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Optimization of Programming Parameters in Children with the Advanced Bionics Cochlear Implant

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Abstract

Background—Cochlear implants provide access to soft intensity sounds and therefore improved audibility for children with severe-to-profound hearing loss. Speech processor programming parameters, such as threshold or T-level, Input Dynamic Range (IDR) and microphone sensitivity, contribute to the recipient's program and influence audibility. When soundfield thresholds obtained through the speech processor are elevated, programming parameters can be modified to improve soft sound detection. Adult recipients show improved detection for low-level sounds when T-levels are set at raised levels, and show better speech understanding in quiet when wider IDRs are used. Little is known about the effects of parameter settings on detection and speech recognition in children using today's cochlear implant technology.

Purpose—The overall study aim was to assess optimal T-level, IDR and sensitivity settings in pediatric recipients of the Advanced Bionics cochlear implant.

Research Design—Two experiments were conducted. Experiment 1 examined the effects of two T-level settings on soundfield thresholds and detection of the Ling 6 Sounds. One program set Ts at 10% of M-levels and another at 10 current units (CUs) below the level judged as “soft”. Experiment 2 examined the effects of IDR and sensitivity settings on speech recognition in quiet and noise.

Study Sample—Participants were eleven children 7 to 17 years of age (mean 11.3) implanted with the Advanced Bionics High Resolution 90K or CII cochlear implant system and had speech recognition scores of 20% or greater on a monosyllabic word test.

Data Collection and Analysis—Two T-level programs were compared for detection of the Ling Sounds and frequency modulated (FM) tones. Differing IDR/sensitivity programs (50/0, 50/10, 70/0, 70/10) were compared using Ling and FM-tone detection thresholds, CNC words at 50 dB SPL, and HINT-C sentences at 65 dB SPL in the presence of four talker babble (+8 signal-to-noise ratio). Outcomes were analyzed using a paired t-test and a mixed-model repeated measures analysis of variance (ANOVA).

Results—T-levels set 10 CUs below “soft” resulted in significantly lower detection thresholds for all six Ling sounds and FM-tones at 250, 1000, 3000, 4000 and 6000 Hz. When comparing

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programs differing by IDR and sensitivity, a 50 dB IDR with a 0 sensitivity setting showed significantly poorer thresholds for low frequency FM-tones and voiced Ling sounds. Analysis of group mean scores for CNC words in quiet or HINT-C sentences in noise indicated no significant differences across IDR/sensitivity settings. Individual data, however showed significant differences between IDR/sensitivity programs in noise; the optimal program differed across participants.

Conclusions—In pediatric recipients of the Advanced Bionics cochlear implant device, manually setting T-levels with ascending loudness judgments should be considered when possible or when low-level sounds are inaudible. Study findings confirm the need to determine program settings on an individual basis as well as the importance of speech recognition verification measures in both quiet and noise. Clinical guidelines are suggested for selection of programming parameters in both young and older children.

Keywords

Cochlear implant; pediatric recipient; threshold level; input dynamic range; sensitivity; speech processor; optimization; speech recognition

INTRODUCTION

For individuals with severe-to-profound hearing loss, cochlear implants provide improved detection and recognition of sounds that range from soft to comfortably loud. To confirm the ability to detect soft sounds, threshold levels for varied stimuli are obtained in the soundfield while the recipient wears a cochlear implant speech processor. These soundfield detection thresholds can be used as a clinical guide when fitting a speech processor and are especially helpful when fitting young children who cannot provide verbal feedback. In previous studies, soundfield thresholds between 15 to 30 dB HL for frequencies 250–4000 Hz verified soft sound detection (Skinner et al, 1997, 1999, 2003) and correlated with speech recognition scores at average (60 dB SPL) and soft (50 dB SPL) conversational levels (Firszt et al, 2004). When soundfield thresholds are elevated, various speech processor program parameters can be modified to improve soft sound detection.

Parameter settings that can affect soundfield thresholds with the Advanced Bionics Harmony Processor include threshold levels (T-levels), most comfortable levels (M-levels), Input Dynamic Range (IDR) and microphone sensitivity. T-levels represent the minimum amount of electrical current needed for each electrode to elicit a low-level or soft percept for the recipient. M-levels reflect the amount of electrical current needed for each electrode to elicit a comfortable loudness percept. The setting of T- and M-levels for each active electrode is required to create a speech processor program. When using the manufacturer's software (SoundWave™) to set T-levels for an Advanced Bionics speech processor, a "default" setting can be selected. By doing so, T-levels are automatically calculated as a level that represents 10% of the recipient's M-levels. Alternately, T-levels can be set manually based on the patient's perception of minimally audible sounds, for example "very soft" or "first hearing".

The effect of setting T-levels manually compared to the recommended default setting was recently evaluated in 10 adults using the Advanced Bionics Harmony, Auria, and Platinum Series processors (Holden et al, 2011). For each participant, three programs were created that differed in T-level setting. Program 1 had T-levels set manually between "barely audible" and "very soft" using ascending loudness judgments. Program 2 also set T-levels manually but at 10 current units (CUs) below "soft." Program 3 set T-levels at 10% of M-levels. Group mean results showed significantly better soundfield thresholds for frequency

modulated (FM) tones when T-levels were set manually compared to setting Ts at 10% of M-levels. For six of the 10 participants, T-levels set 10 CUs below “soft” were optimal for sound detection. For one person, T-levels set between “barely audible” and “very soft” provided the best threshold levels. For three individuals, T-levels set at 10% of M-levels (the default) were optimal. Optimal T-level settings are expected to vary for different implant manufacturers due to differences in the internal and external components and the manner in which the parameters function. Skinner et al (1999) examined adult recipients using the Spectra 22 Cochlear Corporation device and found soundfield thresholds of 30 dB HL or better could be obtained by setting T-levels above 100% detection. In addition, T-levels set above 100% detection rather than at threshold were associated with higher speech recognition scores, especially at soft presentation levels. Finally, participants chose to keep the program with higher T-levels on their speech processors for everyday listening providing further support for the use of raised T-levels.

Input Dynamic Range (IDR) also affects the ability to detect soft sounds. The width of the IDR determines the intensity range of sound captured by the device’s front end processing that is fit within the user’s electrical dynamic range. The IDR setting for the Advanced Bionics system can vary from 20 to 80 dB but the recommended default is 60 dB (Advanced Bionics, 2006). Holden et al (2011) investigated the effects of three IDR settings in 10 adult recipients of the Advanced Bionics Harmony device. Three programs that differed in IDR width (50, 65 and 80 dB) were compared using FM-tone thresholds and speech recognition measures. Group mean scores for the Consonant-Vowel Nucleus-Consonant (CNC) monosyllabic word test (Peterson and Lehiste, 1962) presented at 50 dB SPL in quiet were significantly higher for IDRs of 65 and 80 compared to an IDR of 50. No significant group mean differences were found across the three tested IDRs for the City University of New York (CUNY) sentence test (Boothroyd et al, 1988) presented at 65 dB SPL in four-talker babble at individually determined signal-to-noise ratios (SNRs). However, significant differences were observed among individuals. Four of the 10 recipients showed significant improvement for sentences in noise with the 50 dB IDR compared to wider settings.

With an earlier Advanced Bionics processor, the CII, Spahr et al (2007) examined the effect of four IDRs (30, 40, 50, and 60 dB) on speech recognition in 10 adult users. For AzBio sentences (Spahr and Dorman, 2004; Gifford et al, 2008) presented in quiet at 57 dB SPL, scores significantly improved with each 10 dB increase in IDR. When the sentences were presented in quiet at 77 dB SPL, scores with a 30 dB IDR were significantly lower, however there were no score differences using 40, 50 or 60 dB IDRs. A similar result was obtained when AzBio sentences were presented at 77 dB SPL in noise (four-talker babble at a +10 dB SNR); scores with IDRs of 40, 50 and 60 dB were not significantly different compared to lower scores with an IDR of 30 dB. Zeng et al (2002) also examined speech recognition as a function of IDR in ten Clarion study participants using their clinical programs on an S-series speech processor. Six to seven IDR settings were evaluated in ten dB steps, either 10–60 dB or 20–80 dB, depending on the speech coding strategy used by the individual. Results showed that an IDR of 50–60 dB compared to narrower IDRs was optimal for the perception of vowels and consonants in quiet. Donaldson and Allen (2003) evaluated seven Clarion 1.2 and seven Nucleus 22 implant recipients for recognition of vowels, consonants and HINT sentences at five presentation levels (30 to 70 dBA, in 10 dB steps). At higher presentation levels (70 dBA), performance was equivalent, however below 50 dBA, the decrease in score for Nucleus 22 subjects was greater than Clarion recipients. Differences were thought to relate to audibility (e.g., poorer soundfield thresholds in Nucleus users) and size of the acoustic dynamic range incorporated by the device (e.g., narrower IDR range of 26–30 dB in Nucleus users).

A wider IDR improved speech recognition in quiet in patients using the Cochlear device (Dawson et al, 2007; Holden, et al 2007; Spahr et al, 2007). For example, Dawson et al (2007) examined speech recognition with IDRs of 31, 46 and 56 dB in nine adults using the SPEAR3 research processor. When CNC words were presented at 45 and 55 dB SPL in quiet, group mean scores significantly improved with the two wider IDRs compared to a 31 dB IDR. No significant differences were observed across IDRs for CUNY sentences presented at 65 dB SPL in the presence of eight-talker babble with individually determined SNRs. In 10 newly implanted adults using the Cochlear Freedom processor (Holden et al, 2007), two IDRs were compared using FM-tone soundfield thresholds, CNC words, Hearing in Noise Test sentences (HINT; Nilsson et al, 1994) presented at 50 dB SPL in quiet, and CUNY sentences presented at 65 dB SPL in eight-talker babble at individually determined SNRs. A wider IDR of 40 versus 30 dB resulted in significant group mean improvements for soundfield thresholds, word recognition in quiet, and sentence recognition in noise. Spahr et al (2007) also examined the effects of a 30 and 40 dB IDR in 10 adult users with the Cochlear Esprit 3G processor. The two IDRs were compared using AzBio sentences presented at 57 and 72 dB SPL in quiet and at 72 dB SPL in four-talker babble at a +10 SNR. An increased IDR improved sentence recognition at 57 dB SPL in quiet but reduced sentence recognition in noise. Sentence recognition at 72 dB SPL in quiet was not affected by IDR. Results may have differed across studies due to different speech processors, test materials, stimulus presentation levels, IDR levels tested, and study designs.

Microphone sensitivity is a third parameter that affects audibility of soft sound. In the Advanced Bionics device, sensitivity provides an additional range of amplification or attenuation (+/- 10 dB) to the input signal before the Automatic Gain Control (AGC) compresses sound. The amplification or attenuation does not change the amount of current used, but changes where the input is placed within the patient's electrical dynamic range. James et al (2003) examined the effect of microphone sensitivity settings in 12 adults using the Cochlear Sprint processor. A sensitivity setting of 15 compared to 8 (on a scale of 0 to 20) resulted in significantly improved vowel and consonant recognition at soft levels (40 and 55 dB SPL) without a detrimental effect in noise (measured with BKB everyday sentences, Bench et al, 1979, presented at 65 dB SPL in multi-talker babble at individually determined SNRs). Spahr et al (2007) also examined the effect of three sensitivity settings: low (3.5), medium (5), and high (7) (on a scale of 1–7) for 10 adult users of the Cochlear Esprit 3G processor. Increases in sensitivity improved sentence recognition at a soft level of 57 dB SPL in quiet but reduced sentence recognition at 72 dB SPL in the presence of four-talker babble at a +10 SNR. Sentence recognition at 72 dB SPL in quiet was generally not affected by sensitivity. Similar results were reported in a small sample of two Nucleus 22 users who adjusted their Spectra processor sensitivity settings from 2 to 4 to 6 (range 0–8) (Donaldson and Allen, 2003). Vowel and consonant recognition scores improved with higher sensitivity settings for stimuli at 40–60 dBA. Speech stimuli at higher levels (60–70 dBA) were sometimes reported as too loud with a sensitivity of 6. Settings/adjustments that improve audibility can also affect quality or reduce speech recognition at higher intensities for some individuals. Programming adjustments must be considered in conjunction with each other and with the individual's varied and dynamic listening conditions.

Little research has been conducted to evaluate the effects of speech processor parameter settings in children. Low soundfield thresholds (i.e., at or below 30 dB HL) were reported in pediatric recipients of the Nucleus 24 system when T-levels for the ESPrIt 3G or Sprint processors were set at or above 100% detection and when possible, using counted thresholds (Holstad et al 2009). Another study examined the effects of 30 and 40 dB IDRs in children wearing Cochlear's Freedom speech processor (Davidson et al, 2009). The two IDRs were compared using FM-tone soundfield thresholds, CNC words presented at 50 and 60 dB SPL, and the Bamford-Kowal-Bench Speech in Noise Test (BKB-SIN; Bench et al 1979;

Etymotic Research 2005) which presents sentences with four-talker babble at pre-recorded SNRs, decreasing in 3 dB steps from easy to difficult. The 40 dB IDR resulted in significantly improved soundfield thresholds at 250 to 6000 Hz and significantly improved word recognition at a soft presentation level (50 dB SPL) without impairing speech recognition at louder presentation levels or in the presence of noise. The effect of IDR width in pediatric recipients of the Advanced Bionics device remains unknown. Likewise, there is little information available regarding the effects of sensitivity settings in recipients of Advanced Bionics devices, either children or adults.

To summarize, parameter settings of T-level, IDR and sensitivity affect soundfield thresholds and speech recognition performance in quiet and noise. In adults, wider IDRs tend to improve speech recognition at soft presentation levels (i.e., Zeng et al, 2002; Donaldson and Allen, 2003; Spahr et al, 2007; Holden et al, 2007, 2011). Speech recognition in noise varies from no change in performance (Dawson et al, 2007; Davidson et al, 2009; Holden et al, 2011) to some improvement (Holden et al, 2007; Spahr et al, 2007) to a reduction in performance (Spahr et al, 2007). Results also differ across implant manufacturer types and patients. Study findings do encourage the use of different speech processor programs with varied IDRs and sensitivity settings to assist in various listening situations. Like adults, children are in varied listening environments. Hearing successfully, both at a distance and in background noise, is critical for effective communication and incidental learning.

The overall aim of this study was to investigate optimal T-level, IDR and sensitivity settings for children with the Advanced Bionics cochlear implant. Experiment 1 examined the effects of two T-level settings on soundfield thresholds. We hypothesized that soundfield thresholds would be lower with T-levels set manually rather than Ts at 10% of M-levels. Experiment 2 examined the effects of IDR and sensitivity settings on speech recognition in quiet and noise. We hypothesized that a wide IDR would result in better speech recognition in quiet and a narrow IDR would result in improved speech recognition in noise.

METHODS

The study protocol was reviewed and approved by the Institutional Review Board of Washington University (HRPO # 08-0764). Informed consent was obtained from the parent(s) or guardian(s) and the participant prior to study enrollment.

Participants

Eleven children who had been implanted at St. Louis Children's Hospital and met the study criteria participated. Participants ranged in age from 7–17 years with a mean of 11.4 years. The mean age at onset of hearing loss was 1.8 years (SD 1.3, range .25 – 4.5) and the mean age at onset of severe-to-profound hearing loss was 3.9 years (SD 3.6, range .25 – 11). The participants had received their first implants between the ages of 2 and 16 years with a mean of 7.1 years (SD 4.2). Eight participants had unilateral 90K Advanced Bionics cochlear implant systems. Three participants were bilateral recipients, implanted with CII or 1.2 internal devices in their first implanted ear and the 90k device in their second implanted ear. All participants used their 90K device during the study except participants 1 and 9, who were tested in their first implanted ear which had received a CII implant. Length of implant use in the tested ear ranged from 6 months to 12 years with an average of 3.5 years (SD 3.7). The etiologies of hearing loss consisted of enlarged vestibular aqueduct ($n = 1$), familial ($n = 3$), unknown with suspected cause ($n = 2$), and unknown ($n = 5$). Enrollment requirements included English as a first language and speech recognition scores of 20% or greater on a monosyllabic word test. Demographic information for individual participants is provided in Table 1.

All participants were tested with their Harmony processor and clinically determined speech coding strategy, High Resolution 120 (Sequential). The number of active electrodes used in the participant's everyday program was not altered for the study procedures. Three participants used programs with all 16 electrodes active and the remaining eight participants had 12 to 15 active electrodes. The participant's everyday volume dial setting (at or near 12:00) remained constant for all study conditions.

Detection Threshold Levels

FM-tone threshold levels were obtained in the soundfield using a 2 dB step-size and Hughson-Westlake (Carhart and Jerger, 1959) procedure for frequencies 250, 500, 1000, 2000, 3000, 4000 and 6000 Hz. Detection thresholds for recorded Ling sounds were obtained using the same procedure and step-size. The Ling 6 sounds test (Ling 1976, 1989) uses isolated phonemes consisting of three vowels ([ah], [oo], [ee]) and three consonants ([m], [s], [sh]) that span the speech frequency range of 250–8000 Hz. The Ling 6 sounds are often used by educators, parents and clinicians to assess audibility across the frequency range with hearing-impaired children. These phonemes were recorded by a female speaker, were approximately 800 ms in duration, and had an RMS level within 1 dB of each other.

Speech Recognition Tests

Consonant-Vowel Nucleus-Consonant (CNC) Monosyllabic Words were presented at 50 dB SPL. CNC lists 2, 5, and 6 were selected since these lists had equivalent intelligibility scores for adult cochlear implant recipients (Skinner et al, 2006). Hearing in Noise Test for Children (HINT-C) sentences (Nilsson et al, 1996) (lists 1 through 6) were presented at 65 dB SPL in the presence of four-talker babble with a +8 dB signal-to-noise ratio (SNR). One CNC list of 50 words and two HINT-C lists (10 sentences per list) were used for each test condition. Word and sentence lists and test order of the processor programs were randomized for each participant. All stimuli were calibrated using dB Lin SPL (slow RMS) at the approximate location of the center of the child's head at 0° azimuth, one meter from the loudspeaker. A Bruel and Kjaer 2230 sound level meter, 1625 filter set, and 4155 microphone (Bruel and Kjaer, Denmark) were used to measure the SPL of the test stimuli.

Test Equipment and Materials

The participants' processors were programmed using SoundWave™ software (version 1.4.77) installed on a Dell laptop computer (Dell Latitude D520, Model PP17L) provided by Advanced Bionics. All testing occurred in a double-walled booth (Industrial Acoustics Company, Inc 7' 8" by 11' 8") where the child was positioned at 0° azimuth, one meter from the loudspeaker (Grason-Stadler High performance speaker). Speech recognition and detection stimuli were digitized and stored as wave files. The four-talker babble stimulus was presented from a compact disk recording (Auditec, 1971). The computer and disk player (Toshiba, Model SD-K654) were used to deliver the stimulus. Both the babble and stimulus were presented via the two channel audiometer (Grason-Stadler, Model GSI 61) and a loudspeaker in the soundfield.

Experiment 1: Evaluation of T-levels—Participants were seen for two three-hour sessions. Experimental programs were created and stored on the participant's processor for the duration of each test session. The original processor settings were replaced at the end of each session. During the first session, two programs were created differing only by T-levels. One program set T-levels at 10 current units (CUs) below a level judged to be "soft" (this will be referred to "Ts below soft" throughout the manuscript). The "soft" judgment level was determined using ascending loudness judgments on a five-point scale ("very soft," "soft," "medium," "loud but okay," and "loud"). Participants reported subjective loudness

while listening to biphasic electrical pulses presented on five individual electrodes across the array. Unless differences (> 15 CUs) were observed on neighboring electrodes, T-levels were interpolated for electrodes located between the five measured electrodes. The other experimental program had T-levels set at 10% of M-levels (this will be referred to as “Ts at 10% of Ms” throughout the manuscript) which is the default setting recommended by Advanced Bionics. Both programs used the 60 dB default IDR, a 0 dB sensitivity level and 0 dB of gain across all electrodes. Gain amplifies or attenuates (± 10 dB) the input signal through band-pass filters at the front end of the signal processing after automatic gain control (AGC) and sensitivity and does not affect current levels. The M-levels for both experimental programs were those from the child’s current everyday program. All participants had stable M-levels with at least 6 months of device use. For all children, the clinical approach for setting M-levels was to set them at the highest comfortable level based on loudness judgments (“loud but okay”), after which they were adjusted as needed, to provide appropriate FM-tone soundfield thresholds. M-levels for most participants were above the level initially identified as “loud but okay” to improve soundfield thresholds but not at a level that would create any discomfort.

The two T-level programs were compared using FM-tone and Ling detection thresholds obtained in the soundfield. The processor program test order was randomized and participants were blinded to the program used. If a device was worn on the non-test ear, it was removed during testing. Since elevated T-levels can result in unwanted noise for some patients, the participants listened in the quiet sound booth to each program and reported any audible noise, such as a humming or static-type sound.

Experiment 2: Evaluation of IDR and Sensitivity—The program that provided the lowest detection levels in Experiment 1 was selected and used during Experiment 2. If a participant reported that a T-level setting caused a distracting audible noise, it was not chosen, regardless of threshold levels. In two cases when the selected program had thresholds greater than 30 dB HL, slight adjustments were made to the M-levels so that soundfield thresholds were below 30 dB HL for all frequencies and recorded Ling sounds.

Using these T-levels, four new programs were created differing by IDR and sensitivity settings as follows: 50 dB IDR and sensitivity 0 (50/0), 70 dB IDR and sensitivity 0 (70/0), 50 dB IDR and sensitivity 10 (50/10), and 70 dB IDR and sensitivity 10 (70/10). FM-tone and Ling sound detection thresholds were obtained in the soundfield with each of these four programs. As with Experiment 1, the program test order was randomized, participants were blinded to the program used, and devices for the non-test ear were removed during testing. To avoid fatigue and reduce lengthy test session times for children, three of the four programs were evaluated for each listening condition. The settings hypothesized to be optimal for each condition (70/10 in quiet, 50/0 in noise) were tested with two opposing programs that differed by only one parameter. CNC word recognition in quiet was evaluated with 70/10 and two other programs; one with decreased IDR (50/10) and the other with decreased sensitivity (70/0). Similarly, the HINT-C sentences in noise were evaluated with 50/0 and two other programs; one with increased IDR (70/0) and the other with increased sensitivity (50/10).

Data Analysis

Soundfield and Ling detection thresholds for the T-level programs were analyzed using a paired t-test. All other results were analyzed using a mixed-model repeated measures analysis of variance (ANOVA). A p value of 0.05 determined statistical significance. When the overall ANOVA model was significant, a post-hoc Tukey test determined significant pairwise comparisons of the means. The data analysis was generated using SAS

software, version 9.1.3 of the SAS System for Linux (SAS Institute Inc., Cary, NC, USA). Individual results were compared based on tables for the upper and lower limits of the 95% critical range for changes in word recognition scores (Thornton and Raffin, 1978; Carney and Schlauch, 2007).

RESULTS

Experiment 1

Figure 1 shows group mean FM-tone thresholds for the two T-level settings; one with Ts below soft (triangle with solid line) and one with Ts at 10% of Ms (circle with dashed line). FM-tone thresholds with Ts below soft were significantly lower (better) for frequencies 250, 1000, 3000, 4000 and 6000 Hz ($p < 0.05$ except 3000 Hz where $p < 0.01$) compared to Ts at 10% of Ms. When Ts were set below soft, average thresholds ranged from 16.4 dB HL at 250 Hz to 22.5 dB HL at 6000 Hz; no significant threshold differences were found between frequencies. However, with Ts at 10% of Ms, significantly higher (poorer) thresholds occurred at 3000, 4000, and 6000 Hz compared to 500 Hz ($p < 0.05$) and at 3000 Hz compared to 1000 and 2000 Hz ($p < 0.05$). The best average threshold was 19.5 dB HL at 500 Hz and the poorest was 28.5 dB HL at 3000 Hz.

Likewise, detection thresholds obtained using Ts below soft were significantly lower for all Ling 6 sounds compared to Ts at 10% of Ms ($p < 0.01$). With Ts below soft; mean thresholds for [ah], [ee], [m], [oo], [s], and [sh] were 13.6, 19.3, 17.3, 14.4, 17.6 and 17.3 dB HL, respectively. With Ts at 10% of Ms, mean thresholds for the same Ling sounds were 19.1, 26.4, 25.1, 19.6, 23.8 and 22.0 dB HL.

Figure 2 shows the group average CU levels by electrode for three T-level settings: 1) Ts at 10% of Ms (circle with dashed line), 2) Ts below soft (triangle with solid line), and 3) Ts from the participant's everyday program or their Original Ts (square with dashed line) which were set at or near "first hearing." Ts at 10% of Ms resulted in the lowest CU levels followed by T-levels in the participant's everyday program and finally Ts below soft. The group mean CU level across electrodes for Ts at 10% of Ms was 38 CUs lower than the everyday T-level settings and 79 CUs lower than Ts below soft. Figure 2 also shows the average M-levels used in the speech processor programs (square with solid line). Recall that M-levels were set clinically for the participant's everyday program and remained constant for both experimental programs that varied in T-levels. On average, M-levels were well above the level initially identified as "loud but okay" for the majority of children. All participants' clinical programs had been verified as comfortable for everyday use.

For each participant, the T-level setting that resulted in the lowest detection thresholds was selected for use in Experiment 2. All but one participant had lower soundfield and Ling detection thresholds with Ts below soft than with Ts at 10% of Ms. Participant 5 (P5) had equivalent detection thresholds for both T-level settings. Ts at 10% of Ms was selected for this participant because a barely audible noise was reported with higher T-levels. Likewise, P2 used Ts at 10% of Ms due to an audible noise with the Ts below soft program.

Experiment 2

FM-Tone and Ling Sounds Detection Results—Group average soundfield FM-tone thresholds were similar between the four new programs that differed only in IDR (50 or 70) and/or sensitivity (0 or +10) except at 250 and 500 Hz. At 250 Hz, the 50/0 program showed significantly poorer thresholds compared to the other three IDR/sensitivity programs (50/10, $p < 0.05$; 70/0 and 70/10, $p < 0.01$). At 500 Hz, the 50/0 program resulted in poorer thresholds compared to the 50/10 and 70/10 programs ($p < 0.05$). Ling detection thresholds

were significantly poorer ($p = 0.05$) with the 50/0 program for sounds [m], [ah], and [ee] compared to the other IDR/sensitivity programs. The average threshold obtained using the 50/0 program was significantly poorer than the 70/10 program for detection of [oo] ($p < 0.01$). No significant threshold differences were observed for [sh] or [s] across any of the IDR/sensitivity programs. Averaging across participants and all 6 Ling sounds, the mean detection threshold for the 50/0 program was 21.7 dB HL compared to 16.4, 14.6 and 15.1 dB HL for the 70/0, 50/10 and 70/10 programs.

For individuals, the range of differences in FM-tone thresholds for the four IDR/sensitivity programs at discrete frequencies was 2–18 dB. The participants' range of differences across the four programs for Ling 6 sound thresholds was 0–20 dB. Average thresholds for all 6 Ling sounds were poorest with the 50/0 program for 10 of the 11 participants. Increased sensitivity with a 50 IDR (50/10) improved Ling thresholds for 10 participants and improved FM-tone thresholds for seven participants.

Speech Recognition Results—Of the 11 participants, 10 completed speech recognition measures with three IDR/sensitivity settings: 50/10, 70/10 and 70/0 for CNC words in quiet and 50/10, 50/0, and 70/0 for HINT-C sentences in four-talker babble. (Participant 11 was unable to return for this part of the study.) Figure 3 shows individual and group mean CNC scores for each of the tested IDR/sensitivity programs. Average CNC word recognition scores in quiet at 50 dB SPL were 43%, 42% and 47% for the IDR/sensitivity settings 50/10, 70/10, and 70/0, respectively. Analysis of group mean scores indicated no significant differences across the IDR/sensitivity settings. Individual participant word recognition varied with respect to IDR and sensitivity combinations. Different settings resulted in seemingly large changes in word recognition scores (10–18%) for all but two participants (P4 and P6). The differences were not statistically significant however, except for P2, who showed a significant improvement for 70/0 compared to 50/10.

Individual and group mean HINT-C in noise scores for each of the tested IDR/sensitivity programs are shown in Figure 4. Average scores for HINT-C sentences in noise at 65 dB SPL were 47%, 46%, and 53% for IDR/sensitivity settings 50/10, 50/0, and 70/0. Analysis of group mean scores indicated no significant differences across the IDR/sensitivity settings. For 7 of the 10 participants (excluding P3, P4 and P7), there was a significant difference in score between at least two of the three IDR/sensitivity settings tested. Six participants had a significantly better score with a single IDR/sensitivity setting compared to the other two settings (70/0 for P1, P2 and P5; 50/0 for P9 and P10; 50/10 for P6).

Scores indicated that when the sensitivity was 0, four participants (P1, P2, P5, and P8) had significantly better sentence recognition in noise with an IDR of 70 dB than with 50 dB and two (P9 and P10) had significantly better scores with an IDR of 50 dB than 70 dB. Two participants (P9 and P10) had significant differences based on sensitivity settings when the IDR was consistent at 50 dB, scoring significantly higher with sensitivity at 0 than at +10.

DISCUSSION

Experiment 1 examined the effects of two T-level programming settings on soundfield thresholds in children using the Advanced Bionics cochlear implant system. Participants demonstrated significantly improved thresholds with T-levels set manually (10 CUs below soft) based on loudness judgments compared to T-levels set at 10% of M-levels. Improvements were noted for the detection of both FM-tones and recorded Ling 6 sounds. Results are consistent with those obtained with adult recipients of the Advanced Bionics system where Ts set manually using ascending loudness judgments were significantly better than Ts set at 10% of Ms for FM-tone thresholds at 250–1500 Hz (Holden et al, 2011).

Results are also consistent with improved detection in adult patients using Cochlear devices when raised T-levels were incorporated in speech processor programs (Skinner et al, 1999).

Children who are unable to make loudness judgments may potentially benefit from T-levels set manually, and above the default of 10% of M-levels. T-levels in the participant's everyday program (referred to as Original Ts in the current study) were set at "first hearing". In other words, when the electrical current was slowly raised from a minimum level, the point at which the child first indicated detection determined the T-level for that electrode and ultimately for the speech processor program. As shown in Figure 2, T-levels used in everyday programs fell between T-levels at 10% of M-levels (lowest levels) and T-levels at 10 CUs below soft (highest levels). Setting T-levels at first hearing does not require loudness judgments, is clinically viable for very young children, and can be determined through behavioral observations. Other approaches for setting T-levels above the default (10% of Ms) for young children would be to set T-levels 1) between 10% of M-levels and first hearing, or 2) slightly above first hearing. Obtaining soundfield thresholds with various T-level settings could provide guidance for determining the best T-levels and validate that soft sounds are audible across the frequency range. Once children acquire the ability to loudness scale, it is recommended that Ts be set manually to achieve optimal sound detection. Improved audibility is especially important for children who are developing speech and language skills through audition and who need to listen at varied distances throughout the day.

Experiment 2 examined the effects of different IDR widths and sensitivities on detection and speech recognition in this same group of children. Overall, the participants demonstrated the poorest audibility for low frequency FM-tones and the Ling 6 sounds using a 50 dB IDR and a sensitivity of 0 (50/0). The other tested settings, 70/0, 70/10 and 50/10, had comparable group means for FM-tone and Ling sound thresholds. Holden et al (2011) also reported that FM-tone thresholds were significantly poorer with a 50 dB IDR compared to both 65 and 80 dB in adult Advanced Bionics recipients.

In the current study, group mean scores for CNC words in quiet showed no significant differences for the tested IDR and sensitivity settings; this result differs from other studies with adults using the Advanced Bionics device. For example, Holden et al (2011) reported a significant improvement in CNC word scores with an IDR of 80 or 65 dB compared to 50 dB. One difference between the current study and the Holden study was the sensitivity setting. In Holden et al, the comparison between the three IDR widths in adults was made with a sensitivity of zero. In the current study with children, the IDR comparison for words in quiet was between 50 dB and 70 dB and a sensitivity of 10. Testing was not conducted with a 50/0 setting; therefore, a comparison between the two IDR widths with the sensitivity consistent at zero was not feasible. It is possible that a comparison of word understanding in quiet with a 50/0 and 70/0 program would have yielded different results. Spahr et al (2007) showed significant improvements in mean AzBio sentence recognition scores in quiet with increasing IDR widths (30, 40, 50 and 60 dB). An investigation of the interaction between IDR and sensitivity with the Cochlear Esprit 3G indicated that speech recognition scores (for soft input, 57 dB SPL) were similar for 30 and 40 dB IDRs when using a high microphone sensitivity. When the low microphone sensitivity was engaged, scores were vastly different between the two IDRs. Again, with respect to the current study, a sensitivity of zero between the two tested IDRs may have produced larger IDR effects.

Another possible explanation for the difference in study results is the population. As a group, children may not be as sensitive to changes in IDR as adults. In the current study, individual participants with a change in CNC score of 12% or greater (a clinically meaningful change) across IDRs/sensitivities were P1, P2, P3, P5, P7, P9 and P10. For five

of those seven children, the 70/0 setting resulted in the highest or near highest performance; P7 performed best with 70/10 and P1 performed best with 50/10. Although group mean scores did not differ, individual results encourage the use of a wider IDR for word recognition in quiet.

Group mean scores for HINT-C sentences presented in four-talker babble showed no significant differences in tested IDRs and sensitivity settings in children. Holden et al (2011) also found no IDR effect for group mean speech recognition scores in noise with adult users. Spahr et al (2007) did show a significant difference between a 30 dB IDR and higher IDRs, but there were no differences between 40, 50 and 60 dB IDRs. An IDR of 30 was much narrower than the IDRs used in the current study. At the individual level, significant differences between IDR/sensitivity settings occurred for 7 of the 10 participants, excluding P3, P4 and P7. Among those seven, the combination of 70/0 was significantly better for sentence recognition in noise for P1, P2, P5 and P8. 50/10 was best for P6 and 50/0 for P9 and P10. In all cases but three (P6, P9 and P10), 50/0 resulted in the lowest score or was almost equivalent to the lowest score. While the majority of participants showed a significant improvement with a specific IDR/sensitivity setting in noise, no single combination was optimal for all.

A comparison of quiet and noise scores for an individual highlights that an optimal setting for listening in quiet may differ for listening in noise. For example, P8 performed similarly with the three IDR/sensitivity settings in quiet (difference of 8 percentage points) but showed superior performance with one setting (difference of 22 percentage points) in noise. Holden et al (2011) also found significant individual differences in adult participants using the Advanced Bionics device. These findings in both pediatric and adult recipients underscore the importance of individualized programming to fully explore successful combinations of parameters. Importantly, optimal settings for one participant were adverse for another. For example, the optimal setting in noise for P1, P2 and P5 was 70/0, increasing each participant's speech recognition score by 19, 37, and 48 percentage points, respectively. Yet, this same IDR and sensitivity setting resulted in decreased scores for P6 and P10 (32 and 35 percentage points) compared to other settings.

While these results emphasize the need for speech recognition testing in noise to verify cochlear implant settings, young children and children in early stages post-implant may not be capable of this type of measure. Until such time, clinicians often rely on soundfield thresholds and behavioral observation for fitting verification. For the seven participants who had significant differences in speech understanding in noise, the settings that provided the best scores also provided the lowest (or one of the two lowest) FM-tone threshold levels.

Based on the current study results, a narrow IDR of 50 dB with sensitivity 0 is not recommended for young children due to significantly poorer thresholds. However, a program with these settings may be appropriate to evaluate at a later time, since notable improvements might be observed for some individuals (e.g., P9 and P10 in noise with a 50/0 program). Participant 6 scored best in noise with an IDR of 50 but a sensitivity of 10. After completion of the study, P6 requested that the sensitivity be increased to 10 in her everyday program due to enhanced clarity. Program optimization and verification is an ongoing process. As children are able to provide additional information about the quality of sound and participate in speech recognition measures, adjustments may be needed to optimize IDR and sensitivity settings over time.

The following programming guidelines are suggested for choosing parameters in children with the Advanced Bionics device. Initially, particularly for infants and those unable to provide qualitative feedback, set T-levels at 10% of Ms. As soon as "first hearing" levels

can be determined with conditioned responses, use those levels to increase Ts. Obtain soundfield thresholds to verify detection of soft sounds. As soon as “soft” levels can be determined with loudness judgments, use those to set T-levels approximately 10 CUs below soft. Again, obtain soundfield thresholds to verify detection of soft sounds. Since two children in the current study reported an audible noise when T-levels were set below soft, use caution when raising T-levels above “first hearing” and always elicit feedback from the child to ensure there are no additional low-level sounds or unwanted noise perceived. If so, adjust accordingly.

Consider an IDR of 65 or 70 dB combined with 0 sensitivity in the child’s primary program. As children become older and can provide more descriptive information about what they hear, evaluate programs with different IDR and sensitivity settings. Validate settings with speech recognition testing in quiet at soft and average conversational levels and in noise. Multiple programming parameters with varied ranges are offered with each device and should be fully explored to individually optimize each recipient’s hearing.

CONCLUSION

Experiment 1 compared two methods for setting T-levels in pediatric recipients of the Advanced Bionics cochlear implant device. Manually setting T-levels with ascending loudness judgments significantly improved soundfield threshold measures for both FM-tones and Ling sounds compared to T-levels set at 10% of M-levels. Experiment 2 compared word recognition in quiet and sentence recognition in noise using programs differing by IDR width and sensitivity. No group mean score differences were observed for IDR or sensitivity settings. Significant score differences for IDR/sensitivity combinations were noted, however for sentence recognition in noise for a majority of participants. No single IDR and/or sensitivity setting resulted in the best speech understanding for all participants. Study findings confirm the need to determine program settings on an individual basis as well as the importance of speech recognition verification measures in both quiet and noise.

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Abbreviations

AGC	automatic gain control
BKB-SIN	Bamford-Kowal-Bench Speech in Noise Test
CI	cochlear implant
CNC	consonant vowel nucleus-consonant
CUNY	City University of New York
CUs	current units
FM	frequency modulated
HINT	Hearing in Noise Test
IDR	input dynamic range

M-levels/Ms	most comfortable levels
SNR	signal-to-noise ratio
T-levels/Ts	threshold levels

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Figure 1.

Group mean FM-tone soundfield thresholds in dB HL from 250–6000 Hz for two T-level settings (Ts below soft and Ts at 10% of Ms). Error bars represent ± 1 SE of the mean.

Asterisks denote significant threshold differences when Ts were set at 10 below soft compared to Ts at 10% of Ms for a given frequency (* $p < 0.05$ and ** $p < 0.01$).

Figure 2. Group mean CU levels across electrodes for T- and M-levels from participant's everyday programs (Original Ts and Ms) and the two T-level settings examined (Ts below soft and Ts at 10% of Ms). Error bars represent ± 1 SE of the mean.

Figure 3.

Individual and group mean scores for CNC monosyllabic words presented at a soft level (50 dB SPL) in quiet for three IDR/sensitivity settings (50/10, 70/10, 70/0). Error bars represent ± 1 SE of the mean. Asterisks denote significant differences between the indicated settings (* $p < 0.05$) for an individual.

Figure 4.

Individual and group mean scores for HINT-C sentences (65 dB SPL) presented in four-talker babble (+8 SNR) for three IDR/sensitivity settings (50/10, 50/0, 70/0). Error bars represent ± 1 SE of the mean. Asterisks denote significant differences between the indicated settings (* $p < 0.05$ and ** $p < 0.01$) for an individual.

Table 1

Demographic information for pediatric participants.

P#	Age at ID of HL	Age at SPHL	AAI	AAT	Length of CI Use	Internal CI	Etiology
1	0.5	0.5	2 (12)	14	12 (2)	CII (90K)	Unknown
2	4.5	4.5	16	17	1	90K	Unknown
3	1.25	1.25	7	8	1	90K	Unknown
4	3	11	12	12	0.5	90K	Familial
5	0.25	0.25	3	11	8	90K	Unknown
6	.75	.75	5 (13)	15	10 (2)	1.2 (90K)	Unknown - Possible Ototoxicity
7	1.25	9	9	10	0.5	90K	Familial
8	2.5	2.5	8	11	3	90K	Familial
9	2	3	3 (7)	9	6 (2)	CII (90K)	Unknown - Suspected Cytomegalovirus
10	2.5	7	8	11	3	90K	Unknown
11	1	3	5	7	2	90K	Enlarged Vestibular Aqueduct

Note: P# = participant number; Age at ID of HL = Age at identification of hearing loss in years; Age at SPHL = Age at onset of severe-to-profound hearing loss in years; AAI = Age at implantation in years; AAT = Age at test in years; Length of CI Use = Length of cochlear implant device use in years; Internal CI = Internal cochlear implant device. Participants 1 and 9 were tested in the first implanted ear. Participant 6 was tested in the second implanted ear. For the three bilateral participants, values in parentheses reflect the second implanted ear. Internal devices include Clarion 1.2, CII Bionic Ear and HiRes 90K.