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Results in Adult Cochlear Implant Recipients with Varied Asymmetric Hearing: A Prospective Longitudinal Study of Speech Recognition, Localization and Participant Report

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Abstract

Objectives—Asymmetric hearing with severe to profound hearing loss (SPHL) in one ear and better hearing in the other requires increased listening effort and is detrimental for understanding speech in noise and sound localization. Although a cochlear implant (CI) is the only treatment that can restore hearing to an ear with SPHL, current candidacy criteria often disallows this option for patients with asymmetric hearing. The present study aimed to evaluate longitudinal performance outcomes in a relatively large group of adults with asymmetric hearing who received a CI in the poor ear.

Design—Forty-seven post-lingual adults participated. Test materials included objective and subjective measures meant to elucidate communication challenges encountered by those with asymmetric hearing. Test intervals included pre-implant, 6 and 12 months post-implant. Pre-implant testing was completed in participants' Everyday listening condition: bilateral hearing aids (HAs) n=9, better ear HA n=29, no HA n=9; post-implant, each ear was tested separately and in the bimodal condition.

Results—Group mean longitudinal results in the bimodal condition post-implant compared to the pre-implant Everyday listening condition indicated significantly improved sentence scores at soft levels and in noise, improved localization, and higher ratings of communication function by 6 months post-implant. Group mean, 6-month post-implant results were significantly better in the bimodal condition compared to either ear alone. Audibility and speech recognition for the poor ear alone improved significantly with a CI compared to pre-implant. Most participants had clinically meaningful benefit on most measures. Contributory factors reported for traditional CI candidates also impacted results for this population. In general, older participants had poorer bimodal speech recognition in noise and localization abilities than younger participants. Participants with early

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Conflicts of Interest

JBF serves on the audiology advisory boards for Advanced Bionics and Cochlear Americas and LKH serves on the audiology advisory board for Advanced Bionics.

SPHL onset had better bimodal localization than those with later SPHL onset, and participants with longer SPHL duration had poorer CI-alone speech understanding in noise but not in quiet. Better-ear pure-tone average (PTA) correlated with all speech recognition measures in the bimodal condition. To understand the impact of better-ear hearing on bimodal performance, participants were grouped by better-ear PTA: Group 1 PTA = 40 dB HL (n = 19), Group 2 PTA = 41–55 dB HL (n = 14), Group 3 PTA = 56–70 dB HL (n = 14). All groups showed bimodal benefit on speech recognition measures in quiet and in noise; however, only Group 3 obtained benefit when noise was toward the CI ear. All groups showed improved localization and ratings of perceived communication.

Conclusion—Receiving a CI for the poor ear was an effective treatment for this population. Improved audibility and speech recognition was evident by 6-months post-implant. Improvements in sound localization and self-reports of communication benefit were significant and not related to better-ear hearing. Participants with more hearing in the better ear (Group 1), showed less bimodal benefit but greater bimodal performance for speech recognition than Groups 2 and 3. Test batteries for this population should include quality-of-life measures, sound localization and adaptive speech recognition measures with spatially separated noise to capture the hearing loss deficits and treatment benefits reported by this patient population.

Introduction

Individuals who have asymmetric hearing characterized by severe to profound hearing loss (SPHL) in one ear and better hearing in the other ear are a unique and challenging patient population. Research shows that hearing asymmetry is clearly detrimental to communication and is associated with reduced sound quality and increased effort during real-life listening conditions that include noise, reverberation, multiple speakers and distance (Noble and Gatehouse 2004; Wie et al. 2010; Dwyer et al. 2014). Individuals with hearing asymmetry perform poorly on measures of sound localization and speech perception in noise compared to those with normal hearing in both ears (Slattery and Middlebrooks 1994; Rothpletz et al. 2012; Firszt et al. 2017). Results from quality of life measures also suggest negative effects of asymmetric hearing (Vermeire and Van de Heyning 2009; Arndt et al. 2011; Sladen et al. 2016) including feelings of exclusion and reduced well-being (Wie et al. 2010). These communication deficits primarily result from a lack of bilateral input, which leads to diminished or complete loss of binaural hearing advantages, such as binaural squelch to improve understanding in noise, and binaural loudness summation to improve audibility (Bronkhorst and Plomp 1988, 1989; Colburn et al. 2006).

Currently, the standard treatment options for asymmetric hearing are amplification to the poor ear, a contralateral routing of the signal (CROS/BiCROS) hearing aid (HA), or a bone-anchored hearing aid (BAHA) device. Of these, fitting the poor ear with amplification is the only option that directly treats the poor ear; however, a HA is rarely a successful or viable solution because the degree of hearing loss precludes benefit from amplification. Individuals typically cease poor-ear amplification due to lack of improved hearing, reduced or distorted sound quality, or imbalanced sound input between ears. The CROS/BiCROS and BAHA devices bypass the poor ear and attempt to improve communication by routing sound from the side with poor hearing to the better hearing ear. In doing so, improved sound awareness

may occur for sound originating on the poor hearing side, but speech understanding in noise and localization benefits are limited, because both require binaural cues (Lin et al. 2006).

Research has indicated that using a CI in one ear and a HA in the contralateral ear, referred to as bimodal hearing, can provide some binaural hearing abilities for those with asymmetric hearing. Early bimodal research focused on individuals with poor and symmetric hearing in both ears. Results demonstrated that bimodal input could assist speech perception in noise and localization compared to the CI or HA alone, and improvements in sound quality were reported by recipients (Tyler et al. 2002; Ching et al. 2004; Potts 2009). Furthermore, bimodal benefits occurred even when the non-implanted ear had substantial hearing loss and limited speech recognition (Ching et al. 2004; Kong et al. 2005; Potts et al. 2009).

Less common, but of growing interest, is bimodal benefit when individuals use a CI and contralateral HA and have considerable hearing in the non-implanted ear. Mason and Kokkinakis (2014) reported that maximum bimodal performance was associated with hearing thresholds less than 60 dB HL for low frequencies in the non-implanted ear. They investigated bimodal benefit in reverberant conditions for CI recipients whose HA ear had low frequency thresholds in the mild to moderately severe hearing loss range (i.e., more low frequency hearing than in previous studies). Participants had significantly better consonant recognition in reverberant and reverberant plus noise conditions bimodally than with the CI alone due to the availability of low-frequency cues provided by the HA. Similarly, Dorman et al. (2015) reported that participants with low-frequency hearing thresholds (average of .125, .25 and .5 kHz) less than 60 dB HL in the non-implanted ear showed greater bimodal benefit for monosyllabic words and sentences in noise than participants with low-frequency thresholds greater than 60 dB HL. Firszt et al. (2012a) investigated bimodal abilities in a group of 10 participants with large hearing asymmetry. The mean unaided pure tone average (PTA: .5, 1, 2 kHz) in the better ear was 56 dB HL and 101 dB HL in the poor ear. Participants with post-lingual onset of hearing loss showed greater improvements compared to individuals with pre-/peri-lingual onset of hearing loss when using the CI and HA together for sentences presented at a soft level, sentences in the presence of restaurant noise, and sound localization. Those with pre-/peri-lingual onset of hearing loss had limited improvement pre- to post-implant, in both the bimodal condition and the implanted ear alone, despite considerable hearing in the opposite ear. Thus, although individuals with large hearing asymmetry benefited from a CI, onset and duration of hearing loss are factors to consider in this population.

The greatest hearing asymmetry occurs for individuals with normal to near normal thresholds in one ear and SPHL in the other. The earliest studies that focused on this type of asymmetric hearing (also referred to as single-sided deafness, or SSD) provided cochlear implantation of the poor ear as treatment for incapacitating tinnitus (Van de Heyning et al. 2008). Long-term follow up of these patients (between 3 and 10 years after implantation) suggested consistent device use, tinnitus reduction, and binaural listening benefits (Mertens et al. 2017). In other reports, individuals with SSD but without debilitating tinnitus, received CIs to treat SPHL in the impaired ear. Arndt et al. (2011) evaluated three treatment options for 11 adults; CROS and BAHA (softband) devices were used, each for three weeks, followed by cochlear implantation. Six months post-implant, testing showed significant

improvements for the CI on versus off conditions, and for the CI on versus CROS or BAHA conditions for localization. Significant improvements were observed for speech in noise when speech was directed towards the poor ear and noise towards the normal hearing ear. No improvements with the CI were observed when speech and noise were both presented from the front. Importantly, the use of a CI did not disrupt speech recognition in the presence of noise towards the normal hearing ear. Sladen et al. (2016) reported on 15 CI recipients with short duration of deafness (< 24 months) and normal hearing in the contralateral ear at .25-2 kHz. By 6 months post-implant, performance with sentences from the front and restaurant noise from eight surrounding loud speakers was significantly better with the addition of the CI compared to the normal hearing ear alone. Although outcomes are promising for implantation of adults with asymmetric hearing, including those with SSD, results are limited by relatively few studies, small sample sizes and variations in test measures (van Zon et al. 2015; Cabral Junior et al. 2016). The emergent need is for additional longitudinal prospective studies with larger cohorts than previously reported incorporating both objective and subjective test measures to evaluate performance outcomes in patients with hearing asymmetry.

The current prospective, longitudinal study investigated behavioral outcomes in adults with asymmetric hearing who received a CI in the poor ear. The degree of hearing asymmetry varied based on better ear hearing, which ranged from normal hearing to moderately severe impairment. We hypothesized that use of a CI in the poor ear to restore bilateral input would remediate binaural hearing advantages as evidenced by greater post-implant bimodal performance compared to pre-implant performance and greater post-implant bimodal performance compared to either ear alone. We also expected more residual hearing in the non-implanted ear would result in better bimodal performance.

Materials and Methods

This study was approved by the Human Research Protection Office (ID#: 201012936) at Washington University School of Medicine in St. Louis (WUSM) and by the St. Luke's Midwest Ear Institute Internal Review Board in Kansas City, MO (ID#: 09-304).

Participants

Study participants included 47 adults (27 males, 20 females) with post-lingual onset of asymmetric hearing loss, i.e., one poor-hearing ear that met clinical CI candidacy criteria (moderate to profound hearing loss, 50% on open set sentences) and one better-hearing ear. All adult patients (at least 18 years of age) who initiated a CI evaluation to improve overall hearing ability, had insurance coverage, and met study inclusion criteria (poor-ear hearing criteria described above, stable better-ear hearing for at least the previous year, normal cochlear anatomy, and fluent in English) were invited to participate. In addition to those who enrolled in the study, three individuals desired a poor-ear CI but did not receive insurance approval/coverage, two decided against pursuing a CI, and two obtained a CI but declined study participation due to time constraints. As part of the clinical program, participants were seen for routine pre-operative appointments that included counseling on treatment options for asymmetric hearing loss - a CROS or BiCROS HA and osseointegrated

devices. Several participants were wearing a CROS/BiCROS HA at the time of their CI evaluation; others had tried a CROS/BiCROS in the past. Participants with no CROS/BiCROS experience were fit with the appropriate option and either listened with it in the office or took it home for a trial period. A bone conduction implant simulator (Baha Intenso™ attached to a testband) was demonstrated in the office for those with normal or near-normal hearing in the better ear. None chose to continue with these alternative options. All participants expressed a desire to have useable hearing restored to their poor ear to assist with localization and speech understanding.

Unaided, pure-tone threshold levels for the better ear and poor ear are shown for each participant in Figures 1A and 1B, respectively; group mean pure-tone thresholds are shown in black. Figures 1C and 1D show each participant's pre-implant hearing threshold levels in their Everyday listening condition for the better and poor ears, respectively. The Everyday listening condition represented participants' device use in everyday life. Nine participants used a HA in each ear, twenty-nine used a HA in the better ear only, and nine did not use amplification in either ear. In both panels, the dark gray lines represent aided, frequency modulated (FM) tone sound field threshold levels for participants who used a HA, while the light gray lines represent unaided pure-tone thresholds for the participants who did not use a HA. At the time of CI evaluation, the group mean monosyllabic word score in the better ear (38 participants using a HA, 9 unaided) was 71% (Range = 26 - 100%; SD = 20.8%) and in the poor ear (aided when possible) was 4% (Range = 0 - 23%, SD = 6.3%).

Of the 47 participants, 32 were implanted at WUSM and 15 at St. Luke's Midwest Ear Institute. Participants were implanted between 2008 and 2016 with a device from one of three implant manufacturers, Advanced Bionics LLC (Valencia, CA; n=14), Cochlear Limited (Sydney, Australia; n=28), or Med El (Vienna, Austria; n=5). In years, mean age at implant was 62.8 (Range 25 - 83, SD 14.6), mean age at onset of SPHL in the poor ear was 47.5 (Range 2 - 76, SD 18.8), mean length of deafness in the poor ear was 15.3 (Range 1 - 49, SD 13.9), and mean duration of any hearing loss in the poor ear was 25.5 (Range 1 - 58, SD 16.4). Twenty of the 47 participants reported sudden sensorineural hearing loss (SSHL) in either one (n = 17) or both ears (n = 3). The remaining 27 participants had progressive hearing loss. Etiology of hearing loss for the SPHL ear was unknown for the largest segment of participants (n = 22). Reported etiologies for the other participants included Ménière's disease (n = 6), viral infection (n = 4), genetic (n = 4), otosclerosis (n = 3), meningitis (n = 3), trauma (n = 2), radiation/chemotherapy treatment (n = 2), and middle ear disease (n = 1).

General Procedures

This is an ongoing, longitudinal study; interim results reported here include data for participants with at least 6-month post-implant data (n = 47). Twelve-month post-implant data is included for the 40 participants who completed testing at that interval. Pre-implant, all 47 participants were tested in the better-ear alone condition, 30 were tested in the poor-ear alone condition, and 30 were tested in the bilateral condition. Seventeen participants could not be tested in the poor-ear and bilateral conditions; their aided threshold levels were such that they could not detect the test stimuli. For these individuals, the poor-ear alone performance was assigned the lowest score for each test and the bilateral condition was not

assigned a score. Testing was conducted with the participants' own HAs when appropriate; otherwise, they were fit with a clinic HA. When testing the poor ear, the better ear was plugged (Howard Leight MAX foam earplugs) and muffed (Howard Leight Thunder T3 earmuff) for all but three participants. These three participants had pure-tone averages (3fPTAs; .5, 1 and 2 kHz) 10 dB HL in the better ear and reported being able to hear some sound in the better ear even when plugged and muffed. Therefore, their better ear was masked with speech spectrum noise via an insert earphone. At 6 and 12 months post-implant, testing was performed CI alone, better-ear alone (38 aided, 9 unaided), and bimodally (38 CI and HA, 9 CI and unaided better ear). Participants' preferred, daily-use HA settings and speech processor program settings were used during testing. If participants typically changed the HA or speech processor program settings in noisy environments, they were allowed to make these changes prior to being tested in noise (e.g., Autosensitivity Control [ASC], and/or directional microphone technology [Scan, Beam, UltraZoom]). Before testing, hearing aids and CI speech processors were checked to ensure proper fit and function (Audioscan Verifit 2, listening checks, sound field thresholds, troubleshooting equipment, etc.).

Test Measures

Various test measures were used to evaluate CI outcomes. The materials were selected in part to limit floor and ceiling effects and better represent realistic listening contexts. Testing was performed in an IAC double walled sound attenuating booth. Unless otherwise noted, speech stimuli were stored as audio files on a PC and presented through a 24-bit studio sound card (Lynx Studio Technology L22) and power amplifier (Crown D-150A) to a sound field loudspeaker (JBL LSR32) at 0° azimuth and 1.5 meters from the center of the participant's head. Frequency modulated (FM) tone, sound field threshold levels from .25-6 kHz were obtained both pre- and post-implant for each aided or implanted ear. For speech recognition testing, two lists per measure were given for each listening condition (each ear separately, both ears together). Test order and lists were varied across participants, listening conditions, and test intervals to avoid order and list effects. Two tests routinely used in CI candidacy and CI outcome evaluations included the consonant-vowel nucleus-consonant (CNC) monosyllabic word test (Peterson and Lehiste 1962) and the Bamford-Kowal-Bench Sentence in Noise Test (BKB-SIN; Etymotic Research 2005); both are part of the New Minimum Speech Test Battery for Adult Cochlear Implant Users (2011). The CNC word test (50-word lists spoken by a male talker) was presented at 60 dB SPL and given to monitor individual ear performance. (This was the only speech test not given in the bilateral condition.) The BKB-SIN test (two sets of 8 or 10 sentences per list) were presented in pseudo-adaptive 4-talker babble. The sentence level was fixed at 65 dB SPL; for each set, the starting signal-to-noise ratio (SNR) of +21 dB decreased in 3-dB steps with each sentence presentation. Two sentence lists were presented from a loudspeaker at 0° azimuth for each of two noise conditions: coincident noise presented 1) from a loudspeaker at 90° toward the better ear (S_0N_{BE}) and 2) from a loudspeaker at 90° toward the poor ear (S_0N_{PE}). An SNR for 50% sentence recognition was obtained for both noise conditions.

Additional measures were administered that may be informative in the evaluation of CI users with asymmetric hearing loss, including TIMIT sentences (Lamel et al. 1989), Hearing in

Noise Test (HINT; Nilsson et al. 1994) sentences presented in the R-Space test environment (Revit et al. 2002), and sound localization. These measures addressed challenges faced in listening contexts that affect daily communication function. The TIMIT sentences used multiple talkers (male and female with varied regional dialects and speaking rates), the R-Space used diffuse restaurant noise to replicate a common difficult listening situation, and sound source location evaluated a frequently noted concern of individuals with asymmetric hearing loss. TIMIT sentences were presented at a soft level (50 dB SPL) in quiet and at a conversational level (60 dB SPL) in noise (+8 dB SNR, 4-talker babble, S_0N_0). In the R-Space test environment, the participant was surrounded by eight loudspeakers (45° apart) through which restaurant noise was played at a constant 60 dB SPL. Sentences were presented through the front loudspeaker. Participants repeated each sentence; the sentence level was increased by 2 dB with an incorrect response and decreased by 2 dB with a correct response. An SNR was obtained that reflected 50% correct understanding of the sentences.

During sound localization testing, the participant was centered and 1.5 meters from a 140° arc of 15 loudspeakers spaced 10° apart and numbered 1-15. To reduce administration time and allow 10 presentations per loudspeaker, five loudspeakers (at 0°, $\pm 40^\circ$ and $\pm 60^\circ$ azimuth) were inactive; participants were unaware that some loudspeakers were inactive. One hundred monosyllabic words, each preceded by the carrier “Ready,” were played through one of ten active loudspeakers at 60 dB SPL (intensity roved ± 3 dB). Participants fixed their gaze on the middle loudspeaker prior to each presentation but were allowed to turn their heads once the stimulus was heard to better simulate an everyday sound localization experience. After each presentation, participants identified by number the perceived source loudspeaker. A root-mean-square (RMS) error score in degrees was calculated (the mean target-response difference, irrespective of error direction i.e., the square root of the quotient resulting from the sum of each target-response difference squared and divided by the number of trials). Due to distance and time limitations, participants from St. Luke’s Midwest Ear Institute (N = 15) had localization and R-Space testing only at 6 months post-implant and travelled to WUSM for testing.

Quality of Life Questionnaires

The Glasgow Benefit Inventory (GBI; Robinson et al. 1996) is a post-intervention questionnaire that measures benefit following a surgical intervention, in this case cochlear implantation. The GBI was administered at the 6-month post-implant test interval to quantify perceived benefit from cochlear implantation. The GBI is comprised of 18 questions and uses a 5-point response scale (Frequently or all the time, About half the time, Occasionally, Rarely, Never). It provided a total score and three subscale scores (general health, social support and physical health). The range of possible scores was –100 (maximal detriment) to +100 (maximal benefit); a score of 0 represented no change.

The Speech, Spatial and Qualities of Hearing Scale (SSQ; Gatehouse and Noble 2004) was given pre-implant and at both post-implant test intervals. The SSQ is a self-assessment tool consisting of three domains related to Speech Hearing, Spatial Hearing and Sound Qualities. The three domains, respectively, evaluate participants’ perceptions of their ability to 1) understand speech in varying listening environments, 2) localize sound, predict distance of

sound, and estimate direction of movement, and 3) segregate sound, assess naturalness of sound, and gauge listening effort. Postoperatively, the SSQ was anchored (participants were provided their previous responses).

Data Analysis

Data were analyzed for outliers and distribution. For datasets that were not normally distributed, nonparametric statistics were used. An analysis of variance, Friedman Chi-Square test or Kruskal-Wallis H test was used to identify main effects. Post-hoc Bonferroni adjusted comparisons were obtained using t-tests, Wilcoxon Signed Ranks tests or Mann-Whitney U tests. Pearson or Spearman tests analyzed correlations between selected potentially moderating variables and 6-month post-implant bimodal outcomes.

Because only nine participants used bilateral HAs in everyday life prior to implantation, pre-implant group mean test scores obtained in the bilateral HA condition ($n = 30$) were compared to those obtained in the Everyday listening condition ($n = 47$; bilaterally aided = 9, HA better ear only = 29, no aid either ear = 9). Group mean scores for the two listening conditions were not significantly different for TIMIT sentences in quiet (TIMITQ), TIMIT sentences in noise (TIMITN), R-Space or localization. Because performance in the pre-implant Everyday listening condition was comparable to the bilateral HA condition and more accurately represented how participants functioned in daily life, the Everyday listening condition was used as pre-implant baseline data. This nomenclature was also adopted for post-implant analysis and refers to the better ear and CI together. Therefore, longitudinal results reflect the Everyday listening condition for three test intervals, pre-implant (as noted above), 6 months post-implant and 12 months post-implant. In addition to longitudinal results, 6-month test interval scores for the CI-alone, better-ear alone and bimodal Everyday listening conditions were compared to examine individual ear performance as well as each ear's contributions to performance in the bimodal Everyday listening condition. The number of participants included in the analysis varied by test measure, primarily because participants implanted at MEI completed the localization and R-Space tests only at the 6-month test interval and also due to the addition of the GBI after the study was underway. Furthermore, because this study is ongoing, a greater number of participants had 6-month test interval data than had both 6- and 12-month data; consequently, participant numbers differed for the longitudinal and 6-month test interval data analyses. The number of participants is indicated on each figure.

Difference scores for the Everyday listening condition at the pre-implant and 6-month test intervals were calculated for each participant and each measure. Critical differences based on 95% confidence intervals were used to determine significant differences at the individual level for the R-Space (1.4 dB; Revit et al. 2002) and BKB-SIN (1.6 dB; Etymotic Research 2005). The categorization system developed by Noble et al. (2009) was used to determine post-implant benefit for the SSQ (1 = No Benefit; >1-2 = Benefit; >2-4 = High Benefit; >4 = Very High Benefit). For TIMITQ, TIMITN, and localization, criteria were based on test-retest results for these measures obtained in our laboratory and the percentile method to estimate reference limits using the 90th percentile (McMillan et al. 2013). A clinically

meaningful difference using this method was set at 0.07 for the TIMIT and 10 degrees for localization.

Results

Audibility and Speech Recognition

All participants continued CI use throughout the study. Better-ear hearing thresholds, at 6 months post-implant were stable compared to pre-implant (Figures 1C and 1E; $p > 0.05$). Audibility with the CI was confirmed (Figure 1F) and significantly improved compared to pre-implant ($p = 0.001$). Group mean, FM tone sound field threshold levels with the CI alone were 21, 23, 21, 18, 24, 23, and 20 dB HL at .25, .5, 1, 2, 3, 4, and 6 kHz, respectively, indicating significantly improved audibility compared to pre-implant hearing ($p = 0.001$).

Figure 2 shows the Everyday listening condition, group mean speech recognition scores pre-implant and at 6 and 12 months post-implant. A significant test-interval effect was seen for all measures; Chi-Squares were 35.1 ($p = 0.001$) for TIMITQ, 19.9 ($p = 0.001$) for TIMITN, 24.5 ($p = 0.001$) for R-Space, 6.6 ($p = 0.05$) for BKB-SIN S_0N_{PE} , and 23.4 ($p = 0.001$) for BKB-SIN S_0N_{BE} ($p = 0.001$). Post-hoc pairwise comparisons showed a significant improvement by the 6-month test interval ($ps = 0.001$); however, no statistically significant additional improvement was seen at the 12-month interval ($ps > 0.05$) for any of the measures except BKB-SIN S_0N_{BE} ($p = 0.01$). (See Table 1A for Everyday listening condition means and SDs for all measures and test intervals.)

Table 1B indicates means and SDs for all test measures at each test interval for the poor ear alone. Pre-implant, group mean scores were minimal; $< 5\%$ for CNC words, TIMITQ and TIMITN. R-Space and BKB-SIN scores were near floor level with mean SNRs of 21 dB and 22 dB, respectively. Six-month post-implant group mean scores for the poor ear alone significantly improved for all speech recognition measures compared to pre-implant scores. For example, CNC word scores for the poor ear improved from 4% to 49% and 51% between pre-implant and the 6- and 12-months post-implant ($n=39$) test intervals. The Friedman Chi-Square test indicated a significant test-interval effect, Chi-Square = 60.3, $p = 0.001$ and post-hoc pairwise comparisons indicated the improvement occurred by the 6-month test interval ($p = 0.001$). There was no significant difference between 6- and 12-month scores ($p > 0.05$). Performance for the better ear alone remained stable across the three test intervals for most measures ($ps > 0.05$, CNC, TIMITN, BKB-SIN- S_0N_{BE} , Localization). Although a significant interval effect was found for TIMITQ, R-Space and BKB-SIN S_0N_{PE} ; differences were small (< 1 dB SNR for R-Space and BKB-SIN S_0N_{PE} and 8% for TIMITQ).

Group mean speech recognition results for each listening condition (better-ear alone, bimodal, CI alone) at the 6-month test interval are shown in Figure 3. There was a significant listening condition effect for all measures, Chi-Squares were 50.6 for TIMITQ, 53.8 for TIMITN, 70.6 for R-Space, 65.0 for BKB-SIN S_0N_{PE} , and 37.2 for BKB-SIN S_0N_{BE} ($ps = 0.001$). Post-hoc analysis indicated significantly improved scores for the bimodal condition compared to CI or better ear alone ($ps = 0.01$) for the TIMITQ, TIMITN, R-Space, and BKB-SIN (Figure 3A–D). Scores were significantly higher for the better ear

compared to CI alone ($p \leq 0.001$) for all measures except the BKB-SIN S_0N_{BE} (Figure 3D). The mean CNC word score (Figure 3E) was significantly higher with the better ear than with the CI alone, $z = 4.3$, $p \leq 0.001$. (See Table 1C for 6-month means and SDs for all measures.)

Localization

A one-way ANOVA for localization in the Everyday listening condition indicated a significant test-interval effect, $F(1.3, 28.0) = 20.0$, $p \leq 0.001$. As with speech recognition measures, localization ability in the Everyday listening condition (Figure 4A) improved significantly at the 6-month test interval compared to pre-implant ($p \leq 0.001$); performance was stable between the 6- and 12-month test intervals ($p > 0.05$). A one-way ANOVA across listening conditions at the 6-month test interval (Figure 4B) indicated a significant listening condition effect, $F(2,92) = 68.1$, $p \leq 0.001$; each listening condition was significantly different from the others, $p \leq 0.001$. Firszt et al. (2015) determined chance performance on this measure as 59 degrees RMS error. Independent t-tests comparing current study participants to the chance performance group (Firszt et al. 2015) indicated the group mean RMS error with the better ear alone (49.0 degrees) and in the bimodal condition (32.3 degrees) were both significantly better than chance ($p \leq 0.001$). CI alone (57.3 degrees) performance was not significantly different than chance ($p > 0.05$).

Quality of Life Questionnaires

SSQ—Figure 5 plots the Everyday listening condition ratings for each of the three SSQ domains (Speech, Spatial, Qualities) for the 36 participants who completed the questionnaire at all three test intervals (x-axis). A three (Interval) by three (Domain) repeated measures ANOVA indicated a significant Interval effect [$F(1.4,48.0) = 135.8$, $p \leq 0.001$]; ratings were significantly improved at six months post-implant compared to pre-implant. Although the greatest improvement was seen between the pre and 6-month test intervals, the continued improvement between the 6- and 12-month intervals was significant ($p \leq 0.001$). Additionally, there was a significant Domain effect [$F(2,70) = 33.5$, $p \leq 0.001$], that is, Quality ratings were significantly higher than Speech ratings ($p \leq 0.001$) which were significantly higher than Spatial ratings ($p \leq 0.01$). A significant interaction between Domain and Interval [$F(2.5,87.4) = 14.0$, $p \leq 0.001$] indicated greater rating improvements from pre- to post-implant for Speech and Spatial domains than Qualities domain. Significant post-hoc differences between domains at each test interval and between test intervals for each domain are indicated on the figure.

All 6-month bimodal speech recognition results were significantly correlated with 6-month Speech and Quality ratings. Absolute value correlations ranged from 0.36 to 0.57, $p \leq 0.05$. Spatial ratings were mildly correlated only with TIMITQ (0.30, $p \leq 0.05$) and were not correlated with 6-month bimodal localization scores.

GBI—Participants given the GBI ($n = 26$) reported CI benefit with a mean total score of 37.9 (range 5.6 to 77.8; SD 19.3). As a reminder, scores can range from -100 to $+100$ with a score of 0 indicating no benefit. The mean general subscale score was 49.0 (range 4.2 to 91.7; SD 26.4); mean social support subscale score was 23.7 (range -16.7 to 83.3; SD 26.3), and mean physical health subscale score was 5.1 (range -16.7 to 100; SD 20.4). The highest

scores were seen for the general subscale, which mainly was comprised of questions directly related to social and emotional effects of hearing loss. There was no correlation between the GBI total score and improvements on speech recognition and localization measures (i.e., change in the Everyday listening condition score from pre-implant to 6 months post-implant), $p_s > 0.05$. There was a significant positive correlation between the GBI total score and the pre-implant to 6-month post-implant improvement ($n=26$) for each SSQ domain, (Speech $r = 0.71$, $p = 0.001$; Spatial $r = 0.48$, $p = 0.05$; and Qualities $r = 0.56$, $p = 0.01$.)

Individual Participant Outcomes

The majority of participants demonstrated clinically meaningful benefit on multiple measures. Figure 6 displays improvement, per measure, between the Everyday listening condition at the pre-implant and 6-month post-implant test intervals for each participant who had available data at both intervals. Positive values indicate improvement and negative values indicate a decrement in performance. The clinically meaningful difference for each measure is indicated on the graphs as horizontal dashed lines. All measures had a substantial proportion of participants who demonstrated benefit; the only measure with more than one participant demonstrating a decrement was the BKB-SIN (four had a decrement with noise to the better ear and two other participants with noise to the poor ear). Nine participants had a clinically meaningful decrement on one measure and one participant had a clinically meaningful decrement on two measures; all who showed a decrement also had clinically meaningful benefit on multiple measures. Participants who demonstrated decrement on a measure were significantly older (Mean age for those with some decrement = 70.9 yrs, Mean age no decrement = 60.6 yrs, $U = 106$, $p = 0.05$) and performed significantly poorer bimodally at 6 months post-implant on TIMITQ, TIMITN and BKBSIN $S_{0N_{BE}}$ than those without a decrement on any measure. Overall, a substantial portion of participants (81%) demonstrated benefit on at least half of the measures administered.

Factors Contributing to Outcomes

Correlational analysis was conducted between demographic factors (age at CI, age at onset of SPHL, and length of SPHL) and 6-month post-implant outcomes ($n = 47$). To correct for multiple comparisons, the significance criterion was set at 0.01 . (Significant correlations are noted in Table 2.) There was a moderate correlation (Figure 7, A–C) between age at CI and bimodal performance for all measures indicating that older recipients had poorer bimodal performance than younger participants. Age at onset of SPHL was also moderately correlated with localization (Figure 7, D); after 6 months of CI use, participants who were younger at the onset of SPHL had better localization ability in the bimodal condition than those who were older at onset of SPHL. Correlations between bimodal outcomes at the 6-month test interval and length of SPHL were not significant. Six-month SSQ ratings and GBI scores did not correlate with the age-based factors ($p_s > 0.01$). Length of SPHL correlated with CI-alone, 6-month speech recognition performance in noise (Figure 7, E–F).

Correlational analysis was also conducted between better-ear hearing (3fPTA; $n = 47$) and post-implant outcomes (Table 2). A significant correlation was found between better-ear hearing and all 6-month bimodal speech recognition measures. However, better-ear hearing was not correlated with bimodal localization ($p > 0.01$) or with CI alone speech recognition

outcomes ($p > 0.01$). SSQ Quality, but not Speech or Spatial ratings, were significantly correlated with better-ear hearing.

Impact of Better-Ear Hearing

To provide clinical relevance and better understand the impact of better-ear hearing on outcomes, participants were divided into similarly sized groups based on their better-ear 3fPTA using standard clinical audiometric classifications: Group 1 PTA = 40 dB HL (NH to mild hearing loss; $n = 19$), Group 2 PTA = 41 – 55 dB HL (moderate hearing loss; $n = 14$), and Group 3 PTA = 56 – 70 dB HL (moderately-severe hearing loss; $n = 14$). Mean better-ear 3fPTAs for Groups 1–3 respectively were 23.7 dB HL (SD 13.0 dB), 50.5 dB HL (SD 4.0 dB), and 64.5 dB HL (SD 4.1 dB). Groups did not differ for age at implant, age at onset of SPHL or length of SPHL ($p > 0.05$). Figure 8 (panels A-D) shows the three groups at the 6-month test interval for each listening condition, better-ear alone, bimodal, and CI-alone. Groups differed significantly for the better-ear alone and bimodal conditions (Chi-Squares 9.6 to 22.6, $p \leq 0.01$) but not the CI-alone condition ($p > 0.05$). Although group means in the bimodal condition were better than either ear alone for all measures and all three hearing groups, the difference between the better-ear alone and bimodal conditions varied somewhat by group. For Group 1, bimodal was significantly better than the better-ear alone for TIMITQ, R-Space, and BKB-SIN S_0N_{BE} . Group 2's mean bimodal performance was significantly improved for these same measures compared to the better-ear alone; in addition the TIMITN was significantly improved. Group 3 demonstrated significant improvement bimodally compared to the better-ear alone for all speech recognition measures. All three groups had a significant listening condition effect [Chi-Squares 15.6 to 26.9, $p \leq 0.001$] for localization (Figure 8E). Post-hoc analysis indicated localization in the bimodal condition at the 6-month test interval was significantly better than either ear alone ($p \leq 0.05$) for all three hearing groups. Individual ear comparison by group indicated that Group 1 had a significant difference, that is better-ear alone localization was significantly better than CI alone localization ($p \leq 0.01$), but Groups 2 and 3 had no significant individual ear differences. In addition, better-ear alone localization for Group 1 was significantly better than chance ($p \leq 0.05$) which was not the case for Groups 2 and 3 ($p > 0.05$). For CNC words (Figure 8F), Wilcoxon Signed Ranks test indicated significant ear differences for Group 1 ($p \leq 0.001$) but not Group 2 or Group 3 ($p > 0.05$). There was no significant difference between groups for CI-alone CNC word understanding ($p > 0.05$).

Figure 9 plots SSQ domain ratings at each test interval for each hearing group. A three (Interval) by three (Hearing Group) ANOVA for each domain indicated a significant Interval effect for all three domains, $p \leq 0.001$. For the Speech and Spatial domains (Figure 9A and 9B), there was no Hearing Group effect; all three groups had significantly improved ratings at the 6-month test interval compared to pre-implant ($p \leq 0.001$) and no significant additional improvement occurred between the 6- and 12-month test intervals. For the Qualities domain (Figure 9C), there was a Hearing Group effect ($p \leq 0.05$) in addition to the significant Interval effect ($p \leq 0.001$). Pre-implant, Group 3 ratings were significantly poorer than Group 1 ($p \leq 0.05$). All three groups again had significant improvements at the 6-month test interval compared to pre-implant ($p \leq 0.01$). Group 3 continued to show

significant improvement between the 6- and 12-month test intervals ($p = 0.05$). There was no significant difference in GBI scores across the hearing groups ($p > 0.05$).

Discussion

Since a CI is the only treatment option that can restore hearing to an ear with SPHL and reestablish bilateral input, the present study aimed to evaluate longitudinal performance outcomes in a relatively large group of adults with asymmetric hearing who received a CI in the poor ear. Clinically, whether the addition of the CI improved performance beyond that of the participant's pre-implant Everyday listening condition was the relevant question.

Performance Outcomes

Audibility and Speech Recognition—Group mean, FM tone, sound field threshold levels at the 6-month test interval were approximately 20 dB HL across the frequency range, indicating participants could detect soft and even very soft sounds with the implant (Pearsons et al. 1976; Mueller and Killion 1990). For many study participants, the implant provided improved audibility from 3–6 kHz compared to the better ear alone. High frequency information is critical for speech clarity; pre-implant, this information was not available to the majority of participants in either ear, whereas post-implant all had access to high frequencies in at least one ear.

Post-implant Everyday listening condition improvements for speech recognition (Figure 2) may be attributed, at least in part, to improved access to high frequency information. Another contributing factor may be participants' ability to benefit from effects of binaural summation and squelch since the majority of participants' pre-implant Everyday listening condition was better-ear alone (with or without a HA). Our results indicated most improvement in speech recognition occurred within the first 3–6 months of use. While significant improvement beyond 6 months has been reported in bilateral CI use (Koch et al. 2009; Mosnier et al. 2009), current study data are consistent with the literature for traditional unilateral (Chang et al. 2010; Holden et al. 2013), bilateral (Reeder et al. 2014) and SSD CI recipients (Sladen et al. 2016).

For both speech in quiet (TIMITQ) and speech in noise (TIMITN, R-Space and BKB-SIN), bimodal scores were significantly better than either ear alone (Figure 3). Results comparing the better ear alone to the bimodal condition in the R-Space reported by Sladen et al. (2016) are consistent with the current study; the mean bimodal SRT was 2 dB lower (better) than the better ear alone in Sladen et al. and 1.7 dB lower for our participants. Arndt et al. (2011) demonstrated a median bimodal versus better-ear improvement of 5.6 dB using an adaptive sentence procedure in noise when the noise was directed toward the better ear. The larger improvement compared to the current study is presumably due to a difference in loudspeaker arrangement, i.e. two loudspeakers, one for speech, one for noise, each at ± 45 degrees rather than speech from the front and noise at ± 90 degrees. In the current study, the non-implanted better ear continued to be the dominant ear for participants on all measures except the BKB-SIN S_0N_{BE} .

Localization—The significant improvement in localization from the pre-implant to the 6- and 12-month test intervals shown for the Everyday listening condition (Figure 4) is consistent with previous study findings (Potts et al. 2009; Chang et al. 2010; Morera et al. 2012; Mertens et al. 2017). Group mean RMS error in the bimodal condition at 6 months post-implant was 32 degrees. Similar results (28 degrees) were found on the same test measure for bilateral CI recipients (n = 21) after 6-months bilateral CI use (Reeder et al. 2014). Likewise, using a 12-loudspeaker array (97.5 degrees to 262.5 degrees), Aronoff et al. (2010) reported a similar mean RMS error score (27 degrees) for six bilateral CI recipients. However, these results are still considerably poorer than the 3.4 degrees RMS error obtained for a group of 23 normal hearing individuals (Firszt et al. 2017). This is likely due in part to CI limitations for capturing and conveying timing information, which results in poorer interaural timing difference accuracy (van Hoesel 2004; Litovsky et al. 2010). As with the speech recognition results, there was no continued improvement in localization ability between the 6- and 12-month test intervals. Studies of bilateral CI recipients also report a lack of improvement for localization between 6 and 12 months post-implant (Chang et al. 2010; Reeder et al. 2014). Although bimodal participants with better-ear hearing might require additional bimodal listening experience to obtain improvements beyond the first year (Mertens et al. 2017), it is improbable that performance would reach levels of normal hearing individuals.

Among the hearing groups, better-ear alone localization was significantly better than chance for Group 1, suggesting that individuals with normal or mildly impaired better-ear hearing may develop localization strategies. Other studies have demonstrated better than chance localization for adults with unilateral hearing loss (Slattery and Middlebrooks 1994; Rothpletz et al. 2012). Firszt et al. (2017) found that adults with unilateral hearing loss had significantly better localization (n = 26, median RMS error = 23 degrees) than normal hearing participants with one ear plugged and muffed (n = 25, median RMS error = 36 degrees) and that unilateral hearing impaired individuals with early-onset SPHL localized better than those with late-onset SPHL. Additional research is needed to determine the influence of onset of SPHL, degree of better-ear hearing, and test conditions (e.g., roving levels) on localization outcomes.

Quality of Life Questionnaires—SSQ ratings supported speech recognition results in that ratings were significantly higher in the Everyday listening condition at the 6-month test interval compared to pre-implant; however, unlike speech recognition results, ratings continued to improve between the 6- and 12-month test intervals (Figure 5). Congruent with clinical reports by individuals with asymmetric hearing as well as results from Arndt et al. (2011), the Speech and Spatial domains had significantly poorer pre-implant ratings compared to Qualities. Surprisingly, given the degree of hearing in the non-implanted ear, the Qualities domain ratings significantly improved at each test interval. However, the SSQ Qualities domain includes questions related to sound segregation and listening effort in addition to those focused on overall quality of sound and sound identification. The items related to sound segregation and, in particular, listening effort were rated the lowest pre-implant and demonstrated the greatest improvements post-implant. This is consistent with the findings of Dwyer et al. (2014); individuals with SPHL in one ear reported more

difficulty with sound segregation and listening effort than the other areas within the Qualities domain. In conjunction with functional communication improvement, group mean responses from the GBI indicated benefit from cochlear implantation suggesting that the SSQ and GBI provided complementary results. The lack of relation between subjective ratings and speech understanding for this study has been noted by others in this population (Finke et al. 2017a).

Individual Participant Outcomes and Factors Contributing to Outcomes

The majority of study participants had clinically meaningful benefit on most test measures (Figure 6); however, the amount of benefit varied. Outcome variability among CI recipients has been well documented (Firszt et al. 2004; Gifford et al. 2008; Blamey et al. 2013; Holden et al. 2013) and many contributory factors identified. As has been shown in other studies (Gantz et al. 2009; Plant et al. 2016), age at CI negatively correlated with performance. Length of SPHL did not correlate with any bimodal results but did correlate with all CI-alone performance outcomes in noise (Figure 7E – 7F). Plant and colleagues (2016) also found shorter SPHL duration associated with better CI-alone outcomes (in both noise and quiet); however, in contrast to the current study, Plant et al. found shorter SPHL duration correlated with better bimodal outcomes. Better hearing in the contralateral ear (current study PTA = 43.8 dB HL; Plant study PTA = 65.4 dB HL) may explain why length of SPHL was related to CI-alone and not bimodal performance in the current study. Not surprisingly, both studies found better hearing in the contralateral ear correlated with better bimodal outcomes.

All three hearing groups (based on better ear 3fPTA) showed significant improvements in the bimodal condition compared to the better ear alone at the 6-month test interval. Groups 2 and 3 showed improvement on the majority of measures; whereas, ceiling effects may have limited bimodal benefit for Group 1 on some measures. Mertens et al. (2017) found no significant difference between bimodal (CI on) and better ear alone (CI off) conditions for summation and squelch effects at 12 and 36 months post implant for the participant group with more contralateral hearing (SSD); however, significant differences between the two listening conditions were seen for the participant group with hearing loss in the contralateral ear. Speech recognition results of both studies suggest that further consideration is needed regarding test measures sensitive to possible bimodal improvements for those with better hearing in one ear.

CI Only Outcomes

The mean CI-only word score at 6 months post-implant for the current group (49%) was approximately 10 percentage points lower than mean scores reported for traditional CI recipients (Skinner et al. 2006; Gifford et al. 2008; Holden et al. 2013; Sladen et al. 2016). Recent speech recognition studies of CI recipients with SSD have also noted lower performance when compared to other CI study participant groups (Sladen et al. 2016; Finke et al. 2017a). Several authors surmised that individuals with useable hearing in the contralateral ear might rely on their acoustic as opposed to electric hearing for daily communication (Plant et al. 2016; Sladen et al. 2016; Finke et al. 2017a). The performance differences between the current study participants and more traditional CI recipients may support this theory.

Another explanation as to why these participants had lower word scores than traditional CI users relates to aural or ear dominance (Imig and Adrian 1977; Kral et al. 2013a). As suggested by animal studies (Kral et al. 2013b, 2015; Tillein et al. 2016), individuals who have had unilateral acoustic (normal) hearing might find their dominant ear favors the auditory input when a CI is introduced to the poor ear. A potential consequence of this dominance is reduced ability of the poor ear to process auditory input. After implantation, the poor ear may remain weak or in competition with the dominant ear. This is especially highlighted in individuals with prelingual onset of asymmetric hearing loss for whom the ability to use a CI in the poor ear may be diminished due to extended time with imbalanced auditory input between ears. Prelingual unilateral hearing loss onset and subsequent cochlear implantation in children and adults with substantial hearing in the non-implanted ear has shown poor outcomes (Firszt et al. 2012a; Cadieux et al. 2013). In animal models, unilateral congenital deafness compared to binaural deafness resulted in largely reorganized aural dominance and reduced sensitivity to binaural cues, especially interaural time difference (ITD) sensitivity (Tillein et al. 2016). This reorganization during an early sensitive period could have implications for training or learning of the later implanted ear to offset the aural dominance created by unilateral deafness (Kral and Sharma 2012). Negative effects of reorganization due to unilateral input have also been demonstrated in bilaterally deaf children receiving sequential cochlear implants (Gordon et al. 2013, 2015). Studies in adults with unilateral non-congenital hearing loss support that the hearing ear is more extensively represented in the auditory system (Bilecen et al. 2000; Ponton et al. 2001; Burton et al. 2012). This reorganization may slow initial use of a CI for the poor ear or limit potential. Additional study is needed to determine the degree and time-course of aural dominance reorganization in adults with unilateral deafness.

Clinical Considerations

Selection of the most appropriate test measures for individuals with asymmetric hearing is critical for effective evaluation of both status and treatment outcomes. The R-Space and localization tests may best represent the challenging listening environments reported by individuals with asymmetric hearing; however, these test measures are not practical for most CI clinics due to expense and space requirements. Standard clinical tests used with traditional CI recipients are not appropriate because of ceiling effects in the better-ear and bimodal conditions. Based on King et al. (2012) who found results with the TIMIT sentences, as used in the current study, to be approximately 16 percentage points lower than the more commonly used AzBio sentence test (Spahr et al. 2012), we would predict average 6-month bimodal AzBio scores near 90%, even at the soft presentation level of 50 dB SPL used in this study. Ceiling effects could be avoided by using a range of presentation levels e.g., 40, or 45 dB SPL or individually selected presentation levels to compare results over time or in different listening conditions. Likewise, speech-in-noise testing may require adaptive measures and/or varied SNRs to determine bimodal benefit for individual recipients as described in a consensus paper by Van de Heyning et al. (2016). The BKB-SIN, often used in traditional CI evaluations, can be administered with spatially separated speech and noise in test booths with two loudspeakers and might be more sensitive to listening condition differences using $S_{BE}N_{CI}$ and $S_{CI}N_{BE}$ (Arndt et al. 2011; Van de Heyning et al. 2016).

The current study as well as others (Arndt et al. 2011; Firszt et al. 2012a, b; Mertens et al. 2017) showed significant improvement in localization in the bimodal condition compared to the better ear alone, indicating the value of developing a clinically feasible test to assess localization for this population. Horizontal sound localization simulation via direct connect (Chan et al. 2008; Aronoff et al. 2012) can be used with CI speech processors and unaided acoustic hearing; however this system is currently not available for use with hearing aids. Continued refinement of this system or development of a sound field system that could be used in a range of settings is needed to bring assessment of this important communication function into standard clinical practice. The lack of correlation between participant report and speech perception measures emphasizes the importance of quality of life and other participant report measures. In addition, use of a test battery is important for this population since improvement may not be consistent across measures, i.e., performance might decrease on a single measure but show clinically meaningful improvement on several other measures.

Even though individuals with asymmetric hearing will rarely rely on the CI alone for everyday communication, documenting CI-alone performance assists in determining the need for continued programming and/or aural rehabilitation to optimize performance. Because of the CI, effects of decreased hearing or hearing aid function may be more subtle or missed if testing is completed only in the bimodal condition. Evaluating the better-ear alone, especially for those with hearing loss in that ear, continues to be critical. Furthermore, aural rehabilitation needs for this population may differ somewhat from traditional CI candidates. Aural dominance or preference for the stronger ear may necessitate training of the weaker ear to optimize CI outcomes. CI-alone auditory training has been recommended (Finke et al. 2017a) and recipients have used varied methods including audio books, radio or television, and a number of training apps (Finke et al. 2017b). Future research should examine individualized aural rehabilitation strategies for those with asymmetric hearing loss to determine whether CI-alone speech recognition could be improved, and if so, whether the improvements benefit listening bimodally in everyday life.

Conclusion

Cochlear implantation was an effective treatment for this study population, postlingually deafened adults with asymmetric hearing (one ear with SPHL and better hearing in the other ear). By 6-months post-implant, bimodal performance was beyond that of the participants' pre-implant Everyday listening condition, which for most was listening with the better ear alone (with or without a HA). Improvements were documented for speech recognition in noise and at soft levels in quiet, for sound localization, and for everyday communication function. Test batteries for this population should include quality-of-life measures, sound localization and adaptive speech recognition measures with spatially separated noise to capture the hearing loss deficits and treatment benefits reported by this patient population.

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Pre-Implant (n = 47)

Post-Implant (n = 47)

Figure 1.

Hearing thresholds for the pre-implant unaided condition for each ear (A-B), the pre-implant Everyday condition for each ear (C-D) and the 6-month post-implant Everyday condition (E-F) for each ear. Pre-implant, light gray lines indicate individual, unaided pure-tone threshold levels for the better (A) and poor (B) ears and for the Everyday better-ear (C) and poor-ear (D) conditions for participants who did not wear a hearing aid at the respective ears. Pre-implant, medium gray lines represent aided, sound-field thresholds for participants who wore a hearing aid in the better ear (C) and in the (D) poor ear. Post-implant, light gray lines

represent pure-tone thresholds for those who did not wear a hearing aid (E); medium gray lines represent aided, sound-field thresholds for participants who wore a hearing aid in the better ear (E); and dark gray lines represent cochlear implant sound-field threshold levels (F). The black line in each graph represents group mean threshold levels for each condition.

Everyday Listening Condition

Figure 2.

Group mean Everyday Listening condition scores for the pre-implant, 6-month and 12-month test intervals: Panel A shows TIMIT sentences in quiet at 50 dB SPL (TIMITQ), Panel B shows TIMIT sentences in 4-talker babble at 60 dB SPL and +8 dB SNR (TIMITN), Panel C shows Sentences in the R-Space using restaurant noise, and Panel D shows Bamford-Kowal-Bench Sentences in Noise (BKB-SIN) with speech from the front and noise to the poor ear (PE) on the left and noise to the better ear (BE) on the right. Error bars represent ± 1 standard error of the mean. *** $p < 0.001$, ** $p < 0.01$. SNR = signal-to-noise ratio, dB = decibels.

Figure 3.

Group mean 6-month test interval scores for the better ear (BE) alone, bimodal (Bi) and cochlear implant (CI) alone listening conditions. Panel A shows TIMIT sentences in quiet at 50 dB SPL (TIMITQ), Panel B shows TIMIT sentences in 4-talker babble at 60 dB SPL and +8 dB SNR (TIMITN), Panel C shows Sentences in the R-Space using restaurant noise, and Panel D shows Bamford-Kowal-Bench Sentences in Noise (BKB-SIN) with speech from the front and noise to the poor ear (PE) on the left and noise to the better ear (BE) on the right,

Panel E shows Consonant-Vowel Nucleus-Consonant (CNC) words. Error bars represent ± 1 standard error of the mean. *** $p < 0.001$. SNR = signal-to-noise ratio, dB = decibels.

Localization

Figure 4.

Group mean localization scores in degrees root-mean-square (RMS) error. Panel A shows the Everyday Listening condition at the pre-implant, 6-month and 12-month test intervals. Panel B shows the 6-month test-interval results for the better-ear (BE) alone, bimodal and cochlear implant (CI) alone conditions. Error bars represent ± 1 standard error of the mean. Asterisks denote significant differences, *** $p<0.001$.

SSQ Everyday Listening Condition (n = 36)

Figure 5.

Group mean Speech, Spatial and Qualities of Hearing Scale (SSQ) ratings are shown for the pre-implant, 6-month and 12-month test intervals in the Everyday Listening condition. Light gray, medium gray and dark gray lines represent the Speech, Spatial and Qualities domains, respectively. Asterisks indicating significant differences between test intervals are indicated with the same color designations. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Everyday Listening Condition Individual Improvement Between Pre-Implant and 6-Months Post-Implant

Figure 6.

Individual improvement for the Everyday listening condition between the pre-implant and 6-month test intervals are show for each measure: TIMIT sentences in quiet at 50 dB SPL (TIMITQ), TIMIT sentences in 4-talker babble at 60 dB SPL and +8 dB SNR (TIMITN), and Bamford-Kowal-Bench Sentences in Noise (BKB-SIN) with speech from the front and noise to the poor ear (NPE) and to the better ear (NBE), Sentences in the R-Space using restaurant noise, Localization, and each domain of the Speech, Spatial and Qualities of Hearing Scale (SSQ). Positive numbers indicate improvement; negative numbers indicate

decline. The horizontal dashed lines indicate the clinically meaningful difference for each measure. SNR = signal-to-noise ratio, dB = decibels, RMS = root-mean-square

Figure 7.

Scatter plots of significant correlations. Panels A–C indicate the relation between age at cochlear implantation (CI) and 6-month bimodal performance for TIMIT sentences in noise (TIMITN), the R-Space, and localization. Panel D shows the correlation between age at severe to profound hearing loss (SPHL) and 6-month bimodal localization. Length of SPHL correlated with CI-alone speech understanding in noise and is shown for the TIMIT sentences (E) and the R-Space (F). Correlation coefficients (r_s) and p-values are indicated on each scatter plot.

Figure 8.

Group mean 6-month test interval scores for each hearing group for the better-ear (BE) alone, bimodal (Bi) and cochlear implant (CI) alone listening conditions. Panel A shows TIMIT sentences in quiet at 50 dB SPL (TIMITQ), Panel B shows TIMIT sentences in 4-talker babble at 60 dB SPL and +8 dB SNR (TIMITN), Panel C shows Sentences in the R-Space using restaurant noise, Panel D shows Bamford-Kowal-Bench Sentences in Noise (BKB-SIN) with speech from the front and noise to the CI ear on the left and noise to the BE on the right, Panel E shows localization scores in degree root-mean-square (RMS) error and

Panel F shows Consonant-Vowel Nucleus-Consonant (CNC) word scores. Error bars represent ± 1 standard error of the mean. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. SNR = signal-to-noise ratio, dB = decibels.

SSQ Everyday Listening Condition - Hearing Groups

Figure 9.

Group mean ratings for each Speech, Spatial and Qualities of Hearing Scale (SSQ) domain are shown for the pre-implant, 6-month and 12-month test intervals in the Everyday Listening condition for the three hearing groups. Light gray, medium gray and dark gray lines represent Groups 1, 2 and 3 respectively. Asterisks indicating significant differences between test intervals are indicated with the same color designations. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Table 1

Group means and standard deviations for participants with data at all three test intervals or conditions.

A. Everyday Listening Condition				
Measure	n	Test Interval	Mean	SD
TIMITQ	40	Pre-implant	0.55	0.30
		6 months	0.74	0.23
		12 months	0.78	0.20
TIMITN	40	Pre-implant	0.58	0.28
		6 months	0.68	0.25
		12 months	0.69	0.24
R-Space	25	Pre-implant	4.01	3.41
		6 months	0.98	3.50
		12 months	1.29	3.70
BKB-SIN NPE	39	Pre-implant	2.06	3.98
		6 months	0.86	2.58
		12 months	0.81	2.33
BKB-SIN NBE	39	Pre-implant	5.10	4.25
		6 months	3.04	3.57
		12 months	2.39	3.53
Localization	22	Pre-implant	47.87	16.69
		6 months	32.87	9.67
		12 months	31.67	12.67
B. Poor Ear Alone				
Measure	n	Test Interval	Mean	SD
TIMITQ	38	Pre-implant	0.01	0.04
		6 months	0.37	0.24
		12 months	0.38	0.27
TIMITN	38	Pre-implant	0.01	0.21
		6 months	0.27	0.21
		12 months	0.27	0.23
R-Space	25	Pre-implant	20.93	3.29
		6 months	8.69	5.65
		12 months	8.56	6.11
BKB-SIN NPE	38	Pre-implant	22.32	3.25
		6 months	13.16	5.23
		12 months	11.25	5.33

A. Everyday Listening Condition

Measure	n	Test Interval	Mean	SD
BKB-SIN NBE	38	Pre-implant	21.50	4.55
		6 months	7.63	4.90
		12 months	6.51	5.16
CNC	39	Pre-implant	0.04	0.07
		6 months	0.49	0.20
		12 months	0.51	0.22

C. Six-Month Post-Implant Test Interval

Measure	n	Condition	Mean	SD
TIMITQ	46	BE alone	0.60	0.30
		Bimodal	0.75	0.23
		CI alone	0.37	0.23
TIMITN	46	BE alone	0.60	0.29
		Bimodal	0.69	0.24
		CI alone	0.27	0.20
R-Space	47	BE alone	3.40	4.87
		Bimodal	1.72	4.35
		CI alone	10.25	5.94
BKB-SIN NPE	46	BE alone	1.54	3.17
		Bimodal	0.90	2.49
		CI alone	12.88	5.05
BKB-SIN NBE	46	BE alone	5.88	4.43
		Bimodal	2.93	3.44
		CI alone	7.33	4.82
Localization	47	BE alone	48.96	17.02
		Bimodal	32.35	10.25
		CI alone	57.29	13.72
CNC	46	BE alone	0.75	0.19
		CI alone	0.50	0.19

Note: n = number of participants; SD = standard deviation; TIMITQ = TIMIT sentences at 50 dB SPL in quiet; TIMITN = TIMIT sentences at 60 dB SPL with four talker babble at +8 dB signal-to-noise ratio; BE = better ear; CI = cochlear implant

Table 2

Significant correlations between demographic factors and 6-month outcomes.

Variable	6-month Condition	Measure	Correlation	p-value
Age at CI	Bimodal	TIMITQ	−0.39	0.01
		TIMITN	−0.46	0.001
		R-Space	0.52	0.001
		BKB-SIN N _{PE}	0.40	0.01
		BKB-SIN N _{BE}	0.52	0.001
		Localization	0.61	0.001
Age at SPHL	Bimodal	Localization	0.37	0.01
Length SPHL	CI-alone	TIMITN	−0.44	0.01
		R-Space	0.52	0.001
BE 3fPTA	Bimodal	TIMIT	−0.69	0.001
		TIMITN	−0.58	0.001
		R-Space	0.46	0.001
		BKB-SIN N _{PE}	0.59	0.001
		BKB-SIN N _{BE}	0.37	0.01
		SSQ Quality	−0.42	0.01

Note: CI = cochlear implant; SPHL = severe to profound hearing loss; BE 3fPTA = better ear pure-tone average of .5, 1 and 2 kHz.