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Auditory Abilities after Cochlear Implantation in Adults with Unilateral Deafness: A Pilot Study

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Abstract

Objective—This pilot study examined speech recognition, localization, temporal and spectral discrimination and subjective reports of cochlear implant (CI) recipients with unilateral deafness.

Study Design—Three adult males with short-term unilateral deafness (< 5 years) participated. All had sudden onset of severe to profound hearing loss in one ear, which then received a CI, and normal or near normal hearing in the other ear. Speech recognition in quiet and noise, localization, discrimination of temporal and spectral cues and a subjective questionnaire were obtained over several days. Listening conditions were CI, normal hearing (NH) ear, and bilaterally (CI and NH).

Results—All participants had open-set speech recognition and excellent audibility (250–6000 Hz) with the CI. Localization improved bilaterally compared to the NH ear alone. Word recognition in noise was significantly better bilaterally than with the NH ear for two participants. Sentence recognition in various noise conditions did not show significant bilateral improvement; however, the CI did not hinder performance in noise even when noise was toward the CI side. The addition of the CI improved temporal difference discrimination for two participants and spectral difference discrimination for all participants. Participants wore the CI full time and subjective reports were positive.

Conclusion—Overall, the CI recipients with unilateral deafness obtained open-set speech recognition, improved localization, improved word recognition in noise, and improved perception of their ability to hear in everyday life. A larger study is warranted to further quantify the benefits and limitations of cochlear implantation in individuals with unilateral deafness.

Keywords

cochlear implant; unilateral deafness; single-sided deafness; speech recognition; localization

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INTRODUCTION

Several recent studies have shown that cochlear implantation can benefit individuals with unilateral deafness. The benefits include: a) significantly improved post-operative compared to pre-operative speech recognition scores in the implanted ear (1); b) tinnitus suppression (2–7); c) increased balance control (8); d) improved localization bilaterally (cochlear implant [CI] and normal hearing [NH] ear) compared to the NH ear alone (2, 8, 9); and e) better speech recognition in noise bilaterally compared to the NH ear alone (2, 5, 6, 9). In addition, Arndt and colleagues (2) compared speech in noise and localization for 11 adults with unilateral deafness using three devices; a Bone Anchored Hearing Aid (BAHA), a contralateral routing of signal (CROS) hearing aid, and a CI. Participants had three weeks use of the BAHA (softband/tension clamp) and CROS hearing aid prior to assessment and six months CI use. All testing was performed in the bilateral condition; that is, with the device and NH ear together. Scores in noise and localization were significantly better with the CI than with the other devices which are conventional treatments for unilateral deafness. Furthermore, improvement in noise and localization with the CI compared to the other devices was supported by the patients' subjective reports on the Speech, Spatial and Qualities of Hearing Scale (SSQ) (10).

Presently, cochlear implantation is not a common treatment for unilateral deafness in the United States, even for those with short-term deafness. Most published studies have been conducted in Europe; Roland and colleagues (1) reported on three cases in the US. Cochlear implantation as a treatment for unilateral deafness may not be widely accepted in the US for several reasons: lack of FDA approval, unknown insurance coverage, and greater cost compared to other treatments (e.g., CROS hearing aid). However, the advantages of obtaining bilateral hearing through cochlear implantation may outweigh the cost and surgical risks. Our research (11, 12) and study results noted above lend support to providing patients with the best hearing possible for each ear to optimize speech understanding and auditory function in everyday life. The objective of the current pilot study was to examine speech recognition in quiet and noise, localization, discrimination of temporal and spectral cues and subjective reports of CI recipients with short-term unilateral deafness.

MATERIALS and METHODS

This study was approved by the Human Research Protection Office (HRPO #201013033) at Washington University School of Medicine (WUSM).

Participants

Three adult male CI recipients participated. All had severe to profound sensorineural hearing loss (SPHL) with poor word recognition in one ear and normal to near-normal hearing in the other ear. Participants (P) 1 and 2 reported normal hearing prior to sudden onset of SPHL in one ear with no recovery after steroid treatment. Unexpectedly, an acoustic neuroma in the NH ear was discovered during P1's work-up for sudden SPHL in the other ear. P3 had high-frequency hearing loss in both ears for several years prior to left ear surgery to treat an internal auditory canal osteoma; after surgery, P3 had SPHL in that ear. Table 1 shows participants' pure tone thresholds for each ear prior to implantation. All three reported tinnitus in the ear with SPHL; P2 and P3 reported severe and debilitating tinnitus. Following evaluation and extensive counseling, participants were implanted in the deaf ear (right ear for each) with a Nucleus System 5 Cochlear Implant, (Centennial, CO, USA). P1 (age 62) was implanted at New York University Medical Center; P2 and P3 (ages 57 and 56, respectively) were implanted at University Medical Center Freiburg, Freiburg, Germany. All had relatively short duration of SPHL, 0.75, 4.5, and 2.5 years for P1-P3, respectively. P1 travelled to WUSM twice, four and 17 months after initial device activation. P2 and P3

travelled to WUSM once, 15 and eight months after initial activation, respectively. P1 and P3 spoke English as their primary language. P2 spoke German as his primary language but was fluent in English and spent several months annually in the US.

Test Conditions/Measures

Testing was completed over several days. For the majority of tests, participants were evaluated in three conditions, CI alone, NH ear alone and bilaterally (CI and NH ear). When testing the CI alone, the NH ear was plugged and muffed (EAR plug and Howard Leight muff). Roland (1) obtained CI alone monosyllabic word and speech in noise scores for three unilaterally deaf adults using two methods, plugging and muffing the NH ear and directly connecting to the CI speech processor. Scores did not differ significantly between the two methods. The current study participants reported hearing from the CI alone when the NH ear was blocked. All measures were administered twice in each condition except one psychoacoustic measure given four times per condition. For speech recognition measures, two lists were used for each administration. Participants had been seen recently at their respective CI centers for programming and equipment checks. Each was tested with their everyday speech processor programs and settings. Table 2 provides an overview of these parameters. While at WUSM, hearing thresholds were obtained using frequency-modulated (FM) tones in the sound-field (250–6000 Hz) with the CI alone and pure tones via insert earphones (250-8000 Hz) for the NH ear. All testing occurred in double-walled audiometric test booths with the participant seated at 0° azimuth, 1.5 meters from the front loudspeaker.

The test battery included both research and clinical test measures. The CNC monosyllabic word test (13) was presented at 60 dB SPL in quiet with participants using the CI alone and NH ear alone. For P2 (native German speaker), the test was also given bilaterally. CNC words were presented at 60 dB SPL in 4-talker babble (−2 dB signal-to-noise ratio [SNR], speech and noise from the front loudspeaker) while participants listened with the NH ear and bilaterally. Localization testing was completed with the participant facing an arc of 15 loudspeakers situated 10° apart and numbered 1–15. Monosyllabic words (100 words) were presented pseudorandomly through 10 active loudspeakers at 60 dB SPL (± 3 dB) and participants identified the source loudspeaker by number (14). A root mean square (RMS) error, measured in degrees, was determined for each condition.

Two assessments of sentence understanding in noise were included. The Bamford-Kowal-Bench Speech-in-Noise Test (BKB-SIN) (15) was administered in the sound-field with speech at 65 dB SPL from the front loudspeaker and noise (4-talker babble) from the front, 90° to the participant's right, and 90° to the participant's left. The SNR began at +21 dB for the first of 8 sentences and decreased until an SNR-50 was reached (SNR for which 50% of the key words were repeated); this was repeated for a total of 16 sentences per list. The Hearing In Noise Test (HINT) (16) was administered in the R-SPACE (17–19) using diffuse restaurant noise. Participants sat in the center of eight loudspeakers with noise presented at 60 dB SPL from each loudspeaker. The sentence intensity varied by 2 dB (softer for correct and louder for incorrect responses). A total of 17 responses per list were averaged to determine an SNR-50.

Two psychoacoustic measures used in ongoing WUSM studies were administered. The first used random spectrogram sounds (RSS) stimuli that were noise-like with no resemblance to speech or music (20). These stimuli allowed independent variation of spectral and temporal complexity without changing bandwidth, energy or duration (21). An “odd-man out,” three-interval, three-alternative, forced-choice adaptive paradigm was used to determine the minimum detectable changes in complexity (JND). Feedback was provided for correct responses and each of 4 test runs concluded with 8 reversals. The JND was an average of the last 4 reversals.

The second psychoacoustic task, an adaptive speech reception threshold (SRT) measure, was adapted from methods described by Litovsky and Johnstone (22, 23, 24). Target stimuli were 25 spondees spoken by a male talker presented in a 4-alternative forced-choice paradigm. No feedback was provided. Spondees were always presented from the front loudspeaker; noise was from the front, 90° to the right, or 90° to the left. Three types of competing noise (60 dB SPL) were randomly presented: male talker Harvard IEEE sentences (25), female talker Harvard IEEE sentences, and multi-talker babble (MTB). The spondee presentation level, which began at 60 dB SPL, varied adaptively based on participant responses. Testing for each noise condition ended after four reversals and the SRT was an average of the last three reversals.

Lastly, participant perceptions were documented through the SSQ (10) scales (speech, spatial and qualities) and discussions with the participants during their time at WUSM. The speech scale queries the ability to understand in difficult listening situations. The spatial scale probes the ability to judge direction or distance of sound. The qualities scale probes naturalness and clarity of sound and the ability to segment sound. Participants rated their ability for each item from 0–10 with a higher number representing greater ability.

RESULTS

All three participants had excellent audibility across the frequency range with the CI alone. Table 3 shows CI-alone FM tone sound-field thresholds and NH ear pure-tone thresholds. Each participant's CI sound-field thresholds were 12–26 dB HL from .25–6k Hz. Moreover, CI thresholds were similar to or better than pure-tone thresholds for the NH ear at 2k Hz and above. All three reported considerable improvement in their tinnitus when wearing the CI. P1 stated that his tinnitus worsened immediately after surgery but subsided prior to implant activation. P1 was seen for testing at 4 and 17 months post initial activation as stated above. The 17 month results will be reported as results were either similar between the two intervals or better at 17 months.

Figure 1A indicates that participants had open-set speech recognition using the CI alone. Significant differences between conditions for individuals were determined using a binomial model (26, 27) and p-values at least 0.05. CI alone CNC word scores were 75%, 30% and 37% for P1–P3, respectively, while NH ear scores were at ceiling for P1 and P3 (95% and 100%, respectively). The NH ear CNC score (84%) for P2 was below ceiling, possibly because English is his second language; therefore, CNC words were also presented bilaterally which resulted in a significantly higher score (97%, $p < 0.05$) than the NH ear. For CNC words presented in 4-talker babble (Figure 1B), participants' scores were higher when listening bilaterally than with the NH ear. Differences for P2 (15%) and P3 (14%) were statistically significant ($p < 0.05$).

Localization results are plotted in Figure 2 for each of the three listening conditions. RMS errors (in degrees) are shown in the upper left hand corner of each plot. An RMS error of 0° signifies complete accuracy. The x-axis represents the source location of the stimulus, and the y-axis the location of the participant's responses. Each participant's mean response and standard deviation in degrees azimuth is plotted for the ten active loudspeakers. A diagonal line from the lower left corner of the plot to the upper right corner represents 100% accuracy. The slopes of the fitted lines for each participant were compared across conditions using ordinary least squares (OLS) regression with correction of standard errors for unequal variance between conditions. For all participants, localization was significantly better bilaterally compared to the NH ear [P1, $F(1, 594) = 14.83$; P2, $F(1, 594) = 40.78$; P3, $F(1, 594) = 69.02$, all $ps < 0.001$]. P1 and P3 in particular had considerably less variability bilaterally than with the NH ear. Visual inspection of individual responses indicated that

bilaterally the preponderance of responses were heard as originating from the correct side, even when there was error identifying the specific source loudspeaker. Performance with a single ear varied among participants. Notably, P2 was unable to localize at all with the CI and had relatively accurate NH ear localization.

Mean SNR-50 BKB-SIN results are shown for each participant and test condition in Figure 3. In each panel, sentences are presented from the front. Noise (babble) location varies, from either the front loudspeaker (panel A), towards the NH ear (panel B) and towards the CI (panel C). An SNR-50 of 23.5 dB indicates inability to understand key words from the sentences at the highest SNR. For all three noise locations, participants understood sentences with the CI alone. The lowest (best) CI alone SNR-50 (4 dB for P1 and 10 dB for P2 and P3) occurred with noise to the NH ear. No significant differences (> 3.1 dB for 95% confidence interval with adult CI users and two lists, [28]) were seen between the NH ear and bilaterally for any noise location indicating that the CI did not improve performance nor did it hinder performance, even when noise was presented to the CI. Similarly, as shown in Figure 4, no significant differences (> 1.4 dB for 95% confidence interval; [18]) were seen in SNR-50 between the NH ear and bilaterally in the R-SPACE. Using the CI alone, P1 and P3 understood sentences in restaurant noise with SNRs of 5.06 dB and 12.29 dB, respectively, whereas P2 did not understand sentences at the highest SNR of 22 dB.

Figure 5 shows results of the psychoacoustic task using RSS stimuli with JND scores for stimuli that differed in temporal (panel A) and spectral (panel B) complexity. Lower JNDs indicate better performance. Each panel shows individual participant results for the NH ear (left), bilaterally (center) and the CI (right) for test runs 1 through 4. Data from our laboratory with 20 NH participants, ages 23 – 62 years (mean 41, SD 13) listening bilaterally are displayed in gray (mean as solid line, ± 1 SD as dashed lines). Panel A (Temporal RSS) shows that most JNDs for participants' NH ear were within one SD of the NH group mean. Most JNDs bilaterally and some JNDs with the CI alone were at least one SD better than the NH group mean. Panel B (Spectral RSS) shows that with the NH ear alone and CI alone, all participants had most or all JNDs within one SD of the NH mean. Bilaterally, P1 and P2's JNDs were better than one SD of the NH mean with their bilateral scores being the best of the three listening conditions.

Figure 6 shows the results of the adaptive SRT test with a similar format to Figure 5. The NH means and SD in gray are from 24 NH adults, ages 22 – 67 (mean 49, SD 13). For each listening condition, SRTs are shown in quiet as the average across trials and in noise as the average across trials and noise types by location of the noise (toward CI, toward NH ear, from the front). In quiet, listening bilaterally produced the lowest SRT with the biggest difference between the NH ear and bilaterally for P1 (7.5 dB). With noise, the score bilaterally continued to be equal to or lower than the NH ear for most conditions and participants indicating that the CI did not hinder nor improve speech perception. However, compared to NH group data (in gray), most SRTs for P1–P3 were poorer than one SD of the mean. In addition, the functions were steeper in the NH group data and considerably improved in quiet (mean 14 dB, SD 8 dB) compared to the noise conditions. In contrast, P1–P3 showed a shallower function with higher SRTs in quiet (means 43, 31, and 39 dB for P1–P3, respectively) and less difference between quiet and noise.

Lastly, results from the SSQ are presented in Figure 7. P1 (at 4 months post-implant) and P3, the native English speakers, were asked to complete the scale retrospectively recalling pre-implant hearing ability. Vermeire and Van de Heyning (6) asked unilaterally deaf participants to complete the SSQ prior to surgery and then to recall listening with one ear in the pre-implant condition after 12 months CI use. No significant difference in SSQ scores were found between the prospective and retrospective ratings. All three participants were

also asked to complete the scale as they currently hear, with the CI and NH ear (bilaterally). Mean participant ratings across items are plotted for the three SSQ scales. The plus symbols denote “benefit” as described by Noble and colleagues (29, 30). Bilaterally, P1 and P2 rated themselves as having relatively high overall ability (scores of 7.0 – 8.8). P3 rated his ability lower (scores of 5.8 – 6.2). The addition of the CI resulted in marked improvement for P1 and P3 (3.3 and 4.7 respectively) on the spatial scale, an increase for P1 on the speech scale (1.1) and a decrease for P1 on the quality scale (1.5). Primary areas of decreased quality for P1 were related to the naturalness of music and ignoring unwanted sounds.

DISCUSSION

Many benefits reported in the recent literature for CI users with unilateral deafness are similar to benefits obtained by the three participants in this pilot study. P2 and P3 reported their primary interest in obtaining a CI was relief from severe tinnitus that began after sudden SPHL. P1 also reported pre-implant tinnitus, but tinnitus relief was not his motivation for implantation. All three reported substantial tinnitus relief with CI use. All three participants had open-set speech recognition and excellent audibility with the CI alone; however, to determine benefit to auditory function, the primary comparison was between the NH ear and bilateral listening conditions. Localization for all three participants was significantly better bilaterally than with the NH ear alone ($p < 0.001$). Not only were mean responses for each loudspeaker location more accurate but response variability decreased (Figure 2). Similarly, Arndt et al. (2) showed significantly improved localization bilaterally (CI and NH ear) compared to the NH ear alone and to the more conventional treatments of unilateral deafness, BAHA and CROS hearing aid.

Speech recognition improvements in noise were not as evident. P2 and P3 showed significant improvement for CNC word scores in noise bilaterally compared to the NH ear ($p < 0.05$). Sentence and closed-set word understanding in noise (BKB-SIN, R-SPACE, and adaptive SRT) did not differ between the NH ear and bilateral conditions. Others have demonstrated significantly higher scores bilaterally compared to the NH ear alone when speech was presented to the CI and noise presented to either the NH ear (2, 9) or from the front loudspeaker (6). Arndt et al. (2) also found significantly higher scores bilaterally (CI and NH ear) compared to the BAHA or CROS hearing aid with speech to the device and noise to the NH ear. Furthermore, Arndt et al. (31) showed a trend towards higher scores bilaterally (speech presented to the NH ear and noise to the CI) compared to the NH ear alone (11 participants with 12 months CI use). Similar to the current study results, there was no decrement when noise was presented to the CI. In the current study, speech was always presented from the front loudspeaker with the noise presented either from the front or from each side. Speech was never presented to the CI or the NH ear since it is common for hearing-impaired listeners to turn and face the speaker; therefore, speech is often located in front of the individual. The speech-in-noise tests and conditions used in this pilot study were originally designed to study effects of CI treatment for bilateral SPHL and therefore may not be sensitive to outcomes when adding a CI to a NH ear. Although in noise sentence understanding did not improve bilaterally, no decrement in understanding was seen indicating that the CI does not hinder performance in noise.

For the psychoacoustic task and RSS stimuli, all participants had lower JNDs for temporal complexity bilaterally compared to the NH ear alone and two participants (P1 and P2) had lower JNDs for spectral complexity bilaterally. Together, these results suggest enhanced discrimination for temporal and spectral cues when the CI is added to the NH ear. Participants' SSQ scores were within the range reported in other studies (2, 6, 31) and were in agreement with those studies' in that CI users with unilateral deafness reported most benefit in spatial hearing and speech understanding and less if any benefit in quality of

hearing with the addition of a CI. Likewise, Arndt et al. (2) reported SSQ results for 11 unilaterally deaf CI users. Bilateral scores were significantly higher for speech understanding and spatial hearing compared to the NH ear alone, BAHA, or CROS aid. No significant difference in scores was seen for quality of hearing. All participants in the current study wear the CI full time, reported high satisfaction with their decision to be implanted, and identified improved sound localization in daily life as a substantial benefit. Although P1 and P3's mean quality scores were slightly poorer when adding the CI, their responses to individual items suggested an increased ability for certain situations (less effort when listening) and a decreased ability for others (differentiating concurrent sounds, ignoring unwanted sounds). Additionally, P1 expressed appreciation for the supplementary CI input to confirm what was heard from the NH ear. Hearing sound in stereo rather than mono was an important improvement for P2 who stated that overall he had "a better life". P3 indicated adjusting to the CI took time but that it was "absolutely the right solution".

Although rehabilitation activities were recommended for all three participants, implementation varied. Given the inability of a CI to restore natural hearing and the advantage of a holistic approach to patient care that includes aural rehabilitation (32, 33), post-implant therapy may be an important factor to maximize CI benefit. In addition, rehabilitation approaches and overall outcomes may differ for unilaterally deaf patients who are implanted primarily for tinnitus relief than those who seek improved communication abilities.

The participants in this study and those in the Arndt et al. (2) study chose cochlear implantation over conventional treatments of unilateral deafness. This may have biased their SSQ ratings and their reports of satisfaction with the CI. On the other hand, localization and listening in noise were significantly improved with the CI compared to the NH ear, BAHA or CROS aid (2). Those results along with results from this pilot study support fitting individual patients with a device that provides the best hearing for each ear to optimize speech understanding in everyday listening situations and improve overall communication abilities. Additional study is needed with a large group of unilaterally deaf participants over a longer time period to delineate indications and further quantify outcomes and potential mitigating factors of cochlear implantation in this population.

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Figure 1.

CNC word scores in quiet for the CI and NH ear and bilaterally for P2 (panel A). CNC word scores in noise (−2 dB SNR with four-talker babble) for the NH ear and bilaterally (panel B). Asterisks denote significant differences ($p < 0.05$).

Figure 2.

Participants' localization results for the three listening conditions, CI, NH ear, and bilaterally. For each plot, the x- and y-axes represent the locations of the stimulus and the participants' responses to the stimulus, respectively. The RMS error, in degrees, is indicated in the upper left hand corner of each plot. Asterisks denote significant differences between the NH ear and bilaterally ($p < 0.001$).

Figure 3.

Participants' mean SNR-50 obtained for each listening condition for the BKB-SIN test when sentences were presented from the front loudspeaker and noise was presented from the front (panel A), from the left (panel B), and from the right (panel C).

Figure 4. Participants' average SNR-50 obtained for the HINT in the R-SPACE for each listening condition.

Figure 5. Participants' mean JNDs for Temporal (panel A) and Spectral (panel B) RSS stimuli are displayed for test runs 1 through 4 and the three listening conditions. Data from NH adults are shown in gray (mean and ± 1 SD).

Figure 6.

Participants' mean SRTs are displayed in quiet and noise (noise to CI, noise to NH, noise front) for the three listening conditions. Data from NH adults are shown in gray (mean and ± 1 SD).

Figure 7.

Participants' average rating across test items for each SSQ scale. P1 and P3 completed the SSQ as they would have prior to obtaining a CI (NoCI). P1–P3 completed the SSQ as they currently hear with the CI and NH ear (CI). The plus symbols denote “benefit” as described by Noble and colleagues (30).

Table 1

Hearing thresholds in dB HL from 250–8000 Hz for both ears prior to cochlear implantation

Participant	Ear	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	6000 Hz	8000 Hz
P1	Right	60	85	85	85	100		95
	Left	20	20	25	25	15	20	25
P2	Right	70	90	105	100	105		NR
	Left	10	20	30	30	30	40	50
P3	Right	70	70	90	85	90	90	80
	Left	10	10	15	20	45	30	40

dB = decibel, HL = hearing level, Hz = hertz, NR = no response

Table 2

Speech processor program or MAP parameters for each participant

Participant	Processing Strategy	Rate/ch (pps/ch)	Total Stim Rate	No Active Electrodes	Stim Mode	PW μ sec/phase	FAT	Avg Elect DR (Avg C – Avg T)
P1	ACE	900 Hz	7200 Hz	22	MP1+2	25	Default	58 CL
P2	ACE	1200 Hz	9600 Hz	20	MP1+2	25	Default	72 CL
P3	MP3000	900 Hz	7200 Hz	22	MP1+2	25	Default	50 CL

Avg = average, C = comfort level, ch = channel, FAT = frequency allocation table, No = number, pps = pulses per second, sec = second, Stim = stimulation, T = threshold level

FM tone, sound-field threshold levels in dB HL obtained with the CI from 250–6000 Hz and pure tone threshold levels for the NH ear obtained with insert earphones

Table 3

Participant	Ear	250 Hz	500 Hz	750 Hz	1000 Hz	2000 Hz	3000 Hz	4000 Hz	6000 Hz
P1	CI	12	14	14	12	14	22	18	20
	NH	25	25	30	30	30	25	20	25
P2	CI	16	20	12	20	16	24	22	18
	NH	10	15	15	10	15	30	40	30
P3	CI	16	18	14	18	14	20	20	26
	NH	15	20	30	30	30	30	30	45

CI = cochlear implant, dB = decibel, FM = frequency modulated, HL = hearing level, Hz = hertz, NH = normal hearing