scores. Age at implant predicted 20% of the variance in language scores a year later even after the effects of duration of implant use had been removed. When results were compared on a range of language measures, similar findings were observed on a parent report measure, a global language measure and on a receptive vocabulary test. Children in auditory-oral education settings who received a CI by about 20 months of age could be expected to score within the average range for hearing age-mates before entering kindergarten (i.e., age 4.5 years).

Sixty of these children returned for follow-up testing in elementary grades when their average age was 10 years. A comparison of language test scores at 4.5 and 10 years of age indicated a narrowing of the language gap compared to hearing age-mates. The average standard score for vocabulary increased from 84 to 96 and for global language skills from 78 to 89 (the normative average is 100 with a standard deviation of 15). Thus, the group average improved from below average in preschool to within the average range for hearing age-mates during elementary grades. Children who received a second implant between 4 and 10 years of age exhibited better speech perception in noise and faster growth of expressive language skills than those children who continued using a single device, suggesting that bilateral implantation may be beneficial even when it occurs several years after the initial cochlear implantation.

In yet another study evaluating the impact of implantation age on communication development, Tobey and colleagues at the House Research Institute, The John Hopkins School of Medicine, University of Miami, University of Michigan, and University of North Carolina are carefully monitoring the longitudinal development of In 285 children with CIs or typical hearing and their families on several communication measures. Data to date

indicate children undergoing cochlear implantation showed greater improvement in spoken language performance than predicted by their pre-implantation baseline scores; however, mean scores were not restored to age-appropriate levels after 3 years (Lin et al., 2008; Markman et al., 2011; Niparko et al., 2010). Younger ages at cochlear implantation were associated with significantly steeper rate increases in global language comprehension and expression measures. Age of implantation appeared to be impacted by how long a child experienced a hearing loss with and without amplification, in addition, to how long a child may have experienced a period of normal hearing. Shorter histories of hearing deficit were associated with steeper rates of increase in language comprehension and expression. Greater amounts of residual hearing prior to cochlear implantation, higher ratings of parent-child interactions, and higher socioeconomic status also were associated with greater rates of improvement in comprehension and expression.

LANGUAGE DEVELOPMENT IN PRIMARY SCHOOL-AGED CHILDREN

Geers and her colleagues at the Moog Center for Deaf Education and Washington University Medical School also studied language outcomes in 5- and 6-year-old children who used a CI for at least one year (Geers et al., 2009; Hayes et al., 2009; Moog and Geers, 2010).

Children were recruited from 39 different oral education settings across the United States and administered tests of vocabulary (receptive and expressive), verbal intelligence and global language skills (receptive and expressive) to determine the factors most associated with language outcomes in pediatric CI users. Students with higher nonverbal intelligence, younger ages at implantation and more highly educated parents scored higher on all language measures. Regression analysis was applied to examine the effect of implant age on each language outcome after controlling for the effects of intelligence and parent education. Children who received a CI as late as 4 years of age reached normal levels of expressive vocabulary by kindergarten. Children needed to receive an implant by 2.5 years for their expected receptive vocabulary score to fall in the normal range and by 2.0 years for their verbal intelligence quotient to fall within in normal limits by kindergarten. Achieving expected normal global language scores required even younger ages at implant: 1.5 years for receptive language and 1.0 years for expressive language.

The type of early intervention received at 1, 2, 3 and 4 years of age also influenced language outcomes at 5 and 6 years of age. The type of intervention provided at 1 and 2 years of age significantly impacted language scores at kindergarten age. Children who received a combination of a cochlear implant and parent-infant intervention at age one had significantly higher language scores at age 5 or 6 years than children who were implanted and received intervention later. Higher language scores in kindergarten were observed in children placed in an oral nursery school class with other deaf children at age 2, compared to those who remained in individual parent-infant therapy or a mainstream nursery class with hearing preschoolers. These results favor providing a cochlear implant by age 1 year and supplementing early parent-infant intervention with a nursery school experience designed specifically for developing spoken language in children with hearing loss by age 2 years.

LONG-TERM OUTCOMES ASSOCIATED WITH ADOLESCENT USERS

Geers, Tobey and their colleagues recently completed a follow-up study of children who received a cochlear implant between 1990 and 1996 when they were between 2 and 5 years old. The 112 participants in the recent study represent a large portion (62%) of the 181 children with prelingual profound deafness who were tested at 8 or 9 years of age (Geers et al., 2003). The 181 children were among the first to receive CIs following Food and Drug Administration approval of multichannel devices and were drawn from the most common educational environments available in North America, including both public and private schools, both special education and mainstream classrooms, and both oral communication modes and modes of communication augmented with signed language. The study was initiated to learn whether language and reading skills, which were close to age-mates with normal hearing in elementary grades, kept pace with normal development or fell further behind hearing peers by their high school years. In addition, speech intelligibility was explored in adolescence for the first time in teenagers using CIs

Results from the original study of 181 8- and 9-year-old children revealed that more than half of the children performed similarly to hearing peers on measures of verbal reasoning and narrative ability and produced language samples with age-appropriate utterance length and lexical diversity. However, only about a third of the sample scored normally on measures of syntax. Significant predictors of higher language scores included greater nonverbal intelligence, smaller family size, higher family income/education and female gender. After the variance due to these variables was controlled, rehabilitative factors predicting significant added variance in linguistic outcome were amount of mainstream class placement and educational emphasis on speech and listening skills. An oral educational focus provided a significant advantage over speech and sign together for developing language skills in many of the children.

One hundred twelve of these children returned for follow-up testing when they were in high school between the ages of 15 – 18 years (Geers and Sedey, 2011; Geers et al., 2011). Comparison of language scores obtained in high school with those documented in elementary grades confirmed that these children were catching up with hearing age mates in language as they progressed through the academic grades. About 70% of the adolescents scored within one standard deviation of the normative sample on tests of language and verbal reasoning. More than half of the sample achieved language and reading scores that were age-appropriate for hearing teenagers. Better scores were associated with a shorter duration of deafness before receiving a CI (roughly corresponding to younger age at implant), higher nonverbal intelligence and higher family income/education. Once the influence of these factors was removed from the analysis, language outcomes were associated with cognitive variables, including better working memory (i.e., digit span) and faster verbal rehearsal speed (i.e., sentence repetition rate). Speech intelligibility appeared strongly associated with exposure to environments where speaking and listening were included as integral pieces of the therapeutic regime (Fink et al., 2007; Tobey et al., 2011a; Tobey et al., 2011b). Students who relied on sign to improve their vocabulary comprehension typically exhibited poorer English language outcomes than children whose spoken language comprehension paralleled or exceeded their comprehension of speech +

sign. The majority of teenagers (85%) were placed in the appropriate grade for their age. 95% of the teenagers were mainstreamed for more than half of the school day. The best performers in elementary grades continue to exhibit the best outcomes in high school.

These results indicate that the advantage provided to children with the shortest period of auditory deprivation before receiving a (i.e. younger age at implant) is long lasting and continues to influence the level of language skill exhibited 10 or 15 years later. Furthermore these results reveal the importance of speed and efficiency of phonological processing as explanatory constructs underlying the development of language. Early educational emphasis on listening and spoken language appears to affect later language by facilitating the development of phonological processing skills (Geers et al., 2011).

QUALITY OF LIFE IN CHILDREN WHO USE COCHLEAR IMPLANTS

The DCIP is challenging conventional wisdom by viewing quality of life from the perspective of not only the parent, but also the pediatric cochlear implant user. First, the DCIP group has included both parent proxy report and child self-report of the child's health-related quality of life (HRQoL) to afford a clearer picture of the child's state. Second, DCIP researchers have assessed both generic domains and CI-specific issues. The DCIP's investigation of HRQoL in 138 pediatric CI users between 4 and 16 years of age has resulted in a series of manuscripts featuring the child's personal perspective on quality of life from both a generic and CI-specific point of view. We assessed generic quality of life with the KINDL^R, an established measure with three versions to address developmental changes in children between 4 and 16 years. Findings on quality of life issues specific to CI come from a preliminary version of a CI-specific instrument. Preschoolers (4- to 7-year-old children) using CI rate overall generic quality of life significantly more positively than their parents and on par with typically hearing peers (Warner-Czyz et al., 2009). Children between 8 and 16 years of age rate overall quality of life similarly to typically hearing peers and parents (Loy et al., 2010). Children and adolescents (8- to 16-year-olds) rate the psychosocial domains of self-esteem, school, and friends less positively than family, physical well-being, or emotional well-being - similar to reports by other researchers. CI users between 8 and 11 years scored the family domain less positively than normal-hearing peers. CI users between 12 and 16 years scored the school domain lower compared with their parents. Chronologic age of the CI users impacts ratings of quality of life. Younger children (4-7 years) rate generic quality of life significantly more positively than older children (8-16 years). Preschool users also rate CI-specific items on friends and self-image more positively than older groups, but report greater difficulties hearing teachers at school. Adolescents (12-16 years) provide more consistent responses than younger groups on the CI-specific module (Warner-Czyz et al., 2011).

CONCLUSIONS

Multiple studies conducted by the DCIP indicate progress is made in the communication outcomes of many users of cochlear implants. The Program continues to follow children and their families as a means of further determining how communication may be enhanced. Further studies will continue to explore techniques to reduce surgical trauma in order to

preserve residual hearing. Signal processing investigations will continue to determine techniques for maximizing mapping to meet the needs of individuals listening in different environments.

Acknowledgments

This work was sponsored, in part, by the National Institutes of Health, NIDCD R01DC04797 (J. Niparko, Principal Investigator, E. Tobey, Co-Investigator); NIDCD R01 DC008335 (A. Geers, Principal Investigator, E. Tobey, Co-Investigator); NIDCD R01 DC004168 (J. Nicholas, Principal Investigator, A. Geers and E. Tobey, Co-Investigators), NIDCD R01 DC04558 (E. Tobey, Principal Investigator, P. Roland, Co-Investigator), Dana Foundation Innovations in Functional Brain Imaging (M. Devous, Principal Investigator, E. Tobey and P. Roland, Co-Investigators). Portions of this manuscript have been presented at the 13th Symposium on Cochlear Implants in Children in Chicago, Illinois (July, 2011). Funding for this project was supported in part by Grant Number 1 UL1 RR024982-01, titled, “North and Central Texas Clinical and Translational Science Initiative” (M. Packer, M.D., PI; A. Warner-Czyz, Clinical Research Scholar) from the National Center for Research Resources (NCRR), a component of the National Institutes of Health (NIH), and NIH Roadmap for Medical Research; Clinical and Translational Science Pilot Grant Award entitled “Effects of reduced spectral resolution on speech discrimination in hearing infants” from the North and Central Texas Clinical and Translational Science Initiative (A. Warner-Czyz, PI) and the American Academy of Audiology Foundation New Investigator’s Award, “Effect of Reduced Spectral Resolution on Vowel Discrimination in Infants with Normal Hearing Infants.” (A. Warner-Czyz, PI).

Abbreviations

DCIP	Dallas Cochlear Implant Program
UT Dallas	The University of Texas at Dallas
UT Southwestern Medical Center	The University of Texas Southwestern Medical Center
CI	Cochlear Implant
T	Threshold
M	Comfort
HA	Hearing Aid
MAP	Programming parameters
PDA	Personal Digital Assistant
IDE	Investigational Device Exemption
SPRITE	Spectral Resolution in Infant Testing

References Cited

- Berrettini S, Forli F, Passetti S. Preservation of residual hearing following cochlear implantation: comparison between three surgical techniques. *J Laryngol Otol*. 2008; 122(3):246–252. [PubMed: 17666134]
- Dorman MF, Loizou PC, Fitzke J, Tu Z. The recognition of sentences in noise by normal-hearing listeners using simulations of cochlear-implant signal processors with 6–20 channels. *J Acoust Soc Am*. 1998; 104(6):3583–3585. [PubMed: 9857516]
- Dorman MF, Loizou PC, Kemp LL, Kirk KI. Word recognition by children listening to speech processed into a small number of channels: data from normal-hearing children and children with cochlear implants. *Ear Hear*. 2000; 21(6):590–596. [PubMed: 11132785]

- Dorman MF, Loizou PC, Rainey D. Speech intelligibility as a function of the number of channels of stimulation for signal processors using sine-wave and noise-band outputs. *J Acoust Soc Am.* 1997; 102(4):2403–2411. [PubMed: 9348698]
- Eisenberg LS, Martinez AS, Holowecky SR, Pogorelsky S. Recognition of lexically controlled words and sentences by children with normal hearing and children with cochlear implants. *Ear Hear.* 2002; 23(5):450–462. [PubMed: 12411778]
- Eisenberg LS, Shannon RV, Martinez AS, Wygonski J, Boothroyd A. Speech recognition with reduced spectral cues as a function of age. *J Acoust Soc Am.* 2000; 107(5 Pt 1):2704–2710. [PubMed: 10830392]
- Fink NE, Wang NY, Visaya J, Niparko JK, Quittner A, Eisenberg LS, Tobey EA. Childhood Development after Cochlear Implantation (CDaCI) study: design and baseline characteristics. *Cochlear Implants Int.* 2007; 8(2):92–116. [PubMed: 17549807]
- Geers A, Sedey AL. Language and verbal reasoning skills in adolescents with 10 or more years of cochlear implant experience. *Ear and Hearing.* 2011; 32:39S–48S. [PubMed: 21832889]
- Geers A, Strube M, Tobey E, Pisoni DB, Moog J. Epilogue: factors contributing to long-term outcomes of cochlear implantation in early childhood. *Ear and Hearing.* 2011; 32:84S–92S. [PubMed: 21832892]
- Geers AE, Moog JS, Biedenstein J, Brenner C, Hayes H. Spoken language scores of children using cochlear implants compared to hearing age-mates at school entry. *J Deaf Stud Deaf Educ.* 2009; 14(3):371–385. [PubMed: 19155289]
- Geers AE, Nicholas JG, Moog JS. Estimating the Influence of Cochlear Implantation on Language Development in Children. *Audiol Med.* 2007; 5(4):262–273. [PubMed: 21243079]
- Geers AE, Nicholas JG, Sedey AL. Language skills of children with early cochlear implantation. *Ear Hear.* 2003; 24(1 Suppl):46S–58S. [PubMed: 12612480]
- Hayes H, Geers AE, Treiman R, Moog JS. Receptive vocabulary development in deaf children with cochlear implants: achievement in an intensive auditory-oral educational setting. *Ear Hear.* 2009; 30(1):128–135. [PubMed: 19125035]
- Hu Y, Loizou PC. Environment-specific noise suppression for improved speech intelligibility by cochlear implant users. *J Acoust Soc Am.* 2010a; 127(6):3689–3695. [PubMed: 20550267]
- Hu Y, Loizou PC. Environment-specific noise suppression for improved speech intelligibility by cochlear implant users. *J Acoust Soc Am.* 2010b; 127(6):3689–3695. [PubMed: 20550267]
- Isaacson B, Roland PS, Wright CG. Anatomy of the middle-turn cochleostomy. *Laryngoscope.* 2008; 118(12):2200–2204. [PubMed: 18948831]
- Lin FR, Wang NY, Fink NE, Quittner AL, Eisenberg LS, Tobey EA, Niparko JK. Assessing the use of speech and language measures in relation to parental perceptions of development after early cochlear implantation. *Otol Neurotol.* 2008; 29(2):208–213. [PubMed: 18309575]
- Lobo, A.; Loizou, P.; Kehtarnavaz, N.; Torlak, M.; Lee, H.; Sharma, A.; Gilley, P.; Peddigari, V.; Ramanna, L. A PDA-based research platform for cochlear implants: Proceedings of Third International IEEE/EMBS Conference on Neuroengineering; 2007. p. 28-31.
- Loizou P, Kim G. Reasons why Current Speech-Enhancement Algorithms do not Improve Speech Intelligibility and Suggested Solutions. *IEEE Transactions on Audio, Speech and Language Processing.* 2011; 19(1):47–56.
- Loy B, Warner-Czyz AD, Tong L, Tobey EA, Roland PS. The children speak: an examination of the quality of life of pediatric cochlear implant users. *Otolaryngol Head Neck Surg.* 2010; 142(2): 247–253. [PubMed: 20115983]
- Markman TM, Quittner AL, Eisenberg LS, Tobey EA, Thal D, Niparko JK, Wang NY. Language development after cochlear implantation: an epigenetic model. *J Neurodev Disord.* 2011; 3(4): 388–404. [PubMed: 22101809]
- Moog JS, Geers AE. Early educational placement and later language outcomes for children with cochlear implants. *Otol Neurotol.* 2010; 31(8):1315–1319. [PubMed: 20729785]
- Nicholas JG, Geers AE. Will they catch up? The role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss. *J Speech Lang Hear Res.* 2007; 50(4):1048–1062. [PubMed: 17675604]

- Nicholas JG, Geers AE. Expected test scores for preschoolers with a cochlear implant who use spoken language. *Am J Speech Lang Pathol*. 2008; 17(2):121–138. [PubMed: 18448600]
- Niparko JK, Tobey EA, Thal DJ, Eisenberg LS, Wang NY, Quittner AL, Fink NE. Spoken language development in children following cochlear implantation. *JAMA*. 2010; 303(15):1498–1506. [PubMed: 20407059]
- O’Leary MJ, Fayad J, House WF, Linthicum FH Jr. Electrode insertion trauma in cochlear implantation. *Ann Otol Rhinol Laryngol*. 1991; 100(9 Pt 1):695–699. [PubMed: 1952658]
- Pawlowski KS, Koulich E, Cuda D, Wright CG. Effects of cochlear drilling with Piezosurgery medical device in rats. *Laryngoscope*. 2010; 121:182–186. [PubMed: 21154673]
- Roland PS, Wright CG, Isaacson B. Cochlear implant electrode insertion: the round window revisited. *Laryngoscope*. 2007a; 117:1397–1402. [PubMed: 17585282]
- Roland PS, Wright CG, Isaacson B. Cochlear implant electrode insertion: the round window revisited. *Laryngoscope*. 2007b; 117(8):1397–1402. [PubMed: 17585282]
- Schuman TA, Noble JH, Wright CG. Anatomic verification of a novel method for precise interscalar localization of cochlear implant electrodes. *Laryngoscope*. 2011; 121
- Shannon RV, Fu QJ, Galvin J III. The number of spectral channels required for speech recognition depends on the difficulty of the listening situation. *Acta Otolaryngol Suppl*. 2004; (552):50–54. [PubMed: 15219048]
- Shannon RV, Zeng FG, Kamath V, Wygonski J, Ekelid M. Speech recognition with primarily temporal cues. *Science*. 1995; 270:303–304. [PubMed: 7569981]
- Souter MA, Briggs RJ, Wright CG, Roland PS. Round window insertion of precurved perimodiolar electrode arrays: how successful is it? *Otol Neurotol*. 2011; 32(1):58–63. [PubMed: 21131883]
- Tobey EA, Geers AE, Sundarajan M, Lane J. Factors Influencing Elementary and High-School Aged Cochlear Implant Users. *Ear Hear*. 2011a; 32(1):27S–38S.
- Tobey EA, Shin S, Sundarajan M, Geers AE. Spoken Word Recognition in Adolescent Cochlear Implant Users During Quiet and Multispeaker Babble Conditions. *Otol Neurotol*. 2011b
- Warner-Czyz AD, Loy B, Roland PS, Tong L, Tobey EA. Parent versus child assessment of quality of life in children using cochlear implants. *Int J Pediatr Otorhinolaryngol*. 2009; 73(10):1423–1429. [PubMed: 19674798]
- Warner-Czyz AD, Loy B, Tobey EA, Nakonezny P, Roland PS. Health-related quality of life in children and adolescents who use cochlear implants. *Int J Pediatr Otorhinolaryngol*. 2011; 75(1): 95–105. [PubMed: 21074282]
- Wolfe, J.; Schafer, E. *Programming Cochlear Implants*. San Diego, CA: Plural Publishing; 2010.
- Wright CG, Pawlowski KS, Roland PS. The vasculature of scala tympani in relation to cochlear implantation. *National Temporal Bone Registry*. 2008; 16:1–5.
- Wright, CG.; Roland, PS. *Inner Ear Anatomy and Cochlear Implantation*. 2011.

Figure 1.
Impact of chronological age on speech perception outcomes as a function of the number of spectral channels presenting signals to a cochlear implant.

Figure 2.

Discrimination of spectrally reduced vowel stimuli (/ti/-/ta/) in 6-month-old infants.

Difference in mean looking time (novel minus familiar) is shown on the y-axis. Individual infant data is shown across the x-axis. A positive difference in mean looking time indicates longer attention to the novel vs. familiar stimuli, suggesting the infant can discriminate the two sounds.