

Preimplant Hearing Aid Fittings and Aided Audibility for Pediatric Cochlear Implant Recipients

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Abstract

Background: Audibility of speech for children with hearing loss (HL) depends on the degree of HL and the fitting of the hearing aids (HAs) themselves. Many studies on cochlear implant (CI) users have demonstrated that preimplant hearing is associated with postimplant outcomes, but there have been very few reports on the fitting of HAs before surgery.

Purpose: The aims of this study were to characterize HA fittings and aided audibility of speech for pediatric HA users with severe to profound HL and to examine the relation between preimplant aided audibility and postimplant speech perception.

Research Design: A descriptive/observational and correlational study. Audiologic records of pediatric CI participants involved in a larger study examining the effects of early acoustic hearing were analyzed retrospectively; when available, these records included HA verification and speech recognition performance.

Study Sample: The CI participants were enrolled in audiology centers and oral schools for the deaf across the United States.

Data Collection and Analysis: To determine whether deviations from prescribed DSL target were significantly greater than zero, 95% confidence intervals of the mean deviation were calculated for each frequency (250, 500, 1000, 2000, and 4000 Hz). Correlational analyses were used to examine the relationship between preimplant aided Speech Intelligibility Indices (SIIs) and postimplant speech perception in noise. Correlational analyses were also used to explore the relationship between preimplant aided SIIs and demographic data. T-tests were used to compare preimplant-aided SIIs of HAs of listeners who later became users of either sequential CIs, simultaneous CIs, or bimodal devices.

Results: Preimplant fittings of HAs were generally very close to prescriptive targets, except at 4000 Hz for those HAs with active frequency-lowering processing, and preimplant SIIs, albeit low, were correlated with postimplant speech recognition performance in noise. These results suggest that aided audibility should be maximized throughout the HA trial for later speech recognition purposes.

Conclusions: It is recommended that HA fittings be optimized to support speech audibility even when considering implantation. In addition to the age at which HA use begins, the aided audibility itself is important in determining CI candidacy and decisions regarding bimodal HA use.

Key Words: cochlear implants, hearing aids, hearing loss, pediatric, SII, verification

Abbreviations: CI = cochlear implant(s); HA = hearing aid(s); HL = hearing loss; DSL = Desired Sensation Level; IQR = interquartile range; LL = lower limits; LNT = Lexical Neighborhood Test; PTA = pure-tone average; SD = standard deviation; SII = Speech Intelligibility Index; SPL = sound pressure level; UL = upper limits; UWO-PedAMP = University of Western Ontario Pediatric Audiological Monitoring Protocol

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INTRODUCTION

It is well known that children with hearing loss (HL) demonstrate deficits in speech and language skills compared with similarly aged children with normal hearing sensitivity (Nicholas, 2000; Geers et al, 2009; Pittman and Schuett, 2013; Davidson et al, 2014; Tomblin et al, 2014). The major reason for these deficits is the reduced ability to hear spoken language (Tomblin et al, 2014). That is, infants and children with HL have reduced audibility of speech and sounds in their environment compared with those without HL and, hence, much of spoken language is inaudible. When audibility is reduced, the ability to learn a spoken language is affected. For children with HL, hearing aids (HA) are often used as a (re)habilitation approach to improve the audibility of speech and sounds. For infants and children who do not adequately benefit from appropriately fit amplification, additional approaches, such as cochlear implant(s) (CI), may be considered.

Even though many children with severe to profound HL will eventually receive CI(s) (Sininger et al, 2010), a trial with well-fit HAs is typically recommended before CI surgery (often as part of the CI candidacy process). Before implant surgery, the everyday audibility of speech for these children will depend on both the child's degree of HL (e.g., unaided pure-tone average [PTA]) and on how well his/her HA(s) is/are fit. Many studies of pediatric CI users focus on the first item and ignore the second; they report the amount of preimplant hearing and its relation to various eventual outcomes, such as speech perception and vocabulary development. For example, several studies of pediatric CI recipients found that greater amounts of preimplant residual hearing were associated with better speech perception and language outcomes (Cowan et al, 1997; Nicholas and Geers, 2006; 2007). Likewise, Phan et al (2016) found that more preimplant residual hearing (i.e., lower unaided better-ear PTA; 0.5, 1, and 2 kHz) was associated with better speech discrimination performance at two to four weeks post-CI stimulation for infants ($N = 17$) with a mean age of 16.4 months (standard deviation [SD] = 3.6). Notably, this result was found even though the average "best unaided" PTA was 108.7 dB HL and ranged from 87 to 120 dB HL. Thus, Phan et al (2016) concluded that even very-limited residual preimplant hearing may facilitate speech discrimination abilities in the time period immediately following implantation.

In contrast to the many studies that report degree of preimplant hearing for eventual pediatric CI recipients, there are few reports on the second factor affecting audibility, namely, HA fittings before CI surgery. Although some clinicians and researchers may report the age at which HA use was initiated (Geers et al, 2013; Davidson et al, 2014), very few report on the fittings of the HAs

themselves or on the amount of speech that is audible during HA trials. For children with less profound degrees of HL, there are some studies of HA fittings. In studies of children with mild to severe HL, McCreery et al (2013) and McCreery et al (2015) report that HA fittings were variable. In these two studies, the proximity of the HA output to prescribed pediatric targets (Desired Sensation Level-[DSL]) was examined for each child's HAs (defined as "deviation from target"). Then, aided Speech Intelligibility Indices (SII; ANSI S3.5, 1997) were calculated and compared with published normative ranges for children (Bagatto et al, 2011; 2016; Moodie et al, 2017). Approximately 55% of the children's HAs deviated significantly from their prescribed targets in both ears (McCreery et al, 2013). "Deviations from target" tended in the direction of underfitting, such that children's HAs with greater deviations tended to have SIIs that were lower (poorer) than the normative range for a given degree of HL; 35% of the HAs had SIIs that were below the published normative range for their severity of HL (McCreery et al, 2015).

For children with profound levels of HL, however, there is only one report on HA fittings (Strauss and van Dijk, 2008) and none that report the amount of speech that is audible when aided (SII data). In several reports of an association between better preimplant residual hearing and better postimplant outcomes (e.g., Cowan et al, 1997; Nicholas and Geers, 2006; 2007), there is an assumption that speech was optimally audible during the preimplant period. Yet, these studies provided no verification or documentation of the aided HA fit (i.e., HA verification) and/or quantification of the audibility of speech. One study, by Davidson and Skinner (2006), examined relations among PTAs, SIIs, and speech recognition scores for 26 children with severe to profound HL. Although HA fits were not reported explicitly, SIIs for two input speech levels (soft: 55 dB SPL [at the time of this study, the lowest input level available on the Audioscan system was 55 dB SPL] and raised: 70 dB SPL) were calculated using the Audioscan Verifit System (Etymonic Design Inc., Ontario, Canada). The mean better-ear unaided PTA for the group was 79 dB HL (range: 60–98 dB HL), and mean SIIs were 27% and 42% for the soft and raised input levels, respectively. Although the calculated SIIs were relatively low, they were significantly correlated with speech recognition scores on the Lexical Neighborhood Test (LNT; Kirk et al, 1995) test at both levels. That is, soft-input SIIs were significantly correlated with speech recognition scores for soft speech (50 dB SPL) and raised-input SIIs were significantly correlated with speech recognition scores for loud speech (70 dB SPL).

Because many children with profound HL will eventually receive one or two CIs, some may question the value of ensuring good, or best-possible, HA fits and speech audibility during the period when these children

are using HAs. Before implant surgery, the everyday audibility of speech will depend, as stated previously, on both a child's degree of HL (e.g., preimplant unaided PTA) and on how well his/her HA is fit. Clinically, although the audiologist has no influence on a child's degree of HL (i.e., unaided PTA), the audiologist does have some influence on how well fit a child's HAs are such that speech is as audible as possible. Presumably, any improvement in the audibility of speech, albeit even small increases in aided SII, might help the child while likely not causing any harm. Thus, a careful and systematic examination of HA fittings is warranted. In addition, because children with greater degrees of residual hearing are now potential CI candidates, the need for careful HA fitting and adjustment, and documentation thereof, are critical (Gifford et al, 2010; Sampaio et al, 2011; Mowry et al, 2012). Such information may assist in determining CI candidacy and with decisions about continued use of an HA at a nonimplanted ear (i.e., bimodal use). Thus, the primary aim of this project is to characterize HA fittings and aided audibility of speech for pediatric HA users with severe to profound HL who later received CI(s). A secondary aim is to examine the relation between preimplant aided audibility and postimplant speech perception.

METHODS

Participants

Participants were drawn from a larger study examining the effects of early acoustic hearing for pediatric CI recipients, and were recruited from audiology centers and oral schools for the deaf across the United States. Participants met the following criteria: severe to profound sensorineural HL in at least the poorer ear (a few exceptions were children with etiologies of auditory neuropathy spectrum disorder, enlarged vestibular aqueduct, and/or cytomegalovirus), HL that was congenital or acquired before 15 months of age, educated in an oral communication setting, and at least one CI surgery before 4.5 years of age. For this present study (HA fits & SII), data were collected retrospectively using pre-CI audiologic records.

Although there are 117 children in the larger study, only those participants with HA verification information

in their *pre-CI* audiological records were included in this present study. In addition, for some participants, more than one ear fit the inclusion criteria (e.g., child has bilateral CIs and HA verification data for both ears). When available, data collected from the participants' records included gender, age at HA fitting(s), age at CI(s), unaided air conduction thresholds, aided thresholds, etiology of HL, device history (i.e., type of device, manufacturer, and date fit), present device use (i.e., simultaneous bilateral CIs, sequential bilateral CIs, and bimodal devices), and manufacturer of devices (HA manufacturers: Phonak, Widex, Oticon, and Unitron; CI manufacturers: Cochlear Americas [Englewood, CO], Advanced Bionics [Valencia, CA], Med-EL [Innsbruck, Austria]). A total of 45 pediatric participants (23 female and 22 male) consisting of 71 ears were included in this present study (see Table 1). These participants include bilateral CI users, simultaneous ($n = 9$) and sequentially ($n = 21$) implanted, and bimodal CI users ($n = 15$), that is, those who use an HA at the nonimplanted ear. For these 45 participants, the average age at the time of the test (testing performed for the larger study) was 6.8 years ($SD = 1.3$), and the average age at first CI was 2.3 years ($SD = 1.1$) with a mean preimplant unaided PTA of 99 dB HL ($SD = 16$). For the other 72 participants from the larger study, that is, those who did not have preimplant HA-fitting data available in their audiological records, the average age at the time of test was 7.2 years ($SD = 1.3$), average age at first CI was 2.0 years ($SD = 1.1$), and mean preimplant unaided PTA was 98 dB HL ($SD = 17$).

HA Verification

HA-fitting data from Audioscan Verifit™ records were collected and included the following (when available): measured HA output in dB SPL for running speech (carrot passage) at different input levels ranging from soft to loud and Audioscan software-computed SII's (ANSI S3.5, 1997) for different input levels (when available). For most participants, age-related average real ear to coupler difference values were used to simulate in situ measurements of HA output in the coupler of the Audioscan system. From audiology records and HA-fitting reports, participants who used HAs with frequency-lowering capability,

Table 1. Participants and Ears with Verification Data; HAs with Active Frequency Lowering

HA Verification Data	Number of Participants			Number of Aided Ears	Number of HAs with Active Frequency Lowering
	With Data for One Ear	With Data for Two Ears	Total		
Any input level	19	26	45	71	35
Soft level	16	14	30	44	26
Conversational level	16	20	36	56	30
Loud level	13	17	30	47	23

Note: Number of participants and aided ears with available HA verification data, and number of HAs with active frequency lowering, in total (any input level) and for three verification speech input levels.

specifically nonlinear frequency compression, were identified. Centers differed in their definition of input levels, with 5 dB differences noted at each level: soft = 50 or 55 dB SPL, conversational = 60 or 65 dB SPL, and loud = 70 or 75 dB SPL. From Audioscan Verifit™ records, deviations of HA output from DSL targets (defined as HA output *minus* DSL target) were examined for octave frequencies from 250 to 4000 Hz, when available. Only the deviations for the conversational speech input level (60 or 65 dB SPL) are reported here (N = 56 HAs; 56 ears) because that level was most frequently used with the Verifit™ (see Table 1). In some audiologic records, graphical data were provided in lieu of numerical data; in these instances, a MATLAB (Mathworks, Natick, MA) script named Graph Picker was used to estimate the numerical values of prescriptive targets and HA output at each frequency. Finally, aided SII as a function of unaided preimplant PTA for these participants' ears were compared with normative data from the University of Western Ontario Pediatric Audiological Monitoring Protocol (UWO-PedAMP) (Bagatto et al, 2011; 2016; Moodie et al, 2017).

Speech Recognition Performance

As part of the larger study, participants, at ages five to eight years, were administered the LNT while using their bilateral devices (2 CIs or CI+HA). This open-set word recognition test consists of monosyllabic, 50-word lists drawn from the vocabulary of three- to five-year-old typically developing children. Each child heard one 50-word list in the presence of four-talker babble presented with an 8-dB signal to noise ratio, with the speech level at 60 dB(A). The speech tests were administered in a sound booth, with the prerecorded signals presented via an audiometer to a speaker located at 0° azimuth about 3 feet from the child. The child was instructed to repeat what he/she heard. A percent-correct word score was computed that represents the percent of words (responses) that were recognizable as the target word.

STATISTICAL ANALYSES

To determine whether the deviations from target (HA output – DSL target) were significantly greater than zero, 95% confidence intervals of the mean deviation (upper and lower limits [LL, UL]) for each frequency (250, 500, 1000, 2000, and 4000 Hz) were calculated. In addition, *t*-tests were used to compare preimplant-aided SII of HAs of listeners in each of the three present device groups (simultaneous CIs, sequential CIs, and bimodal) and to compare aided SII across ears for two groups of listeners: those who were sequentially implanted with CIs and those who used bimodal devices. Correlational analyses were used to examine the relationship between preimplant-aided SII (for the ear receiving the first CI) and postimplant

speech perception in noise. In addition, correlational analyses were used to explore relationships between preimplant-aided SII and demographic data.

RESULTS

For the ears in this study, that is, those with HA verification data, mean unaided preimplant thresholds at octave frequencies from 250 to 4000 Hz are shown in Figure 1. Mean preimplant thresholds are severe to profound at all octave frequencies.

Deviation from (Prescriptive DSL) Target

Deviations from prescriptive target, defined as “HA output *minus* DSL target,” at octave frequencies from 250 to 4000 Hz for conversational speech input levels (60 or 65 dB SPL) are shown in Figure 2. Because HA outputs were not available at every frequency for every ear, there are different Ns (different numbers of ears) at each frequency. Table 2 shows, for each octave frequency, the mean, SD, and LL and UL of the 95% confidence interval of the mean for the deviations from prescriptive target for 56 HAs (or, equivalently, for 56 ears). Overall, for conversational speech levels, HA outputs were very close to prescriptive targets, that is, the deviations from target are close to zero. At 4000 Hz, however, the average HA output was significantly below the prescriptive (DSL) target, with a mean deviation of –14.2 dB. At all other frequencies, deviations from target were not significantly different from zero. Because this analysis included different numbers of HAs (ears) at each frequency, the analysis was repeated using only those HAs

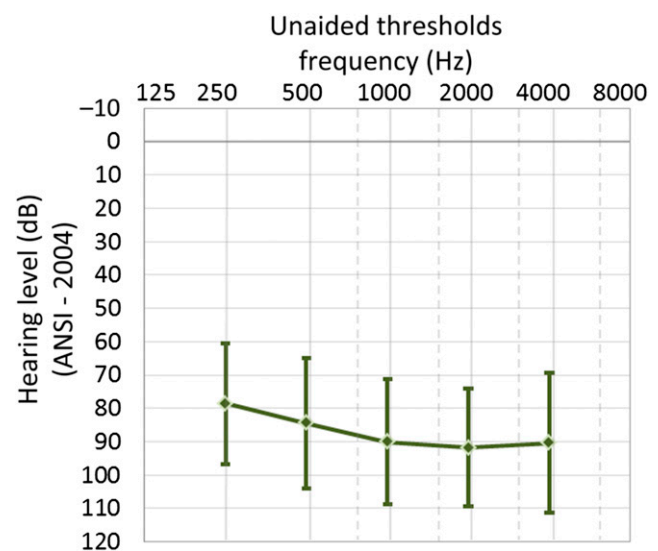


Figure 1. Mean unaided preimplant thresholds are plotted in dB HL with $+1/-1$ SD at octave frequencies from 250 to 4000 Hz, for the pediatric participants in this study (N = 45). The mean unaided thresholds are 78, 83, 89, 91, and 88, at octave frequencies 250, 500, 1000, 2000, and 4000 Hz, respectively. (This figure appears in color in the online version of this article.)

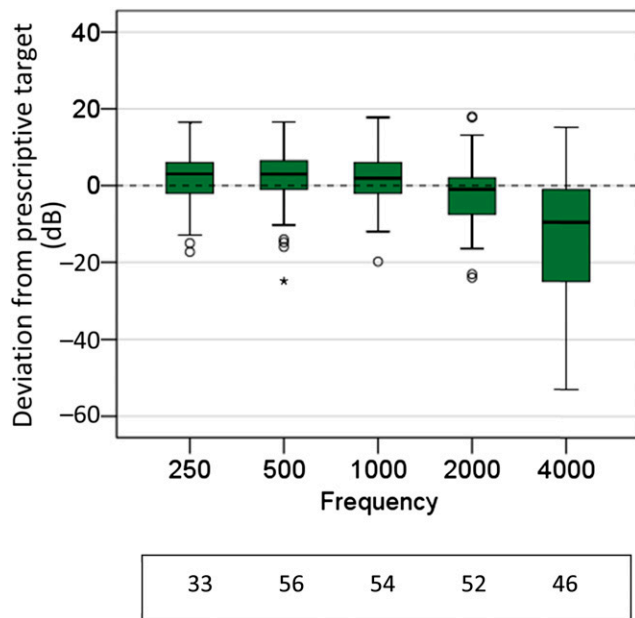


Figure 2. Box plots of “deviation from prescriptive target” for conversational input levels (60 or 65 dB SPL); box plots include HAs with active frequency lowering, from a total of 56 HAs. In each box plot, median and interquartile range (IQR) are indicated by the thick line in the middle, and the distance between the upper and lower extent of the box. Whiskers indicate the minimum and maximum values, except for outliers (circles indicate outliers >1.5 IQR’s but <3 IQR’s from the median, whereas asterisks represent outliers >3 IQR’s from the median). Numbers of HAs included in the box plots are listed below the graph at each octave frequency. The activation of frequency lowering in some HAs (30 out of 56) is reflected in larger deviations from prescriptive target at the high frequencies, particularly 4000 Hz. Use of frequency lowering is presumably related to poor audibility at high frequencies for some participants and suggests that clinicians were likely seeking to improve high-frequency audibility when it was not achieved with conventional amplification. (This figure appears in color in the online version of this article.)

(participants’ ears) for which conversational-level data were available at all octave frequencies ($N = 28$). The pattern of results remained unchanged, namely, only at 4000 Hz did deviations from target differ significantly from 0 (at 4000 Hz, mean deviation = -17 dB).

Figure 3 and Table 3 show analogous results, deviations from prescriptive DSL target, but excluding HAs using fre-

quency compression. Again, deviations from target are shown and provided at octave frequencies from 250 to 4000 Hz for conversational speech input levels (60 or 65 dB SPL), and again, because HA outputs were not available at every frequency for every ear, there are different Ns at each frequency. At 1000 Hz, the average deviation was 3 dB ($SD = 7.2$) above target and was significantly different from zero. At all other frequencies, the deviations from target were not significantly different from zero.

SII

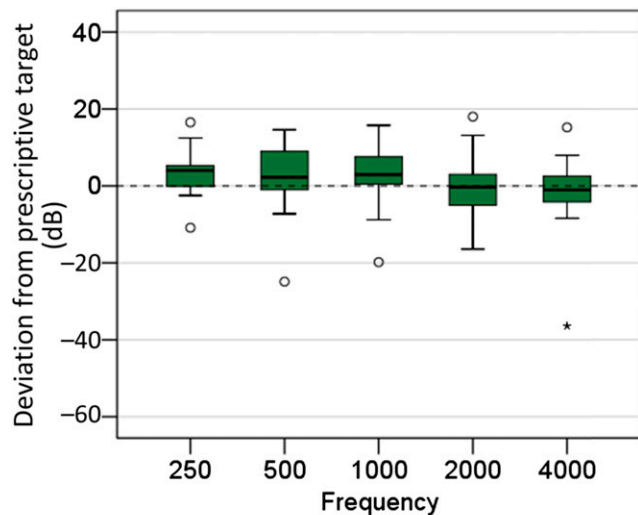
Audioscan software–computed aided SII for soft, conversational, and loud speech input levels are shown, using box plots, in Figure 4 ($N = 52$ aided ears; only those aided ears with SII values at all three speech-input levels are shown in this figure). As expected, SII are lowest for soft levels (mean = 22; $SD = 19$), slightly higher for conversational levels (mean = 30; $SD = 20$), and then, again slightly higher for loud levels (mean = 36; $SD = 20$). SII were also examined for various subgroups of participants. For the simultaneously implanted bilateral CI participants ($N = 9$), the aided SII associated with the better ear’s preimplant HA records are used. For the sequentially implanted bilateral CI participants ($N = 21$), the aided SII associated with the first-CI ear’s preimplant HA records are used, and for the participants with bimodal devices ($N = 15$), the aided SII associated with the (only) CI ear’s preimplant HA records are used. For aided ears of listeners in these present “device” groups, mean preimplant SII values for conversational speech input levels were 35 ($SD = 24$) for the simultaneous bilateral CI group, 27 ($SD = 19$) for the sequential bilateral CI group, and 30 ($SD = 22$) for the bimodal group. Mean SII was not significantly different across these three groups. Finally, SII for conversational speech input levels were also compared, across ears, for the participants in the sequential CI and bimodal device groups. (A similar comparison was not done for participants who received bilateral CIs simultaneously because presumably, they would have had similar unaided preimplant PTAs in both ears.) For the sequential bilateral CI participants, preimplant-aided SII for the first CI

Table 2. Deviations from Target

Frequency (Hz)	N	Mean (dB)	SD (dB)	95% Confidence Interval [LL, UL] (dB)
250	33	1.4	7.8	[−1.4, 4.1]
500	56	2.0	7.8	[−0.1, 4.1]
1000	54	1.5	7.2	[−0.5, 3.5]
2000	52	−2.1	8.6	[−4.5, 0.3]
4000	46	−14.2	17.3	[−19.3, −9.1]*

*Denotes significant.

Notes: Deviations from (prescriptive DSL) target (“HA output minus target”) for conversational speech input levels and for all HAs. The number of ears (N), mean, SD, and the LL and UL of the 95% confidence intervals of the mean are listed. If the 95% confidence interval does not include zero, then the mean deviation from prescriptive target is considered significantly different from zero; any such instances are indicated with an asterisk.



11	26	26	26	23
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Figure 3. Box plots of “deviation from prescriptive target” for conversational input levels (60 or 65 dB SPL); box plots exclude HAs with active frequency lowering, from a total of 26 HAs. For details on the box plots, see the caption for Figure 2. Numbers of HAs included in the box plots are listed below the graph at each octave frequency. (This figure appears in color in the online version of this article.)

ear (mean = 28; SD = 28) were generally lower than preimplant-aided SII_s for the second CI ear (mean = 37; SD = 21), although this difference was not statistically significant. For the bimodal device users, aided SII_s for the preimplant ears (mean = 30; SD = 22) were significantly lower [$t_{(14)} = -3.34, p < 0.01$] than the aided SII_s for the ears currently wearing HAs (mean = 52; SD = 18).

In Figure 5, Audioscan software-computed aided SII_s, for these participants’ ears for conversational speech input levels, are plotted as a function of unaided, preimplant PTA. Also shown are the normative data from the UWO-PedAMP (Bagatto et al, 2011; 2016; Moodie et al, 2017). Shown in red is the line of best fit for the 67 ears in our sample; these are all the aided

ears with SII_s available for a conversational-level speech input. (For four aided ears, SII_s were available only for soft- and/or loud-level speech inputs.) The red line departs from the UWO-PedAMP data, especially for unaided PTAs > 75 dB HL. Note that there are a few ears with PTAs in the moderate loss range; these ears belong to children who had a diagnosis of progressive HL (i.e., enlarged vestibular aqueduct or cytomegalovirus) or auditory neuropathy spectrum disorder.

Postimplant Speech Recognition Scores

The mean score for the LNT word list presented in noise (+8 dB signal to noise ratio) was 60% correct (SD: 22.7; range 0–92%).

Correlations

Aided SII_s (at conversational speech input levels) were not significantly correlated with age at first HA nor were they correlated with age at first CI. As expected, unaided PTA was significantly correlated with preimplant-aided conversational-level SII_s ($r = -0.936, p < 0.01$) (see Figure 5). Preimplant-aided conversational SII_s for the first CI ear were also significantly correlated with postimplant LNT in noise scores ($r = 0.35, p < 0.05$), when tested in these same children at ages five to eight years. Interestingly, however, age at first CI was not correlated with postimplant LNT in noise scores.

DISCUSSION

The pediatric CI candidacy process typically includes a trial period with an HA, or HAs, before any possible CI surgery. Not only does this practice assist in determining CI candidacy but it also allows the child to receive some audibility of speech, although perhaps quite limited. Pediatric Amplification Guidelines (AAA, 2013) provide specific protocols for achieving and verifying audibility targets with HAs. Studies from children with mild to severe loss have demonstrated

Table 3. Deviations from Target Excluding Frequency Lowering

Frequency (Hz)	N	Mean (dB)	SD (dB)	95% Confidence Interval [LL, UL] (dB)
250	11	3.3	7.3	[-1.6, 8.2]
500	26	2.7	8.0	[-0.5, 5.9]
1000	26	3.0	7.2	[0.1, 5.9]*
2000	26	-0.7	8.0	[-3.9, 2.6]
4000	23	-1.6	9.4	[-5.7, 2.4]

*Denotes significance.

Notes: Deviations from (prescriptive DSL) target (“HA output minus target”) for conversational speech input levels, excluding HAs that use frequency compression. The number of ears (N), mean, SD, and the LL and UL of the 95% confidence intervals of the mean are listed. If the 95% confidence interval does not include zero, then the mean deviation from prescriptive target is considered significantly different from zero; any such instances are indicated with an asterisk.

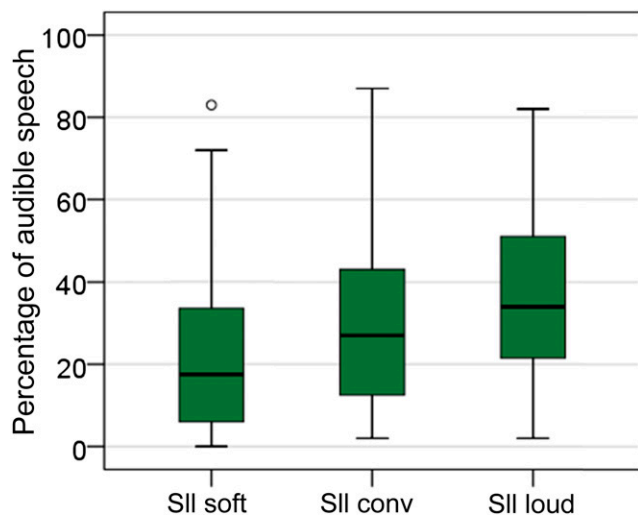


Figure 4. Box plots of aided SIIs (percentage of audible speech), computed from Audioscan software, for three speech input levels. Only those aided ears with SII values at all three speech-input levels are shown in this figure ($N = 52$). (This figure appears in color in the online version of this article.)

positive effects of well-fit HAs on spoken language outcomes (McCreery et al, 2015). Thus, for pediatric recipients, it is reasonable to attribute the positive effects of preimplant residual hearing on post-CI outcomes *in part* to the audibility of speech provided by HAs.

This study sought to characterize, for pediatric CI recipients, preimplant HA fittings and aided audibility (which is, of course, affected by PTAs and HA fittings). Of a total of 117 participants in a larger study (NIH

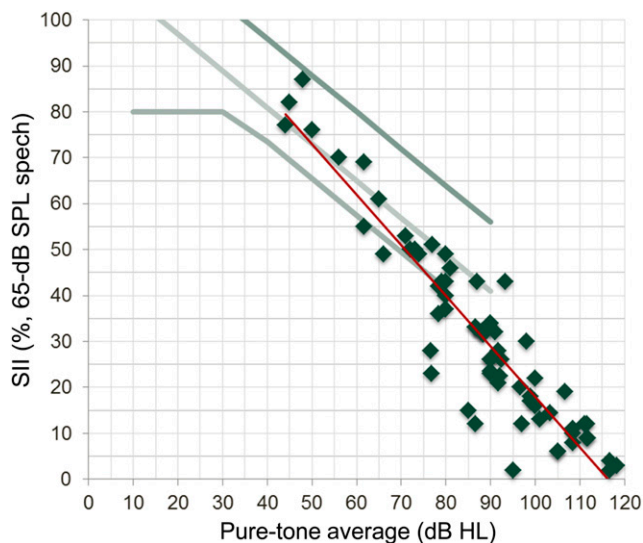


Figure 5. Aided SII vs. unaided preimplant PTA for these participants' ears ($N = 67$) are shown individually by diamonds, and the line of best fit is shown in red. Normative data are from the UWO-PedAMP. For the normative data, the light gray line represents average aided SII values and the dark gray lines represent SDs (2 SD above and 1 SD below) about the mean normative data. (This figure appears in color in the online version of this article.)

R01 DC012778), preimplant HA fitting records were retrievable for 45 participants (approximately 38%). Many CI and audiology centers reported that such data were not routinely saved in their patient records. Although there was some variation in the speech input levels (soft, conversational, or loud) used for matching prescriptive targets, most centers used a 60–65-dB SPL level to represent average conversational speech. Overall, in this sample of children with severe to profound HLs, who later received at least one CI, HAs were generally closely matched to prescriptive targets. Because HA fitting data were unavailable for most of the participants (i.e., the other 62%), it is uncertain whether these data are representative of pediatric CI recipients in general. These 45 participants, however, are seemingly no different from the remaining 72 participants with respect to preimplant PTA, age at first CI, and age at the time of speech perception tests (see description of participants in “Methods”).

For children with mild to profound losses, studies evaluating proximity to HA fitting targets have found that a substantial number of children have HA outputs that deviate significantly from target (Strauss and van Dijk, 2008; McCreery et al, 2013; Ching et al, 2015; McCreery et al, 2015). Moreover, some researchers suggest that deviations from target increase with more severe HLs, especially deviations at high frequencies such as 4–6 kHz (Ching et al, 2015). Yet, for speech recognition and ultimate development of spoken language skills, high-frequency audibility is critical for children (Stelmachowicz et al, 2004; Stelmachowicz et al, 2008). Thus, clinicians do their best, using any method possible—including frequency-lowering methods—to provide at least limited high-frequency audibility before receiving CIs. For the present study, children with HA outputs that deviated significantly from target at 4000 Hz were those who used HAs with active frequency lowering. This type of processing shifts (or lowers) high-frequency information to lower frequency regions, where listeners generally have better residual hearing (Simpson et al, 2005; Glista et al, 2009). This type of processing aims overcoming limitations in high-frequency audibility resulting from a combination of poor residual hearing and limited HA bandwidths. When the data in this present study were analyzed with frequency-lowering HAs excluded, deviations from target were not significantly different from zero. This result makes sense because HAs with frequency-lowering do not amplify high-frequency energy (beyond a specified cut-off frequency), but instead transmit high-frequency information at lower frequencies.

The aided SIIs, for these participants, estimate the audibility of speech, preimplant, in specific circumstances. When the distance between a talker and a child was approximately 1 m, then approximately 22% of softly spoken speech would have been audible (mean preimplant SII = 22). Similarly, ~30% and ~36% of conversationally

spoken and loudly produced speech would have been audible, respectively, to an infant (preimplant) at this same 1-m distance. All these values are very low. Stiles et al (2012) suggest that for children with mild to moderately severe HL, those with aided SII values < 65 exhibit greater delays in vocabulary development. For the children in the present study, with more severe to profound HL, these low SIIs represent inadequate audibility of speech (even of “loud” speech) such that CI surgery appears clearly warranted for all participants (recall, there was no significant difference in preimplant-aided SII across the three device groups). For the children who currently use bimodal devices, the significant difference in aided SII of the preimplant ear versus that of the present HA ear indicates that the ear with poorer hearing was chosen for implantation.

Calculation of the aided SII depends on both unaided PTA and on the fit of the HA to DSL target (McCreery et al, 2015). Consequently, it is unsurprising that for this study, SII and unaided PTA are highly correlated with each other, a result consistent with other studies (Sininger et al, 2010; McCreery et al, 2015). The correlation ($r = -0.936, p < 0.01$) is especially strong in this study because HA fits were all very close to DSL target. That is, overall, deviations from target were approximately zero. The exact relation, between PTA and SII, for children with HL that range from mild to severe, is shown by the UWO-PedAMP normative data (Bagatto et al, 2011; 2016; Moodie et al, 2017). The regression line for SII versus PTA in the present sample, however, departs from the normative data for PTAs > 75 dB HL. This seems likely due to the fact that the normative values were obtained from children with greater residual hearing (i.e., with less severe HL) than those in the present sample. Despite these reasonably well-fit HAs, these children were deemed ultimately and quite appropriately as candidates for CIs.

Interestingly, despite limited residual hearing (PTA) and limited aided audibility (SII), there was a positive and significant, albeit somewhat weak, correlation between aided SII and post-CI speech perception in noise (and, equivalently, between unaided PTA and post-CI speech perception in noise). These results along with those from other studies support the notion that even limited audibility before receiving a CI may be beneficial for speech recognition (Cowan et al, 1997; Nicholas and Geers, 2006; 2007; Sininger et al, 2010). Unlike other studies (Dowell et al, 2002; Geers et al, 2013), age at first CI was not correlated with speech perception in noise for this sample. The potential effects of age at first CI on eventual speech perception ability may have been mitigated by the consistent use of HAs, before receiving CIs, for the participants in this study. Regardless, this weak positive correlation provides further support that early audibility of speech, presumably provided via HAs, could have positive effects for children who subsequently receive CIs.

There are several considerations that may limit generalizing the results of the present study to other pediatric CI recipients. Although most of the participants in the present study had HAs that were fit to prescriptive target, these participants represent only about one-third of the total population of participants in the larger study. It is possible that centers that keep carefully documented HA-fitting records may be more likely to place a high priority on preimplant fitting procedures and thus bias the results toward more optimal HA fittings. In addition, all of the preimplant data were obtained retrospectively from centers across the United States several years after the measurements were obtained. Thus, differences in equipment, procedures, and personnel, across centers and across time, may contribute to variations in these measurements. There are, of course, many demographic and child factors that are very likely to affect post-CI outcomes (i.e., maternal education, enrollment in early intervention programs, etc.). The sample size ($N = 71$ ears) in the present study, however, is not adequate for sophisticated regression analyses that would allow quantitative determination of the contributions of child, family, educational, and audiological variables to post-CI outcomes. Rather, the primary scope of the present study was to characterize preimplant-aided audibility profiles of children who receive CIs and determine whether preimplant audibility, as measured by HA fitting parameters, is related to postimplant outcomes. An examination of aided audibility (SII), using the HA fit to target, may guide clinicians in determining CI candidacy and should be encouraged. As children with more residual hearing are considered for CIs, such an examination may be more critically important than in the past.

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