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Clinical Selection Criteria for a Second Cochlear Implant for Bimodal Listeners

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Abstract

Objective—To compare the speech perception benefit, provided by a contralateral hearing aid (HA) or a second cochlear implant (CI).

Study Design—Repeated measures.

Patients—A total of 25 adult subjects participated in the study, including 12 bilateral (10 females and 2 males) and 13 bimodal (6 females and 7 males) users. All bilateral users were sequentially implanted. The bimodal users were separated into a poor group (n=5, aided pure-tone average (PTA) 55 dB HL at audiometric frequencies 1 kHz) and a good group (n=8, aided PTA < 55 dB HL).

Main Outcome Measures—Consonant, vowel, and sentence recognition was measured in quiet and noise at +5 dB and +10 dB signal-to-noise ratios (SNRs). Speech recognition performance was evaluated under three listening conditions: CI alone, HA alone, and CI+HA for bimodal users; first CI alone, second CI alone, and first CI + second CI for bilateral users when speech and noise were presented from the front.

Results—There was no significant difference in the binaural benefit between the good bimodal and bilateral groups in vowel and sentence recognition. However, the binaural benefit is significantly better in the bilateral group than in the poor bimodal group for all three speech measures.

Conclusion—These results suggest that the aided pure-tone average at audiometric frequencies 1 kHz may serve as one of the clinical criteria for the recommendation of whether or not bimodal patients should consider a second cochlear implant in order to maximize their binaural listening ability.

Keywords

Binaural hearing; cochlear implant; hearing aid; speech recognition

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Introduction

With the increased interest in bilateral cochlear implants (CIs) in recent years, establishing clinical selection criteria for the second (2nd) CI has become very important for bimodal listeners who have a CI in one ear and a hearing aid (HA) in the opposite ear. For bimodal listeners with no residual hearing that can be aided by a HA in the non-implanted ear, the decision is straightforward because the evidence of additional benefit from bilateral implants compared to a unilateral CI has been thoroughly demonstrated (1–4). In contrast, for bimodal listeners with relatively good residual hearing in the non-implanted ear, the decision is complicated because the relative benefit provided by a HA versus a 2nd CI is unclear.

The evidence to date establishes that the use of bimodal hearing brings improvement over the use of a CI alone for speech perception (5–8) and localization (5,9–11). It is also well documented that the use of bilateral CIs enhances speech intelligibility (1–3,9) and the acuity of sound localization (2,9–11) over the use of a unilateral CI. However, the direct comparisons of a binaural benefit between bilateral and bimodal listeners from these previous studies, particularly for speech perception tasks are seriously limited by the fact that the methods of assessments were not uniform. In these studies different testing materials and different types and levels of noise maskers were used.

For sound localization, three studies made direct comparisons between bimodal and bilateral users (9–11). Seeber et al. (9) tested the ability of adult patients (11 bimodal and 4 bilateral users) to localize wideband noise that randomly varied in level between 64 and 76 dB sound pressure level (SPL) with 11 speakers spanning an angle of $\pm 50^\circ$. Both adults groups received similar amount of the binaural benefit in the localization task. Litovsky et al. (10) measured the minimum audible angle for children (6 bimodal and 13 bilateral users) by presenting male-voice spondee presented at 60 dB SPL a roving level of 4 dB using a series of loudspeakers placed in an arc. They reported that children with bilateral CIs received greater advantage than those with bimodal devices, even though performance with a unilateral implant alone is similar between two groups. Litovsky et al. (11) also measured the minimum audible angle from children (10 bimodal and bilateral users) with smaller spacing between locations (15 loudspeakers in semicircle spanning $\pm 70^\circ$). The benefit of binaural relative to unilateral CI was greater for the bilateral group than for the bimodal group.

For speech perception, there are only four studies that utilized the same experimental conditions for both bimodal and bilateral listeners (11,13–15). Litovsky et al. (11) compared the word recognition scores for prelingually-deafened children with a bimodal fitting ($n=10$) or bilateral implants ($n=10$). They found a nonsignificant benefit from using either a HA in the contralateral ear or a 2nd CI, even with the noise on the side of the implant in a bimodal fitting or the 1st CI in bilateral implants. In a study by Ching et al. (14), two adult subjects (S1 and S2) who were bimodal listeners and subsequently received a 2nd CI were tested for speech perception. Speech was presented from the front, but uncorrelated noise was simultaneously presented from two loudspeakers positioned at $\pm 90^\circ$. For the subject S1, bimodal performance for consonant recognition was better than bilateral performance but similar to performance for the CI-alone condition. For the subject S2, bimodal performance for consonant recognition was better than both scores for the bilateral and CI-alone conditions. In addition bimodal performance for sentence recognition was better than both scores for the bilateral and CI-alone conditions.

Mok et al. (15) also showed that children with a bimodal fitting received greater benefit from a HA than bilateral CI children did from a 2nd CI when the speech and noise were presented from the front. In contrast, when noise was presented from the side of the CI in a

bimodal fitting or the 1st CI in bilateral implants, children with bilateral implants received greater benefit than children with a bimodal fitting. Mok et al. (14) compared the word recognition scores for children with a bimodal fitting (n=9) or bilateral implants (n=4) at a +10 dB signal-to-noise ratio (SNR). They showed that the benefit provided by a HA was significantly greater than that provided by a 2nd CI when speech and noise were presented from the front. In contrast, the benefit provided by a 2nd CI was significantly greater than that provided by a HA when noise was presented from the side of a 1st CI in a bilateral condition.

Although each of four studies discussed above compared the degree of a benefit provided by a HA versus a 2nd CI under uniform experimental conditions, the studies involved pediatric populations. Since large adult population with a bimodal fitting will be interested in having a second implant in the near future, there is a greater need to have such comparison data between bilateral and bimodal adult listeners. The subsets of both bilateral and bimodal data evaluated here were previously published for totally different analyses (3,17). The bimodal study of Yoon et al. (17) demonstrated that a bimodal benefit was associated with aided PTA at frequencies < 1 kHz. The bilateral study of Yoon et al. (3) demonstrated that a binaural benefit was greater when unilateral performance was similar across ears. In the present study, direct comparisons were made with regard to the benefit of speech recognition gained from an addition of a HA in a bimodal fitting versus that of a 2nd CI in bilateral implants when speech and noise were presented from the front. Thus, data could provide the evidence for a relative efficacy of bimodal hearing devices against bilateral implantation.

Materials and Methods

Subjects

A total of 25 subjects participated in the study. All subjects were postlingually deafened adults and native speakers of American English. All subjects provided informed consent, and the procedures were approved by the local Institutional Review Board.

Thirteen bimodal (BM) listeners (6 females and 7 males) participated in the study. Subjects were between the ages of 24 and 84 years old (average is 62 years old). Thirteen bimodal participants were separated into two groups; BM poor (n=5, aided PTA > 55 dB HL over frequencies of 0.25, 0.5, 0.75, and 1 kHz in a HA ear) and BM good (n=8, aided PTA < 55 dB HL). The cutoff of 55 dB HL for the grouping was chosen because it is the upper cutoff for the moderate hearing loss range (41 – 55 dB HL). Unaided and aided audiometric thresholds for the BM poor and good groups are given in the top and bottom panels of Fig. 1. Nine out of 13 subjects had been bimodal listeners for less than 3 years and 2 subjects who had 11 years of bimodal listening experience. Subject demographics are given in Table 1.

Twelve bilateral (BL) CI listeners (10 females and 2 males) participated in the study. All were sequentially implanted. Ten subjects were between the ages of 50 to 82 years old, and two subjects were 22 and 29 years old. Four out of 12 subjects have had their second implant for six months, and another 8 have used it for more than 2 years along with one subject who has used it for 7 years. Subject demographics are shown in Table 2.

Stimuli

Consonant, vowel, and sentence recognition was measured in quiet and noise at +5 dB and +10 dB SNRs. Sixteen consonants included /b/, /d/, /g/, /p/, /t/, /k/, /m/, /n/, /f/, /s/, /ʃ/, /v/, /ð/, /z/, /dʒ/, and /tʃ/, presented in an /a/-consonant-/a/ context produced by five male and five female talkers (16). Twelve vowels included 10 monophthongs (/i/, /I/, /e/, /æ/, /u/, /ʊ/, /

α /, /ʌ/, /ɔ/, /ɜ:/) and 2 diphthongs (/əʊ/, /eɪ/), presented in an /h/-vowel-/d/ context ('heed', 'hid', 'head', 'had', 'who'd', 'hood', 'hod', 'hud', 'hawed', 'heard', 'hoed', 'hayed') produced by five male and five female talkers (19). Sentence recognition was measured using HINT sentences (20).

During the testing, a stimulus was randomly selected (without replacement) from the stimulus set. Each speech token was presented 20 times (10 talkers $\times$ 2 repetitions) at each SNR. Sentence recognition for each set (10 sentences) was measured three times (total 30 different sentences) at each SNR. No training or trial-by-trial feedback was provided during the test.

Procedure

Consonant, vowel, and sentence recognition was measured under three listening conditions: CI alone, HA alone, and CI+HA for BM listeners; 1st CI alone, 2nd CI alone, and 1st CI+2nd CI for BL listeners. Subjects were seated in a double-walled sound treated booth (IAC) directly facing a loudspeaker (0° azimuth) one meter away. Subjects were tested using their clinical speech processors and settings. The output level of the amplifier was set either to 65 dB or 70 dB sound pressure level (SPL) for each listening condition according to the Cox loudness rating scale (21) in response to 10 sentences in quiet. For the BM listeners the subject's CI was turned off in the HA-alone condition, and his or her HA was turned off and the non-implanted ear was plugged with an ear plug for the CI alone condition. The three listening conditions were tested in random order for each subject.

Since this study focused on documenting the relative benefit provided by a HA as opposed to a 2nd CI, two new terms were defined as follows: 2nd CI benefit = bilateral performance – 1st CI alone performance and HA benefit = bimodal performance – CI alone performance. It should be noted that a bilateral benefit (bilateral performance – the better performing ear alone) could differ from a 2nd CI benefit if performance with a 2nd CI is higher than that with a 1st CI. In the same vein, a bimodal benefit (bimodal performance – the better performing ear alone) might be different from a HA benefit if performance with a HA is higher than that with a CI. Two subjects (BM12 and BM14) in this study had higher scores with a HA than with a CI for vowel recognition.

Results

Figure 2 displays group mean recognition scores and standard errors for consonants (1st column), vowels (2nd column), and sentences (last column) in the binaural condition (1st row), 1st CI alone (2nd row), 2nd CI alone or HA alone (3rd row), as a function of SNR. For the binaural condition (Fig. 2, 1st row), a two-way repeated-measures analysis of variance (ANOVA) with SNR (+5 dB, +10 dB, and quiet) and listener group (BL, BM good, and BM poor) as factors showed no significant effect of listener group for consonant [$F(2,44)=0.69$, $p>0.05$], vowel [$F(2,44)=0.28$, $p>0.05$], and sentence [$F(2,44)=0.44$, $p>0.05$] recognition while the main effect of SNR was highly significant for consonant [$F(2,44)=70.61$, $p<0.001$], vowel [$F(2,44)=21.44$, $p<0.001$], and sentence [$F(2,44)=43.44$, $p<0.001$] recognition. Interactions were not significant for any one of the speech tests ($p>0.05$).

For the 1st CI-alone condition (Fig. 2, 2nd row), a two-way repeated-measures ANOVA showed no significant effect of listener group for consonant [$F(2,44)=0.94$, $p>0.05$], vowel [$F(2,44)=0.94$, $p>0.05$], and sentence [$F(2,44)=1.26$, $p>0.05$] recognition. Again, the main effect of SNR was significant for consonant [$F(2,44)=112.72$, $p<0.001$], vowel [$F(2,44)=35$, $p<0.001$], and sentence [$F(2,44)=64.97$, $p<0.001$] recognition. No significant interactions occurred for any of the speech tests ($p>0.05$).

For the 2nd CI-alone or the HA-alone condition (Fig. 2, last row), a two-way repeated-measures ANOVA showed significant effects of listener group for consonant [$F(2,44)=15.78, p<0.001$], vowel [$F(2,44)=5.93, p<0.05$], and sentence [$F(2,44)=18.73, p<0.001$] recognition. The main effect of SNR was also significant for consonant [$F(2,44)=58.16, p<0.001$], vowel [$F(2,44)=27.34, p<0.001$], and sentence [$F(2,44)=29.16, p<0.001$] recognition. Significant interactions occurred for consonant [$F(4,44)=2.68, p<0.05$] and sentence [$F(4,44)=3.04, p<0.05$] recognition. Post-hoc pair-wise comparisons (Holm-Sidak method) showed a significant difference in performance (asterisk) between the conditions of 2nd CI alone and HA alone for both BM poor and good groups at each SNR across the test materials ($p<0.05$). Even though the performance of the BM good group was better than that of the BM poor group, the difference was not significant ($p>0.05$) except in sentence recognition in quiet, denoted by a plus symbol.

Figure 3 shows the mean 2nd CI and HA benefit as a function of SNR. A two-way repeated-measures ANOVA was performed with SNR and subject group as factors. For consonant recognition, the benefit from the second devices was significantly different among the groups ($F(2,44)=5.7, p<0.01$), but the SNR effect was not significant ($F(2,44)=2.1, p>0.05$). There were no significant interactions ($F(4,44)=0.6, p>0.05$). Post-hoc pair-wise comparisons (Holm-Sidak method) showed a significant difference in the 2nd CI benefit and the HA benefit between the BL group and the BM poor group in noise, as indicated by asterisks ($p<0.05$), but no significant difference was found between the BL group and the BM good group across SNRs ($p>0.05$).

For vowel recognition, a two-way repeated-measures ANOVA showed the main effect of subject group ($F(2,44)=22.8, p<0.001$) and SNR ($F(2,44)=4.5, p<0.01$). There were also significant interactions ($F(4,44)=4, p<0.01$). Post-hoc pair-wise comparisons (Holm-Sidak method) showed a significant difference in the 2nd CI and the HA benefit between the BL group and the BM poor group across SNRs, as indicated by asterisks in Fig. 3 ($p<0.05$), but no significant difference between the BL group and the BM good group across SNRs ($p>0.05$). Post-hoc pair-wise comparisons (Holm-Sidak method) also showed that the difference in the 2nd CI and the HA benefit between the BM good group and the BM poor group was also significant across SNRs ($p<0.05$), as indicated by plus symbols.

For sentence recognition, a two-way repeated-measures ANOVA showed the main effect of subject group ($F(2,44)=38, p<0.001$) and SNR ($F(2,44)=33.6, p<0.001$). Interactions were also significant ($F(4,44)=3.8, p<0.01$). Post-hoc pair-wise comparisons (Holm-Sidak method) showed a significant difference in the 2nd CI and the HA benefit between the BL group and the BM poor group across SNRs, as indicated by asterisks in Fig. 3 ($p<0.05$). The difference in the 2nd CI and the HA benefit between the BM good group and the BM poor group was also significant in noise ($p<0.05$), as indicated by a plus symbol. Significant difference in the benefit between the BL group and the BM good group was observed in quiet, as indicated by a multiplication symbol ($p<0.05$).

Discussion

We compared the benefit provided by a 2nd CI to a HA for consonant, vowel, and sentence recognition among BL listeners, BM listeners with good aided PTA, and BM listeners with poor aided PTA as a function of SNR. Comparisons indicated that the HA benefit obtained by the BM listeners with poor aided PTA was significantly poorer than the 2nd CI benefit obtained by the BL group for all three materials across SNRs. However, the HA benefit obtained by the BM listeners with good aided PTA was not significantly different from the 2nd CI benefit obtained by the BL group for all speech test materials in noise.

Performance Comparisons for CI-alone condition between BM good and poor groups

An observation from the group data in the CI-alone condition for the BM listeners (Fig. 2, 2nd row) is that the performance of the BM poor group was consistently about 20 percentage points higher than that of the BM good group, even though these differences were not statistically significant ($p>0.05$). Such a discrepancy might simply be attributed to performance variability across CI listeners. Two subjects (BM4 and BM10) in the BM poor group outperformed every subject in the BM good group by more than 15% across test materials and SNRs. In addition, the performance of subject BM8 in the BM good group was far below the mean group performance. Consequently, these two good performers in the BM poor group and one poor performer in the BM good group were major contributors to the higher scores for the CI-alone condition in the BM poor group than in the BM good group.

Another possible explanation for the higher scores with a CI alone in the BM poor group is that these patients have to rely more on a CI than on a HA due to the limited contribution from a HA. The better speech input provided by a CI could lead listeners to learn to attend to the better ear alone. If this is the case, this information is clinically important since it would suggest that unilateral CI listeners with considerable residual hearing should use a CI alone for a relatively long period of time in order to fully exploit the benefit of the CI. However the statistical power is too small in the present study due to the limited sample size to make a definitive conclusion regarding this possibility.

Correlation between Aided PTA and the HA Benefit

The present study shows that the HA benefit is greater for the BM good group than for the BM poor group (Fig. 3), suggesting that the HA benefit is somewhat related to aided hearing thresholds. The correlation analyses showed that the bimodal benefit for vowel recognition was significantly correlated with aided PTAs averaged across 0.25, 0.5, 0.75, and 1 kHz, but PTAs were not correlated with consonant and sentence recognition. A better aided PTA might help enhance a transmission of F1, leading to a greater HA benefit in vowel recognition.

It should be noted that evidence to date for such a correlation is generally weak in the literature (13,22–24). It is difficult to understand why better unaided or aided hearing thresholds provide little or no bimodal benefit in speech perception (6). In the same vein, it is unclear how bimodal users with extremely poor to no residual hearing receive significant bimodal benefit (5). One possible answer is that binaural integration is not successful for bimodal users with better residual hearing thresholds due to conflicting cues processed by a HA and a CI, but for the poor residual hearing case, binaural integration might be maximized due to less conflicting cues. This possibility is under investigation.

The HA benefit and Audibility/HA fitting

The BM patients were tested with their clinical setting for each device because the main purpose of the study was to evaluate bimodal benefits in everyday use of HA and CI, not to evaluate the effect of optimal HA or CI fitting on bimodal benefits. However, a possibility exists that the spectral gain prescribed for the HAs may not be optimal for both BM groups. This is more likely for the BM poor group because unaided thresholds were similar between the BM groups, but aided thresholds were largely different (Fig. 1). This possibility is supported by the results of a study by Ching et al. (25). They showed that 15 of the 16 children studied required 6 dB more gain than prescribed by National Acoustic Laboratories-Revised, Profound to balance the loudness of the implanted ear for speech signals presented at 65 dB SPL. This result suggests that the adjustment of a gain for HAs to match loudness in the implanted ear for the BM poor group in the present study may

facilitate the integration process of speech information across ears, leading to a greater bimodal benefit.

To test this possibility, a subject (S4) in the BM poor group was retested with a fixed 80 dB SPL presentation level for sentence recognition in noise and quiet for HA-alone, C- alone and CI+HA conditions. This level provides the subject about 30 dB sensation level at frequencies between .25 and 1 kHz and about 15 dB sensation level at frequencies between 1 and 3 kHz (See Fig. 1). The results (not shown here) showed that no bimodal benefit existed even though performance improved for HA alone at +10 dB SNR and in quiet, but not at +5 dB SNR. In contrast, the performance dropped dramatically, by approximately 30%, due to clipping for both CI-alone and CI+HA conditions in noise, leading to bimodal interference (bimodal performance < CI alone performance). This result suggests that optimal bimodal loudness balancing is needed to facilitate bimodal benefit; it is likely that some degree of bimodal benefit could be observed when 80 dB and 65 dB SPL levels for the HA side and the CI side are presented.

Limitations

The present study has several limitations. First, the small sample size for each group limits the generalization of the current results. It is even more problematic for large variability between subjects and across groups is common. For example, if there is large variability in the magnitude of the binaural benefit, particularly for the BM poor group ($n=5$), one or two extreme performers (either good or poor) would decrease the statistical power.

Second, both the 2nd CI benefit and the HA benefit were evaluated only when speech and noise were presented from the front (binaural summation). Measuring binaural summation is one way to evaluate how a speech signal processed by a HA and CI are integrated in bimodal hearing. However, the non-spatial listening task did not require the subjects to take advantage of head shadow and squelch. It would be interesting to see how the patterns of binaural performance would differ from the current findings if spatial cues were tested.

Third, localization and music perception which are other significant factors in the decision to implant a second ear instead of using bimodal hearing were not considered. Children with bilateral CIs received greater benefit than those with bimodal devices (10–11), but for adults, both bimodal and bilateral groups receive a similar amount of binaural benefit in localization (9). These results suggest that it is important to evaluate the functional relationship between the bimodal benefit in localization and the aided hearing threshold. As for the music perception two studies evaluated music perception for hearing aid users who were possible candidates for implantation (26–27). Both studies showed that rhythm perception and musical instrument recognition were equal in hearing aid and cochlear implant users and that pitch ranking was better in hearing aid users. These results suggest that the BM poor group might appreciate instrumental music better than the BL group does.

Fourth, the lack of training on the unilateral condition for both the BL and BM groups might be problematic. Performance for the unilateral listening condition was measured by having both BL and BM listeners switch off one of their devices. This setting immediately provides an unfamiliar environment, as this configuration does not characterize their everyday listening experience, and, in essence, changes how their auditory system processes cues for speech recognition. Consequently, performance with a CI alone may be higher for listeners with a poorer acoustic hearing threshold due to insufficient amplification in the ear with a HA.

Finally, even though speech recognition tasks were administered under uniform conditions for both the BL and the BM groups, no attempts were made to match pathological factors

between groups. The lack of baseline equivalence among the three groups is a limitation and may lead to the differences in the results of the present study. However, previous studies (6,12,28–29) showed that major pathological factors such as age at implantation, duration of profound deafness, period of bilateral experience, etiology, CI type, CI configurations, or processor strategy were not significantly associated with a binaural benefit in speech perception.

Conclusion

The results of the present study show that the HA benefit obtained by the BM good group was not significantly different from the 2nd CI benefit obtained by the BL group across test materials in noise, but the HA benefit obtained by the BM poor group was significantly poorer than the 2nd CI benefit obtained by the BL group for all three materials across SNRs except for consonant in quiet. Based on the results of the present study, a recommendation for a 2nd CI would be more appropriate for bimodal adult listeners who have poor aided PTA at frequencies ≥ 1 kHz. These findings add to the understanding of the relative efficacy of a bimodal fitting versus bilateral implantation for recipients of unilateral CIs who have significant residual hearing in the nonimplanted ear.

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Figure 1.

Individual unaided and aided hearing thresholds. The top panels present hearing thresholds for the poor group (5 listeners with aided PTA ≥ 55 dB HL) over frequencies of 0.25, 0.5, 0.75, and 1 kHz while the bottom panels present the thresholds for the good group (8 listeners with aided PTA < 55 dB HL). Mean thresholds with standard error are indicated by thick lines. The dashed-dot line represents the range of acceptable hearing thresholds allowing bimodal benefit, recommended by MED-EL.

Figure 2.

Mean speech recognition scores for the bilateral and bimodal conditions, (top row), 1st CI-alone condition (middle row), and 2nd CI-alone condition or HA-alone condition (bottom row) in consonant (left column), vowel (middle column), and sentence (right column) recognition for each group. BL stands for bilateral listeners, BM: Poor and Good is a bimodal listener with poor and good aided PTA calculated over frequencies of 0.25, 0.5, 0.75, and 1 kHz. In the bottom row asterisks indicate significant difference in the 2nd CI and HA performance scores between the BL group and either of the BM groups, while a plus symbol indicates significant difference between the BM good group and poor group in the HA-alone condition. The error bars represents standard error.

Figure 3.

Comparisons of the 2nd CI benefit (BL performance – 1st CI alone performance) versus the HA benefit (BM performance – CI alone performance) across the three groups. Asterisks indicate significant difference between the BL and the BM: poor. Plus symbols indicates significant difference between the BM: Poor and the BM: Good. A multiplication symbol indicates significant difference between BL and BM: Good. The error bars represents standard error.

Table 1

Bimodal subject demographics. Aided pure-tone average (PTA) in dB HL was estimated over frequencies of 0.25, 0.5, 0.75, and 1 kHz in a HA side. SPL = sound pressure level in dB (A), ACE=Advanced Combination Encoder, and HiRes=High Resolution.

	ID (age, gender) (Aided PTA)	Device (use of years)	Onset year of hearing loss	Etiology	Device, Processor, strategy	Presentation Level in dB SPL
BM Poor group (aided PTA ≥ 55 dB HL)	BM1 (77, F) (76)	CI (11)	1971	Unknown	Nucleus 24, Freedom, ACE Phonak, Savia	70
		HA (34)				65
		Both (11)				
	BM3 (73, M) (55)	CI (1)	1977	Unknown	Nucleus 24, Freedom, ACE Phonex, CROS	
		HA (36)				70
		Both (1)				65
	BM4 (71,M) (65)	CI (3)	1977	Otosclerosis	Nucleus 24, Freedom, ACE Simens, BTE	65
		HA (35)				70
		Both (3)				65
BM6 (56, F) (56)	CI (2)	2003	Ototoxicity	C2, Harmony, HiRes Widex Body	70	
	HA (8)					
	Both (2)					
BM9 (67, F) (70)	CI (7)	1945	Hereditary	3G, Freedom, ACE Resound, Metrix	65	
	HA (37)				70	
	Both (7)				65	
BM Good group (aided PTA < 55 dB HL)	BM2 (77, M) (44)	CI (11)	1999	Unknown	120, Harmony, HiRes Widex, Senso Diva	65
		HA (11)				70
		Both (11)				65
	BM5 (25, M) (31)	CI (1.5)	1990	Meningitis	Nucleus 5, Freedom, ACE Phonak, Supero	65
		HA (6)				
		Both (1.5)				
	BM7 (69, M) (37)	CI (3)	1957	Unknown	Nucleus 24, Freedom, ACE Unitron, 360+	65
		HA (50)				70

ID (age, gender) (Aided PTA)	Device (use of years)	Onset year of hearing loss	Etiology	Device, Processor, strategy	Presentation Level in dB SPL
	Both (3)				65
BM8 (47, M) (38)	CI (2) HA (42) Both (2)	1967 2009	Unknown	Nucleus 24, Freedom, ACE Simens, Centra	65 70 65
BM10 (84,F) (37)	CI (1) HA (30) Both (1)	1981	Hereditary	Harmony, HiRes 90K Interton Bionic-bignano	65 70 65
BM11 (69, F) (39)	CI (1) HA (19) Both (1)	1987	Hereditary	Harmony, HiRes 90K Widex, Senso Diva	70 65
BM12 (24,F) (45)	CI (4.5) HA (10) Both (4.5)	1992	Unknown	Nucleus 24, Freedom, ACE Simens Traiano SP	65 70 65
BM13 (71,M) (47)	CI (1.5) HA (50) Both (1.5)	1944	Unknown	Nucleus 5, Freedom, ACE Simens Traiano SP	65 70 65

Table 2

Bilateral CI subject demographics. SPL= sound pressure level in dB(A), SPEAK=Spectral PEAK, ACE=Advanced Combination Encoder, CIS=Continuous Interleaved Sampling, and HiRes=High Resolution.

ID (age, gender)	Device (use of years)	Onset year of hearing loss	Etiology	Device, Processor, strategy	Presentation level in dB SPL
BL1 (63, F)	1 st CI (19) 2 nd CI (7) Both (7)	1950	Ototoxicity	Nucleus 24, Freedom, ACE	70
BL2 (58, M)	1 st CI (15) 2 nd CI (2) Both (2)	1973 1994	Unknown	Nucleus 24, Freedom, SPEAK	70 65
BL3 (56, F)	1 st CI (14) 2 nd CI (2) Both (2)	1962	Unknown	Nucleus 22, Freedom, SPEAK Nucleus 22, Freedom, ACE	70 65
BL4 (59, F)	1 st CI (15) 2 nd CI (3) Both (3)	1958	Ototoxicity	C2, Harmony, HiRes C2, Clarion, CIS	65
BL5 (82, F)	1 st CI (17) 2 nd CI (0.5) Both (0.5)	1960	Hereditary	Nucleus 22, Freedom, ACE	70 65
BL6 (72, F)	1 st CI (8) 2 nd CI (0.5) Both (0.5)	1943	Hereditary	C2, Harmony, HiRes	70 65
BL7 (76, F)	1 st CI (21) 2 nd CI (0.5) Both (0.5)	1945	Otosclerosis	Nucleus, system 5, ACE Nucleus, system 5, ACE	65 70 65
BL8 (22, M)	1 st CI (14) 2 nd CI (0.5)	1988 1989	Hereditary	Nucleus 22, Freedom, ACE	65

ID (age, gender)	Device (use of years)	Onset year of hearing loss	Etiology	Device, Processor, strategy	Presentation level in dB SPL
	Both (0.5)				
BL9 (53, F)	1 st CI (4) 2 nd CI (3) Both (3)	1956	Hereditary	C2, Harmony, HiRes	65
BL10 (50, F)	1st CI (8) 2nd CI (3.5) Both (3.5)	1966	Unknown	Harmony, HiRes 90K	65
BL11 (29, F)	1st CI (4.5) 2nd CI (3) Both (3)	1991	Unknown	Nucleus 22, Freedom, SPEAK	65
BL12 (59, F)	1st CI (3.5) 2nd CI (2.5) Both (2.5)	1962	Hereditary	Harmony, HiRes 90K	65