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A within-subjects comparison of bimodal hearing, bilateral cochlear implantation, and bilateral cochlear implantation with bilateral hearing preservation: High-performing patients

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Abstract

A comparison of bimodal hearing and bilateral cochlear implants (CIs) was completed using a within-subjects, repeated-measures study for eight adult sequential recipients who despite achieving incredibly high performance with the first CI, self-selected for bilateral implantation. Speech understanding was assessed with the minimum speech test battery (MSTB) as well as sentences in semi-diffuse noise using the R-SPACE™ system. Conditions included unilateral hearing aid (HA) in the non-implanted ear, unilateral CI, bimodal (CI+HA), and bilateral CI. Additionally, three participants had bilateral hearing preservation and were also tested with bilateral CIs and bilateral HAs (BiBi). All testing was completed in the bimodal hearing configuration and repeated at least six months following activation of the second CI. Bilateral CIs afforded significant individual improvement in a complex listening environment even for individuals demonstrating near perfect sentence scores with both the 1st CI alone as well as the bimodal condition. The 3 BiBi participants demonstrated additional significant benefit over the bilateral CI condition—presumably due to the availability of interaural time difference cues. These data suggest that for noisy environments, adding a second implant can significantly improve speech understanding—even for high performing unilateral CI with bimodal hearing. In diffuse noise conditions, bilateral acoustic hearing can yield even greater benefit beyond that offered by bilateral implantation.

Keywords

hearing preservation; electric and acoustic stimulation (EAS); bimodal hearing; bilateral cochlear implants; speech recognition

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¹For those bimodal individuals not able to complete a SRT for the HA ear, a score of 20 dB SNR was arbitrarily assigned for analysis purposes; 7 of the 8 participants were unable to track an SRT at any SNR for the HA ear alone.

INTRODUCTION

Bilateral cochlear implantation is considered standard of care for individuals with bilateral severe-to-profound sensorineural hearing loss^{1–3} offering higher levels of speech understanding than observed preoperatively with appropriately fitted hearing aids. Speech recognition with CIs however, is limited by poor spectral resolution and loss of temporal fine structure associated with envelope-based signal processing strategies. On the other hand, bimodal hearing which combines a CI in one ear and hearing aid (HA) in the opposite ear, generally affords greater spectral resolution—albeit across a narrower spectral range than that offered by the CI—and temporal fine structure cues via acoustic hearing in the low- to mid-frequency region of the non-CI ear. Zhang and colleagues have shown that even when acoustic hearing in the non-CI ear is quite poor, that residual frequency selectivity is generally better than that offered by the CI^{4–6} and that the degree of bimodal benefit was correlated with spectral resolution in the non-CI ear⁷. Given the high levels of performance that can be achieved with either bilateral CI or bimodal hearing, clinicians find themselves questioning which is the best intervention for each individual patient. Unfortunately, there is no particular test or set of criteria that can differentially indicate the appropriate intervention. We can look to the literature for answers, however, differences in (i) patient selection, especially the degree of residual hearing in the aided ear^{8,9}, (ii) test materials and (iii) test environments make between-study comparisons problematic, the weight of evidence is that the two interventions can provide similar levels of benefit to CI patients^{4,8,10–20}. All but two of the bimodal vs. bilateral studies used between-subjects designs and studies of this type need large samples and subject heterogeneity to be interpreted with confidence – a condition that is very rarely met. One way to overcome this problem is to use a within-subjects design. We review the two published studies that used a within-subjects design in the following section.

Potts and Litovsky¹³ describe speech understanding and sound source localization for four individuals in bimodal and bilateral CI conditions. The individuals received little benefit from amplification in the bimodal condition, as scores were no different than the unilateral CI condition. None-the-less, only two of the four listeners achieved higher scores on tests of speech understanding with bilateral CIs than with the bimodal fitting. All patients had better sound localization in the bilateral CI condition than in the bimodal condition and all preferred the bilateral fitting which is consistent with previous reports of greater subjective benefit for bilateral implantation²¹.

Luntz and colleagues²² reported speech understanding and lateralization for ten adults also using a within-subjects design. Nine of the ten listeners were postlingually deafened and all were first implanted in adulthood. The gain in speech understanding in the bimodal condition vs. the CI alone condition was not reported – thus it is not clear how much benefit from acoustic hearing the patients enjoyed. When the patients were tested with collocated speech and noise, the mean speech understanding was not significantly different in the bilateral CI and bimodal conditions. However, when speech and noise were spatially separated, speech understanding and sound lateralization were significantly better in the bilateral CI condition than in the bimodal condition.

This outcome points to a significant problem using clinical measures of speech understanding, such as those outlined in the adult minimum speech test battery (MSTB²³), for which speech is typically presented from single loudspeaker placed at 0 degrees. If noise is presented, it is generally collocated with the speech and thus the potential benefits of having a second CI are not being critically evaluated. The purpose of the current study was to investigate the differences between bimodal hearing and bilateral CI in a prospective manner using a within-subjects design for which we assess outcomes for clinical measures of speech understanding as well as more complex, yet realistic listening environments. Our hypothesis was that bilateral cochlear implantation would yield significantly higher levels of speech understanding, but only for complex listening tasks not typically administered in a clinical environment.

An interesting aspect of our sample is that the patients differed significantly from those tested in previous studies in terms of speech understanding scores with a single CI. The mean consonant nucleus consonant (CNC²⁴) word recognition score was 87% correct with a range of 76 to 98% correct. Given that the mean CNC scores for a large sample of patients ranges from 55 to 62% correct^{25,26}, our group of patients ranks in the top 1 to 5% of all patients implanted with a single CI. Despite this stellar performance, all patients selectively pursued a second CI. Thus, our interest was whether a bilateral fitting would result in improved speech understanding even for patients with extraordinarily good single CI performance and considerable low-frequency acoustic hearing in the non-CI ear.

Three of our eight patients were unique in another way: they had successful hearing preservation surgery in both ears. Thus, we were also able to explore the value of a bimodal, a bilateral, and a BiBi fitting—as termed by Dorman and colleagues²⁷—which includes bilateral CI and bilateral acoustic hearing.

MATERIALS AND METHODS

Participants

Demographic information for the eight participants is shown in Table 1. Variables include age at testing, gender, implant type, experience with implants, aided speech intelligibility index (SII) for non-CI ear at 60 dB SPL as evidenced via real-ear measures (Audioscan Verifit). Participants ranged in age from 50 to 75 years old with a mean of 59.4 years. All patients received their implants in sequential surgeries and had an average of 3.0 years (range of 0.6 to 7.5 years) between surgeries.

Individual and mean audiometric thresholds for the non-implanted ears at the bimodal test point are shown in Figure 1A. Mean thresholds were consistent with a moderate sloping to profound sensory hearing loss. Individual audiograms ranged from normal hearing to profound loss at 500 Hz. Three of the eight subjects in this study had preserved acoustic hearing in both implanted ears effectively making them bilateral CI recipients with bilateral hearing preservation or *BiBi patients*²⁷. Figure 1B displays individual and mean postoperative audiograms for the 1st implanted ear of the three BiBi patients and Figure 1C displays individual and mean postoperative audiograms for the 2nd implanted ear of the

three BiBi patients. Audiograms were obtained for all participants immediately prior to experimentation.

Listening conditions

Listening conditions included unilateral HA in the non-implanted ear, unilateral CI, bimodal (CI+HA), and bilateral CI. For all participants, testing was completed in the bimodal hearing configuration and then repeated no sooner than six months following activation of the 2nd CI. At the bimodal test point, the three participants with bilateral hearing preservation (6, 7, & 8) were also tested in the “combined” condition which included the first CI plus bilateral HAs. Subject 8 was not brought into the lab prior to obtaining his 2nd CI; however, speech understanding had been assessed in the 1st CI and bimodal condition for the MSTB materials at his home clinic. Given that he had bilateral hearing preservation, testing for the bimodal condition in the full MSTB and in the R-SPACE™ system was tested comprehensively at the bilateral/BiBi test point. For the MSTB, this patient’s bimodal scores were not significantly different using binomial distribution statistics^{28,29} from those obtained at his home clinic prior to the receipt of his 2nd CI.

At the bilateral test point, the three hearing preservation participants were also tested in the BiBi condition. Each of the BiBi participants had been upgraded to the Nucleus N6 processor with integrated acoustic component in conjunction with custom earmolds—though they had previously been tested in their *bimodal condition* with the previous generation processor (CP810); however, we assessed bilateral and BiBi performance at the same visit with the same processors to maintain consistency across listening conditions at the same test point.

Prior to experimentation, HA audibility was verified for 60-dB-SPL speech using real-ear measurements with NAL-NL1³⁰ prescriptive targets. Participants for whom hearing aids were undershooting target audibility by more than 5 dB at one or more frequencies had their hearing aids reprogrammed to match NAL-NL1 targets. Aided SII values at 60 dB SPL for the non-CI ear for all bimodal test points and for the CI ears for the BiBi patients are shown in Table 1.

Methods

Speech understanding was assessed using consonant nucleus consonant (CNC²⁴) word recognition and AzBio²⁹ sentence recognition as outlined by the adult MSTB²³. Recorded MSTB stimuli were presented in a sound-treated booth at a calibrated level of 60 dBA. Participants used their everyday CI programs and were not permitted to manipulate settings during testing. All MSTB testing was completed with a single loudspeaker placed at 0 degrees at a distance of 1 meter. For AzBio sentence recognition at +5 dB signal-to-noise ratio (SNR), the speech and noise were collocated. For consonant nucleus consonant (CNC²⁴) and AzBio²⁹ sentence recognition, a single list was run for each condition to be consistent with typical clinical practice. Listening conditions were counterbalanced across participants in each listener group with the list numbers chosen in a quasi-random manner.

Speech understanding was also assessed in the R-SPACE™ test environment. In this environment, the listener is seated in the middle of an 8-loudspeaker sound system arrayed in a 360-degree pattern around the listener. Directionally appropriate noise, originally recorded in a restaurant, was played from each loudspeaker. The speech signals were played from the loudspeaker at 0 degrees to the listener (both signal and noise were presented from this loudspeaker). Speech understanding was also assessed using an adaptive speech reception threshold (SRT). The Hearing in Noise Test (HINT³¹) sentences were adaptively varied in the presence of a restaurant noise fixed at 72 dBA using a one-down, one-up stepping rule to track the SNR required for 50% correct.

RESULTS: Bimodal versus Bilateral test point

Individual results for CNC words, AzBio sentences in quiet and noise, and adaptive HINT SRT in the R-SPACE™ system are shown in Figure 2. For all panels in Figure 2, the HA alone is represented by upward slanting bars, the 2nd CI alone is represented by the gray bars, the 1st CI alone is represented by the white bars, the bimodal condition is represented by the downward slanting bars, and the bilateral condition is represented by the black bars. The 1st CI alone was assessed twice—once at the bimodal and again at the bilateral test point. We completed a two-tailed t-test for the 1st CI scores at the bimodal and bilateral test points for each speech metric and found no significant difference ($p > 0.05$ for all analyses). Thus the 1st CI scores were averaged for ease of reporting here.

Group statistics for such a small sample would be of questionable value. For that reason, we assessed changes in individual performance using the 95% confidence limits for 50-item CNC word lists²⁸, for 20-item AzBio sentences²⁹, and for adaptive HINT in noise using four 10-sentence lists (± 1.12 dB³¹).

CNC words

In the HA alone condition, the scores ranged from 0 to 54 percent correct. All eight patients demonstrated significant improvement following receipt of the 2nd CI with scores for that ear ranging from 46 to 86 percent correct. In the 1st CI alone condition, the scores ranged from 76 to 95 percent correct. No patient showed significantly improved performance in the bimodal condition. Only one patient (7) showed significantly improved performance with bilateral CI as compared to the bimodal condition.

AzBio sentences in quiet

In the HA alone condition, the scores ranged from 0 to 75 percent correct. All eight patients demonstrated significant improvement following receipt of the 2nd CI with scores for that ear ranging from 60 to 99 percent correct. In the 1st CI alone condition, the scores ranged from 97 to 100 percent correct. No patient showed improved performance in either the bimodal or bilateral condition.

AzBio sentences at +5 dB SNR

In the HA alone condition, the scores ranged from 0 to 22 percent correct. All but one patient (5) demonstrated significant improvement following receipt of the 2nd CI with scores

for that ear ranging from 16 to 90 percent correct. In the 1st CI alone condition, the scores ranged from 44 to 84 percent correct. Two patients (2 and 6) showed significantly improved performance in the bimodal condition. Four patients (1, 2, 3, and 7) showed significantly improved performance in the bilateral condition over the bimodal condition. Patient 2—who showed significant benefit from both a bimodal and then again from a bilateral fitting—achieved the highest level of performance in the bilateral condition.

R-SPACE™ adaptive HINT

In the HA alone condition, the SRTs ranged from 16.0 to > 20.0 dB SNR, as seven of the eight patients could not complete a SRT in the HA alone condition. All eight patients demonstrated significant improvement following receipt of the 2nd CI with SRTs for that ear ranging from 4.3 to 12.0 dB SNR. In the 1st CI alone condition, SRTs ranged from 5.0 to 11.8 dB SNR. Two patients showed significantly improved performance in the bimodal condition (3 and 7) as compared to the 1st CI alone. Six patients showed significantly improved performance in the bilateral condition as compared to the bimodal condition (1, 2, 3, 5, 6, and 8).

BiBi patient performance: R-SPACE™ adaptive HINT

The adaptive HINT performance of the three bilaterally implanted patients with preserved low-frequency hearing in both ears is shown in Figure 3. For all three patients, bilateral HAs combined with a single CI provided significant benefit over both single CI and bimodal stimulation. Bilateral HAs combined with a single CI provided one patient (6) with significant benefit as compared to bilateral CIs. Critically, bilateral HAs combined with bilateral CIs (BiBi condition) provided the highest level of performance (lowest SRTs) for all three patients with significantly improved performance for all three patients as compared to the bilateral CI condition. In fact, 2 of the 3 patients (6 & 7) exhibited SRTs at a negative SNR in the BiBi condition which approximates mean performance for adults with normal hearing³².

DISCUSSION

Determining appropriate bilateral CI candidacy is a clinical challenge for audiologists and otologists. For the typical bimodal patient, the amount of acoustic hearing in the non-CI ear is alone not sufficient to allow high levels of communication; however, that residual hearing can provide significant benefit when paired with a CI^{33–37}. For these individuals, receiving a second CI can mean risking some or all of the acoustic hearing in the non-CI ear. Thus the decision to pursue bilateral implantation is a difficult one and one that is generally made without data-driven guidance. Bilateral candidacy is generally going to be determined based on both the audiogram for the non-CI ear as well as speech understanding scores on the MSTB.

In the current study, the MSTB was largely insensitive to the potential benefits of bilateral implantation as there was no difference bimodal and bilateral CI scores for seven of the eight patients on CNC words and none of the patients on AzBio sentences in quiet. AzBio sentences at +5 dB SNR held the greatest promise, though only half the sample showed

significant difference between bimodal and bilateral CI scores. In contrast, assessment in a more realistic and challenging listening environment, all eight patients achieved either equivalent or better performance with bilateral CI as compared to the bimodal condition with six of the eight patients (75% of the sample) demonstrating statistically significant bilateral benefit. Thus the current findings were consistent with our primary hypothesis that bilateral CI would yield significantly higher levels of speech understanding, but only for complex listening tasks not typically administered in a clinical setting.

Though clinical measures of speech understanding generally did not show a difference between bimodal and bilateral CI performance, we may still be able to use the MSTB to effectively identify individuals who would be best served with a 2nd CI. For AzBio sentence recognition at a +5 dB SNR, only two of eight patients (25% of the sample) demonstrated a significant difference between performance with the 1st CI alone as compared to bimodal hearing. In contrast, seven of the eight patients (88% of the sample) demonstrated a significant difference between the 1st CI alone and the bilateral CI condition. Thus for those bimodal patients not demonstrating *a significant bimodal benefit*—at the individual level—for AzBio sentences at +5 dB SNR, they may be better served with a 2nd CI; however, this will certainly require a more thorough investigation with a larger sample.

Of interest to note here is that all individuals demonstrated significant improvements in CNC word and AzBio sentence recognition with a 2nd CI as compared to the HA alone condition. For AzBio sentences at +5 dB SNR, all but one patient demonstrated significant improvement with a 2nd CI. In addition to this improvement, bilateral implantation yielded similar levels of performance for each ear individually thereby reducing the need for preferential seating to favor the “better” ear as is the case with bimodal hearing. This point alone will prove useful for counseling bimodal listeners inquiring about a 2nd CI—the greater interaural symmetry in both detection and recognition affords significant communication benefit in diffuse noise environments such as those assessed in the R-SPACE™ system.

BiBi patients

The SRT data in Figure 3 show similar performance for a single CI with bilateral HAs as compared to bilateral CIs. This finding would suggest that similar degrees of auditory benefit may be possible with two very different treatment options—bilateral implantation and unilateral implantation with hearing preservation. Though the small sample size precludes generalization, this finding certainly warrants further investigation—particularly given the diversity of residual acoustic hearing and the fact that all individuals exhibited significantly improved performance with the addition of residual acoustic hearing in the implanted ears. That is, for the BiBi condition, *all three patients demonstrated an individually significant improvement in the SRT with the addition of bilateral HAs*. For patient 8, a single CI + bilateral HAs and bilateral CIs yielded the same level of performance—and both were better than a single CI alone and bimodal hearing. For this patient, interaural time differences (ITDs) available in low-frequency information with bilateral HAs and interaural level differences (ITDs) available in higher frequency information with bilateral CIs provided similar value. Using this logic, for patient 6, ILD cues were of greater

value while for patient 7, ITD cues were of more value. Of course, this assumes that patients with low-frequency hearing preservation as making use of ITDs—a supposition worthy of further evaluation. Never-the-less, with increasing rates of hearing preservation and availability of atraumatic electrodes from all 3 FDA approved implant manufacturers, we should expect more CI recipients with hearing preservation pursuing a second CI—with the goal of a BiBi listening configuration.

CONCLUSION

Bilateral implantation afforded significant individual improvement in a complex listening environment even for individuals who approach ceiling-level word and sentence scores with both the 1st CI alone as well as in the bimodal condition. All patients in this study self-selected with respect to the pursuit of a 2nd CI. In fact, several of these patients were urged to reconsider their decision to pursue a 2nd CI for fear of lost function with the loss of residual acoustic hearing in the non-CI ear. We should assume that these patients pursued a 2nd CI as they thought they could get more benefit from a 2nd CI than they were currently deriving from their residual acoustic hearing. The current data support this supposition as only two patients (2 and 6) showed significant bimodal benefit at the individual level for AzBio sentences at +5 dB. On this view the increased benefit from a 2nd CI isn't very surprising. Unfortunately patients who enjoy high benefit from bimodal hearing will probably not pursue a 2nd CI. So we are unable to make sweeping claims about bimodal vs. bilateral benefit. We can, however, state that good low-frequency hearing does not guarantee bimodal benefit. This is something that we have recognized for some time now, as audiometric thresholds do not correlate with either postoperative benefit with a CI^{34,36–43} nor with degree of bimodal benefit^{4,6,9,37}; however, when presented with such good audiometric thresholds in the non-CI ear, it can understandably be difficult for audiologists and otologists to make recommendations for a 2nd CI.

Our current findings are aligned with bilateral CI being standard of care treatment for bilateral sensory hearing loss^{1–3}. Further significant benefit will be observed with the addition of bilateral preserved acoustic hearing for a BiBi listening configuration—with two of the three BiBi patients achieving speech understanding that rivaling normal-hearing performance. This suggests that bilateral CIs with bilateral hearing preservation will offer the highest possible performance in diffuse noise and should not be overlooked as a treatment option for patients with relatively good low-frequency hearing and severe-to-profound high frequency hearing loss.

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FIGURE 1.

Individual and mean audiometric thresholds (in dB HL) obtained on the day of testing for the non-implemented ears of the bimodal (A) and hearing preservation patients for the 1st implanted ear (B) as well as the 2nd implanted ear (C) of the hearing preservation patients. Error bars in panel A represent ± 1 standard error.

FIGURE 2.

Individual and mean speech understanding for CNC words (upper left), AzBio sentences in quiet (upper right), AzBio sentences at +5 dB SNR (lower left), and adaptive HINT SRT in the R-SPACE™ system (lower right). Listening conditions including the HA alone, 2nd CI alone, 1st CI alone, bimodal and bilateral CI are represented by the upward slanting, gray, white, downward slanting, and black bars, respectively. The 1st CI condition is the mean of scores obtained at the bimodal and bilateral test points. Upward arrows indicate that an SRT could not be tracked for that condition. See text for further details.

FIGURE 3.

Individual SRT, in dB SNR, for HINT sentences in the R-SPACE™ sound simulation system. SRTs for patients 6, 7, and 8 are represented as the white, gray, and black symbols, respectively. An upward arrow indicates that an SRT could not be obtained for that listening condition.

Demographic and device information for the 8 participants. Subjects 6, 7 and 8 were upgraded to the N6 (CP920) processor prior to testing in the BiBi condition to allow for integrated implant processor and acoustic amplification. However, we found no difference in performance with bilateral CP810 and bilateral CP920 processors for the conditions included here. Thus we are confident that the significant improvement noted in the BiBi condition was due to the addition of binaural acoustic hearing, not processor functionality.

TABLE 1

	Age at bimodal testing point (years)	Gender	1 st device and processor	2 nd device and processor	1 st CI experience (years) at bimodal testing	2 nd CI experience (years) at bilateral testing	Time between surgeries (years)	Aided SII for non-CI ear at bimodal test point	Aided SII for CI ears at BiBi test point (1 st CI ear, 2 nd CI ear)
1	75	Male	CI24RE(CA), Freedom	CI512, CP810	6.2	1.4	4.2	4	N/A
2	58	Female	HR90K Ij, Harmony	HR90K Ij, Harmony	5.5	0.8	6.4	19	N/A
3	66	Male	CI24RE(CA), Freedom	CI512, CP810	1.3	1.2	1.3	12	N/A
4	50	Female	HR90K Helix, Harmony	HR90K Helix, Harmony	0.5	1.3	0.6	40	N/A
5	62	Male	CI512, CP810	CI512, CP810	0.6	0.5	0.6	15	N/A
6	52	Male	CI512, CP810	CI24RE(CA), CP810	0.7	0.9	1.9	46	9, 11
7	54	Male	CI512, CP810/ CP920	CI24RE(CA), CP810/ CP920	1.8	1.1	1.7	28	19, 17
8	58	Female	CI24RCA, CP810/ CP920	CI24RE(CA), CP810/ CP920	6.4	1.7	7.5	31	14, 13
Mean	59.4	--	--	--	2.9	1.1	3.0	24.4	14.0, 13.7
Stdev	8.2	--	--	--	2.7	0.4	2.7	14.4	5.0, 3.1