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Relationships between Electrically Evoked Potentials and Loudness Growth in Bilateral Cochlear Implant Users

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SHORT SUMMARY

Bilateral cochlear implantation has motivated efforts to ensure that sounds presented at equal levels to each ear are perceived as equally loud. Psychophysical loudness balancing is not always practical, especially with pediatric users. Electrophysiological potentials -- electrically evoked auditory brain stem response (EABR) and electrically evoked compound action potential (ECAP) measures -- may provide a means of approximating loudness balance. It was hypothesized that stimuli evoking equal amplitude neural responses would be more closely matched in loudness than stimuli with equal current levels. No significant differences in loudness discrepancy across ears were found for ECAP, EABR or matched current levels.

Introduction

Bilateral cochlear implantation has become an increasingly popular option for profoundly hearing-impaired children and their families. Balancing the input from the two ears is considered to be an important part of the programming process. There is a need, therefore, for methods that can be used to insure that acoustic stimuli presented to the two ears at equal sound pressure levels are perceived as equally loud. While psychophysical loudness balancing procedures can be used to equate stimulation levels in the two ears of adult bilateral CI recipients, these procedures are time consuming even for adults and difficult or impossible for young bilateral CI users to perform. As a result, some investigators have suggested that electrophysiological measures might be used to match stimulus intensity levels in the two ears for bilateral CI recipients (Smith & Delgutte 2007, Salloum et al. 2010, He et al. 2010). The goals of this study were to compare the relationships between loudness estimates and evoked potential amplitudes for electrical stimuli across the implanted ears of bilateral CI users and determine the suitability of evoked potentials for the purposes of approximating loudness balance.

Loudness is a subjective psychophysical correlate of stimulus intensity. Studies using acoustic stimuli have shown that the relationship between loudness and acoustic intensity can be modeled as a power function (Stevens 1957). The loudness of a pulsatile electrical stimulus applied to an electrode implanted in the cochlea increases as the current applied to that electrode increases (e.g. Shannon 1983, McKay & McDermott 1998, McKay et al. 2003, Nelson et al. 1996, Botros 2010). Variation in pulse amplitude, duration and rate can all impact the perceived loudness of an electrical stimulus. Changes in stimulus amplitude have been shown to result in greater changes in loudness, when compared to changes in duration, for a given change in net charge (Zeng et al. 1998). Loudness growth models have also been proposed for electrical stimuli (Zeng & Shannon 1992). These models suggest an

exponential growth of loudness for high-frequency electrical stimuli and loudness growth that follows a power function for low-frequency electrical stimuli (Zeng & Shannon 1994). It was postulated that the frequency dependence of loudness growth results from a logarithmic transformation of auditory nerve response amplitudes for low frequency stimuli only (< 300 Hz) at the level of the cochlear nucleus prior to a frequency-independent exponential transformation of stimulus intensity coding higher in the auditory system. Studies have shown psychophysical detection thresholds and the rate of loudness growth vary across electrodes and across subjects (Fu 2005, Sanpetrino & Smith 2006) and that binaural processes such as sound localization depend on accurate interaural representation of signal levels (van Hoesel & Tyler 2003). It follows, given possible differences in loudness growth across implanted ears, that optimal fit of bilateral cochlear implants should include measurements of loudness growth from threshold to maximum comfort level in each ear.

Electrophysiological measures of the response of the auditory nerve and brainstem are known to increase in amplitude as the electrical stimulation level is increased (e.g. Brown et al. 1990; Abbas & Brown 1991). Further, higher order nuclei within the central auditory system that receive binaural input and have been shown to be sensitive to changes in sound source azimuth depend on precise neural encoding of stimulus intensity at the periphery (Brugge et al. 1970, Mast 1973, Aitkin et al. 1988, Helfert & Aschoff 1997).

A number of investigators have compared estimates of electrically evoked compound action potential (ECAP) and/or electrically evoked auditory brainstem response (EABR) threshold with behavioral measures of threshold and described the form of these growth functions (Brown et al. 1999; Brown et al. 2000; Morita et al. 2003; Gordon et al. 2004, Potts et al. 2007, Miller et al. 2008). The majority of these reports have focused on results from individuals who have a single CI. Smith and Delgutte (2007) measured EABRs as well as single unit responses from the inferior colliculi of bilaterally implanted cats and found that the amplitude of the binaural interaction component (BIC) of the EABR (derived by subtracting binaural from summed monaural EABRs) was largest when stimuli were presented to electrode pairs that evoked equal-amplitude monaural responses. They assumed that the stimuli which produced equal amplitude wave IVs in the cat model were effectively equivalent in stimulus strength, though they stress that it was not known conclusively whether the method resulted in a loudness-balanced percept. However, studies with acoustic click stimuli in normal hearing subjects have not indicated a uniform relationship between loudness and evoked potential amplitude growth functions (Pratt & Sohmer 1977).

The purpose of this study was 1) to describe the relationship between ECAP and EABR growth functions and loudness growth functions in adult bilateral cochlear implant users, and 2) to determine whether matching the stimulus levels in the two ears of bilateral cochlear implant users based on equal ECAP amplitude, EABR amplitude, or current level resulted in the smallest discrepancy in loudness rating across the two ears.

Materials and Methods

Subjects

Ten postlingually deaf adults participated in this study. All ten study participants had previously received simultaneous, bilateral, Advanced Bionics CIs. Demographic information for each subject is specified in Table 1. Four of the subjects (subject identifiers beginning with “H”) used the Clarion CII internal device. The remaining six subjects used the HiRes 90K internal device (subject identifiers beginning with “Z”). Two subjects (Z36 and Z34) had experienced failure of one of their cochlear implants following their initial bilateral surgery. However, both subjects were successfully re-implanted, with subject Z36 undergoing reimplantation nine months prior to participating in this study and subject Z34

experiencing device failure and undergoing reimplantation five months subsequent to participation. Electrode impedance measures were obtained for all subjects prior to testing. Subject H36 had abnormally high impedance on electrode 13 of the left cochlear implant; therefore, electrode 14 was used for comparison to the functioning electrode 13 in her right cochlear implant. This study was approved by the University of Iowa Institutional Review Board.

Stimuli

The stimulus used for the psychophysical, ECAP, and EABR tasks consisted of a train of biphasic current pulses (fixed polarity, negative leading phase). Each phase of the biphasic current pulse was 32 μ s in duration. Individual pulses were presented at a rate of 23 pps in a monopolar stimulation mode for all three measures. For psychophysical data collection sessions, the pulses were presented in bursts that were 1000 ms in duration. Some studies have shown larger EABR amplitudes, shorter latencies, and lower thresholds to stimulation of electrodes positioned closer to the apical end of the cochlea (Gordon et al. 2007). For this reason, two different stimulating electrodes were tested. One was located closer to the apex of the cochlea (electrode 3), and the other was chosen because it was located closer to the base of the cochlea (electrode 13). The stimuli were presented monaurally using the manufacturer's Bionic Ear Data Collection System (BEDCS) and a Platinum Sound Processor.

General Procedures

Typically, ECAP measures were obtained first followed by psychophysical loudness estimation procedures; EABR growth functions were collected last. Study participants were tested while seated in a reclining chair and were encouraged to relax and sleep, if possible, during both the ECAP and EABR recording sessions. Testing was typically completed in a single visit, conducted in two blocks of approximately three hours separated by an hour break. The test time required to obtain ECAP growth functions for both electrodes and for both ears was approximately 40 minutes. The test time required to complete the psychophysical loudness estimation procedures was approximately 90 minutes. Recording EABR growth functions from both electrodes and both ears required approximately 3–4 hours. The order of electrodes (3 or 13) and ears (R or L) tested was counterbalanced across tasks and between subjects in order to guard against effects of fatigue, changes in physiologic noise levels and/or adaptation. Given the lesser dependence of ECAP measures on patient state and the need to reduce test time, stimulus level was adjusted in linear, ascending steps when measuring ECAP growth functions. Stimulus current level was randomized for the psychophysical test procedures and EABR measures. Details of the procedures used are provided below.

Electrophysiologic Recording Procedures

ECAPs were recorded through the implant telemetry system using the BEDCS software. Stimulus artifact was minimized in the recordings by using a two pulse forward masking procedure. This protocol has been described in detail elsewhere (e.g. Miller et al. 2000; Brown et al. 1990). In this study, the stimuli used to record the ECAP were presented in pairs with an interpulse interval of 448 μ s and with the level of the first pulse in the sequence (the masker) always presented 64 μ A more intense than the second pulse (the probe). A gain of 300 was used. When electrode 3 was stimulated, electrode 1 was used to record the ECAP; electrode 11 was used as the recording electrode when electrode 13 was stimulated.

Each ECAP consisted of an average of at least 50 sweeps. Three ECAP recordings were obtained for each stimulation level. ECAP amplitude was measured off line using an

automated peak picking algorithm in MATLAB, with manual revisions by a trained examiner as needed using a visual detection method, referencing the initial trough (N1) and the apex (P1) of the following positive peak. Amplitudes were determined a second time for a subset of recordings by a second examiner blind to the results of the first analysis. ECAP growth functions were measured in a linear series with stimulus current levels starting at threshold (T) and ending at the upper limit of comfort (C) and incremented in steps equal to 10% of the dynamic range.

EABRs were obtained using recording electrodes positioned on the vertex (Cz (+), the nape of the neck (-), and the forehead Fz (ground)). The ongoing EEG activity was amplified (gain 50,000) and band pass filtered between 1 and 5000 Hz using an optically isolated, differential amplifier (IHS Opti-Amp 8008) prior to being digitized (National Instruments ADAQ Card 6062E) and averaged using custom-designed, LabView software. Artifact rejection began at 0.3 ms and continued to the end of the 8 ms recording window. Absolute amplitude of rejection varied for each subject, but the default value was $\pm 60 \mu\text{V}$, and typically this was increased to $\pm 100 \mu\text{V}$ when rejects were high ($> 10\%$). The trigger pulse occurred at the onset of the negative leading phase allowing visualization of the positive phase of the stimulus. For each stimulation level, six EABRs were recorded, each consisting of an average of 500 sweeps. EABR amplitude was measured using an automated peak picking algorithm in MATLAB, with manual revisions by a trained examiner as needed using a visual detection method, referencing the peak of wave V and the following trough (V'), with the mean amplitude value calculated from a total of 3000 sweeps. Peak amplitudes were re-picked using the above method by a second trained examiner, blind to the results of the first analysis, for 20% of recordings. EABRs were recorded at stimulus current levels equal to approximately 30, 50, 70 and 90% of the subject's dynamic range. In cases where a robust response was measured at 30% dynamic range, a further recording was made at 10%. Stimulus presentation levels were randomized. In some instances when the stimulus was presented at 90% of the dynamic range the listener indicated it was uncomfortable and/or an electrically evoked myogenic response was recorded. Myogenic responses presented as large amplitude potentials occurring late in the recording window with amplitudes greater than that expected in auditory responses (Cushing, Papsin, and Gordon, 2006). In those cases the maximum stimulus level used was 80% or 70% of the subject's dynamic range.

Psychophysical Loudness Estimation Procedures

The first step in obtaining loudness growth functions was to determine approximate T and C current levels for each electrode. In order to do this, an ascending method was used. The patient was instructed to indicate when the stimulus first became audible and when the stimulus reached their upper limit of comfort. Initially, current level was increased in steps of $64 \mu\text{A}$, with the stimulus presented for a total of 1 second at each level. The step size was then decreased to $16 \mu\text{A}$ and the process was repeated five times. Final estimates of T and C level were determined by averaging the results obtained from each of the 5 ascending runs. In cases where C level was not reached prior to stimulus current levels exceeding voltage compliance limits, the current level equal to the compliance limit served as the 100% dynamic range level for test purposes.

Once the dynamic range of stimulation had been approximated, loudness growth was measured more formally using a method of constant stimuli approach. Stimuli were presented at levels equal to 20, 30, 40, 50, 60, 70, 80, and 90% of the subject's estimated dynamic range. The subject was asked to assign a loudness rank to each stimulus using a scale of 1–100, with 1 equal to “just barely audible” and 100 to “too loud”. Stimulus presentation level was randomized and the procedure was repeated until five trials had been

completed for each stimulation level. Measurements were completed for each condition in blocks counterbalanced for ear and test electrode across subjects.

Results

Figure 1 shows how ECAP (top), EABR (middle) and loudness (bottom) change as stimulation level is increased for all ten subjects. The left column shows data obtained for electrode 3 and the right column shows results obtained for electrode 13. Filled symbols show results obtained in response to stimulation of the right ear and open symbols show results obtained with stimulation of the left ear. ECAP measures were completed for all four electrodes in eight subjects; in the other two cases testing was not completed due to time constraints (subject Z34) or because the responses were contaminated by artifact (stimulus-linked non-physiological noise and/or amplifier saturation evident within the recording window) and excluded prior to analysis (subject Z108). EABR measures were completed for both ears and both electrodes in 7 subjects; in the other three cases testing was not completed due to time constraints (subjects H18b and Z34), or because replicable responses could not be obtained for one or more electrodes (subject Z109). Loudness estimation procedures for electrode 13 were not completed for subject Z34 due to time constraints. Each growth function was fitted using linear regression techniques and the slope and intercept of the regression line for each subject and stimulating condition were computed.

Table 2 shows the average slope and standard error across all ten subjects for ECAP, EABR, and loudness growth functions. Repeated measures ANOVAs of the slope of regression lines for ECAP, EABR, and loudness growth measures for individual subjects were completed. No significant main effect of ear (left ear slope vs. right ear slope) was noted for ECAP ($F[1,7] = 0.1324$, $p=0.73$), EABR ($F[1,7] = 0.1890$, $p=0.68$) or loudness estimation ($F[1,8] = 0.8311$, $p=0.39$). Similarly, no significant differences in slope between electrode 3 and electrode 13 were found for ECAP ($F[1,7] = 0.3345$, $p=0.58$), EABR ($F[1,7] = 5.4129$, $p=0.053$) or loudness measures ($F[1,8] = 0.0759$, $p=0.79$). Goodness-of-fit for each linear regression is reflected in the R^2 values for each individual subject's ECAP, EABR, and loudness growth functions. For ECAP measures mean R^2 was 0.948 and range was 0.788 – 0.999, EABR mean R^2 was 0.733 with a range of 0.015 – 0.992, and mean R^2 for the loudness growth functions was 0.934 with a range of 0.811 – 0.989. For EABRs, R^2 was generally smaller for electrode 13. In the select cases where only two data points were obtained for an individual subject's growth function, linear regression was not computed. Table 3 lists mean R^2 and standard error for each ear and electrode combination for ECAP, EABR, and loudness growth functions.

The purpose of this study was to determine if electrophysiological measures could be used to approximate equal loudness levels in the two ears of a bilateral CI user. Figures 2 through 5 show data obtained from two subjects: Z17 and H16. Data from these two individual subjects are shown because they illustrate how this comparison between electrophysiologic and psychophysical measures was made and the range of variation observed in the individual data.

Figure 2 shows ECAP waveforms obtained for two subjects: Z17 and H16. Panels A and B of Figure 2 show ECAP recordings obtained from subject Z17. For this subject, large differences in ECAP amplitudes obtained in the left and right ears across the dynamic range are apparent for electrode 13. Nearly symmetrical response amplitudes are noted for the more apical electrode (E3). Panels C and D show data from subject H16. For this subject, ECAP responses obtained from stimulation of the right ear are smaller than responses recorded with stimulation of the same electrode in the left ear. This difference is especially apparent for the more apical electrode (E3)

Panels A and B in Figure 3 show EABR waveforms obtained from both electrodes and both ears of subject Z17. Panels C and D in Figure 3 show similar measures obtained for subject H16. For subject Z17, EABR amplitude increases as stimulation level (expressed as % of the perceptual dynamic range) is increased. This subject (Z17) had EABR responses that were similar in both amplitude and general morphology for both ears and for both electrodes (see Fig. 3A and 3B). Comparison of EABRs recorded at lower levels for subject H16 showed differences in wave V amplitude across ears for electrode 3 (see Fig. 3C). Smaller differences across ears were observed in wave V amplitude when stimulation was applied to electrode 13 (see Fig. 3D). For subject H16, the EABR recorded at a stimulation level equal to 90% of the subject's dynamic range on the apical electrode of the left ear is contaminated by myogenic activity (see Fig. 3C). It is notable that at 30% and 50% dynamic range no ECAP is present for subject H16's right electrode 3 (Fig. 2C), although EABRs were measurable for this subject at these stimulation levels (Fig. 3C). Likewise, for subject Z17, no ECAP was recorded at the 30% and 50% levels for the left electrode 13 (Fig. 2B) though EABRs were measurable at those levels (Fig. 3B).

The waveforms shown in Figures 2 and 3 are a subset of the total recordings from each subject and show results obtained as a function of percent of perceptual dynamic range. In Figure 4, ECAP amplitudes, EABR wave V amplitudes, and loudness rankings are plotted for the same two subjects (Z17 and H16) as function of stimulus current level. Filled symbols indicate recordings obtained with stimulation of the right ear. Open symbols show results obtained with stimulation of the left ear. Circles indicate results obtained when stimulation was applied to electrode 3 (the more apical electrode in the intracochlear array) and triangles show results obtained with stimulation of electrode 13 (the more basal electrode). For subject Z17 (Fig. 4C), a consistent difference in loudness is apparent across the range of stimulus levels, with stimuli in both the apical and basal electrodes of the right ear rated louder than those presented to both electrodes in left ear. For subject H16 (Fig. 4F) it is evident that stimulation of the basal electrode was consistently perceived to be louder than stimulation of the more apical electrode at the same current level. These trends are evident but less robust when the ECAP growth functions for subjects Z17 and H16 shown in panels A and D of Figure 4 are compared, i.e. ECAP amplitudes for both electrodes are larger in the right ear than the left for subject Z17 and ECAP amplitudes for the basal electrode (13) are greater than the apical electrode (3) in each ear for subject H16. Panels B and E of Figure 4 show EABR growth functions for both subjects. For subject Z17 (Fig. 4B) the rate of growth of wave V is similar across electrodes and differences across ears in the EABR are less apparent. For subject H16 (Fig. 4E) nonlinear growth of wave V amplitude is evident for the left basal electrode. Electrode differences shown in the ECAP and loudness data are less evident in the EABR growth functions for subject H16. It should also be noted that stimulation levels that yield an EABR on R3 for subject H16 result in an ECAP that is in the noise floor. Stimulation levels that yield an EABR on L13 for Z17 also result in an ECAP that is in the noise floor.

One of the primary goals of this study was to determine if stimulation levels that resulted in equal amplitude electrophysiologic measures were perceived by the subject as being equally loud. To address that question directly, scatter plots for each subject were created that showed the relationship between amplitude of the ECAP or EABR and loudness for a given stimulus current level. Examples of such scatter plots for subjects Z17 and H16 are shown in Figure 5. Again, filled symbols represent data obtained from stimulation of the right ear and open symbols show results obtained with stimulation of the left ear. Triangles show results obtained with stimulation of electrode 13 and circles represent results obtained with stimulation of electrode 3. Data for each electrode and each ear were fit using a linear model and the regression lines that resulted from this analysis are shown in Figure 5. If it is the case that stimuli that elicited similar amplitude evoked potentials were perceived by the

subjects as being equally loud, one would expect to see minimal spread in the data and regression lines that overlapped. As is apparent from examination of Figure 5, this was not always the case.

Figure 5A and 5B show results obtained from subject Z17. For this subject, ECAP versus loudness functions are similar across ears and electrodes. There is a separation (vertical distance) of approximately ten arbitrary loudness units between the regression lines for the apical electrode. Somewhat greater difference in perceived loudness for the same electrode is noted in Figure 5B, where EABR amplitudes are used. Figure 5C and 5D show data obtained from subject H16. This subject had loudness growth functions in his/her two ears with similar slopes (see Figure 5C), although perceived loudness differences for equal amplitude ECAP appear to be greater than those observed in Figure 5A with subject Z17. Figure 5D shows negative slope for the regression equation for the left basal electrode, reflecting a lack of a strong relationship in perceived loudness compared to EABR growth for that electrode. It should be noted that the EABR response at 90% DR for subject H16's left apical electrode, in which artifact was evident, was excluded from the regression analysis and is not shown in the scatterplot in Figure 5D.

In order to quantify these differences and compare across the rest of the subject pool more easily, the error incurred using equal amplitude as a predictor of loudness balance was calculated. This was done by computing the average RMS error in the residuals of the amplitude growth functions for the right ear electrode when fit to the regression line for the same electrode in the left ear. If there was a strong correlation between loudness of a stimulus introduced to the left and right ears when the ECAP or EABR responses were matched, the resulting error values would be small. The larger the difference between ears in perceived loudness for stimuli that were matched on the basis of evoked potential amplitude, the larger the percent error. This procedure was repeated for loudness ratings as a function of stimulus current level to evaluate the error incurred by attempting to balance stimulus current levels across ears.

Group data showing average loudness prediction error are seen in Figure 6. Examination of this graph reveals that the mean difference in loudness rating (expressed as percentage of the subjects dynamic range) assigned to stimuli in the two ears that yielded approximately equal amplitude evoked potentials was 20.25% (SE = 3.32%) for electrode 3 and 13.60% (SE = 2.11%) for electrode 13 when ECAP measures were used and 49.97% (SE = 14.11%) for electrode 3 and 13.09% (SE = 2.71%) for electrode 13 when EABR measures were used. When matched current levels were used, mean difference in loudness rating was 13.92% (SE = 3.99%) for electrode 3 and 16.12% (SE = 2.19%) for electrode 13. It should be noted that in two instances where there were large differences in slope and intercept between ears for loudness and EABR amplitude relationships, loudness prediction errors exceeded 100% of the subject's dynamic range. A two factor repeated measures analysis of variance (ANOVA) revealed no significant main effects of method of matching stimulus intensity ($F[2,10]=0.89$, $p=0.44$) or stimulus electrode ($F[1,5]=1.52$, $p=0.27$) or significant interactions between factors ($F(2,10)=3.15$, $p=0.087$) with $\alpha=0.05$.

Discussion

In this study we report measures of ECAP, EABR and loudness growth for a set of bilateral CI users. For most subjects, both electrophysiologic measures and perceived loudness measures grew monotonically as stimulation level was increased and were well fit by a linear curve (see Fig. 1). No significant ($\alpha = 0.05$) differences across ear or across electrode were found for either the ECAP, EABR or loudness measures. Propst et al. (2006) reported steeper ECAP and EABR growth functions for apical electrodes in patients with non-GJB2

etiology. Gordon et al. (2007) also reported slightly but significantly steeper EABR growth function slope for apical compared to basal stimulating electrodes in patients who used the Nucleus CI device. This trend was evident in our data for EABRs but did not rise to the level of statistical significance. This may have been a consequence of our smaller subject pool (N=10) compared to that of Gordon et al. (2007) (N=50); however, similar trends toward steeper growth functions for apical electrodes were also not apparent in either the ECAP or loudness growth data (see Table 2). Further, no significant contributions of duration of deafness or device type to loudness discrepancy for equal amplitude neural potentials were found in this study.

As can be observed in panels C and F of Fig. 1, loudness ratings did not always match what might be predicted given our estimate of each subject's dynamic range (e.g. a stimulus presented at 90% of the most comfortable current level rated as having a loudness of 70 on a hundred point scale). It may be the case that our method of determining the upper limit of comfort, using ascending levels, resulted in underestimation of true maximum comfort levels. On an individual basis, comparisons of neural potential amplitude and loudness rating in this study appear to represent a smaller subset of each individual's dynamic range than intended. It perhaps would have been preferable to employ an objective measure, such as electrically-evoked stapedia reflex thresholds (eSRTs) to verify M levels in our participants (Hodges et al. 1997; Bresnahan et al. 2001; Allum, Greisiger, and Probst, 2002), prior to commencement of data collection to ensure reliability.

When electrode 13 was stimulated, the mean difference in perceived loudness across ears for stimuli matched in terms of the amplitude of the evoked neural response was about 13% regardless of whether the EABR or ECAP were used. When electrode 3 was stimulated, the error across ears in terms of perceived loudness was about 20% when the ECAP was used and almost 50% when the EABR was used (See Fig. 6). No significant difference in the accuracy of these predictions was seen between ECAP and EABR measures. The lack of significance in apparent differences in predicted loudness estimation error for each physiological measure suggests no advantage of using the EABR for the purposes of approximating loudness balance. This finding was somewhat surprising given that loudness is a percept and as such might be better predicted by evoked potentials that reflect neural processing at higher levels within the auditory system. It might also be assumed that because EABRs from either ear have overlapping neural generators that they would prove superior for the purpose of approximating loudness balance, whereas ECAPs may be expected to differ in the two ears due to possible differences in number of surviving neurons and effects of intracochlear electrode position on recording. Granted, our method of loudness prediction depended heavily on the quality of the linear regressions of loudness when plotted as a function of ECAP and EABR amplitude for a given stimulus intensity, and in all cases a greater number of data points were available for the more peripheral ECAP measure. ECAPs could also be obtained with a greater signal-to-noise ratio than EABRs due to the larger amplitude of the potential. Brown et al. (1995) used a criterion R^2 of 0.65 for analyses of the slope of EABR growth functions, and a subset of growth functions (such as the left electrode 13 in subject H16, Fig. 4E) fell below this level in the present study. However, the magnitude of loudness estimation error for EABR measures was not strictly determined by the fit of linear regressions. For example, subject H36's mean loudness estimation error derived from electrode 3 EABRs exceeded 100% dynamic range, though R^2 values were higher than the (relatively conservative) criterion of 0.65 for regression analyses in each ear. Perhaps it would have been desirable to record EABRs at 10% dynamic range intervals as was done for ECAPs and to average more sweeps to improve SNR, but doing so would have made test time prohibitive. That no significant difference in loudness prediction error was found is a potentially useful finding given the advantages of ECAP measures in terms of cost and test time. It should be noted, however, the mean loudness error estimates that are

based on ECAP measures would only provide an approximation of loudness balance between the ears of a given subject and may be off, on average, by approximately 13–20%. Further, binaural matches based on ECAPs were not found to be significantly better than matched current levels. Nevertheless, for some of our subjects, there was a good agreement across ears for the relationship between growth of evoked neural potentials and loudness, particularly for ECAP.

Previous work indicated a role for EABR amplitude measures in balancing loudness in bilateral implant users. Salloum et al. (2010) reported that for children sequentially implanted with Nucleus devices perceived increases in interaural level difference, as evinced by a behavioral lateralization task, were correlated (at least at the group level) with greater differences in amplitude of EABR wave V across ears for the same stimuli (11 pps pulse train on electrode 18). However, few of the implanted children indicated a centerline localized percept for stimuli approximately matched in intensity according to evoked potential amplitude. This was attributed to possible deficits in binaural fusion of stimuli in congenitally deaf listeners and differences in device generation and hearing age across ears; smaller stimulus intensity increments (5 CU steps instead of 10 CU) were suggested in future testing to better match levels across ears. However, data from the present study, which was collected from post-lingually deafened adults with matched simultaneously implanted internal devices, indicated that stimuli eliciting approximately equal EABR amplitudes still may not be judged to be matched in loudness for some bilateral listeners. Nonetheless, it is evident from inspection of the amplitude growth data in the present study that differences in evoked potential amplitude across ears would generally be expected to increase with greater separation in stimulus intensity across ears, consistent with the observations of Salloum et al. (2010).

As can be observed in Figure 6, neither stimuli that elicit equal amplitude neural potentials nor current pulses presented at the same current level can be assumed to be perceived as equally loud. However, as it was not directly tested, it also cannot be assumed that stimuli with equivalent loudness ratings across ears from a monaural test would be judged to be loudness-balanced in a traditional binaural psychophysical procedure. This is an important distinction. In future work it may be preferable to attempt to balance the loudness of stimuli across ears prior to evoked potentials recording in order to more directly assess whether equal loudness depends on equal amplitude neural potentials. The present results, however, suggest that this may not be the case. Senn et al. (2005) noted that for bilateral cochlear implant users listening to a 50 Hz pulse train, just-noticeable differences of 1.2 dB were obtained using a two alternative forced choice procedure (2AFC), comparable to a just-noticeable difference of 1 dB in normal hearing controls. Given the restricted dynamic range of electric hearing in cochlear implants users, it would be expected that discrepancies in loudness judgments seen in this work for stimuli resulting in equal amplitude neural potentials may exceed the threshold of detection. Whether the average errors incurred by our method of estimating loudness equivalence between the ears are clinically significant remains of interest. Therefore, it still may be beneficial to attempt to balance the amplitude of neural responses across the ears for the purpose of exploiting binaural processes in the central auditory pathways which depend on equivalent neural inputs from the auditory periphery.

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Figure 1.
Group ECAP (top), EABR (middle), and loudness (bottom) growth functions.

Figure 2.

ECAP waveforms for subjects Z17 (A and B), H16 (C and D), stimulating electrode 3 (A and C), and stimulating electrode 13 (B and D) for a range of stimulation levels. N1 and the following peak are marked with vertical lines for convenience of interpretation. Not all waveforms recorded are depicted here.

Figure 3.

EABR waveforms for subjects Z17 (A and B), H16 (C and D), stimulating electrode 3 (A and C), and stimulating electrode electrode 13 (B and D) for a range stimulation levels. Wave V is marked for replications in which a response is present and V' is marked at the 90% dynamic range stimulation level for convenience of interpretation. 90% dynamic range waveform for H16 left ear, stimulating electrode 3 is dashed and wave V is not marked due to likely contamination by myogenic artifact.

Figure 4. Mean ECAP amplitude (A and D), EABR amplitude (B and E), and loudness rating (C and F) as a function of stimulus current level for subjects Z17 (A–C) and H16 (D–F).

Figure 5.

Mean loudness rating as a function of mean ECAP amplitude (A and C) and mean EABR amplitude (B and D) at a given stimulus current level for subjects Z17 (A and B) and H16 (C and D). Solid regression lines correspond to electrode 3 loudness ratings, dashed regression lines correspond to electrode 13 loudness ratings. Mean loudness estimation error is listed for each electrode in the upper right of each panel.

Figure 6.

Group data for all subjects (total N = 10) depicting root mean squared (RMS) estimates of error in loudness matching for equal amplitude ECAP and EABR measures and matched current levels across ears. Mean error is in bold, fine line is median error; whiskers show 5% and 95% range. Complete data was not available for all subjects.

TABLE 1

Demographic information for participating subjects.

Subject ID	Age (yrs)	Gender	Onset profound loss	Etiology ¹	Device	Duration CI Use	Processing Strategy	Abnormal electrodes
H16	61	M	53	EVA	CII	7;2	Hi-Res P Fidelity AS; Hi-Res S AD	None
H18	74	M	65	NIH	CII	7;1	Hi-Res S Fidelity	None
H36	65	F	53	HER	CII	7	Hi-Res S	13L
H47	57	M	16	Measles	CII	5;11	Hi-Res S	None
Z17	70	M	60	UNK	90K	5;1	Hi-Res S	None
Z34 [*]	35	M	18	MEN	90K	3;11	Hi-Res S Fidelity	None
Z36 ^{**}	65	F	57	NIH/UNK	90K	3;1	Hi-Res S Fidelity	None
Z107	75	F	74	UNK	90K	1	Hi-Res S	None
Z108	59	F	57	Viral encephalitis	90K	1	Hi-Res S	None
Z109	61	M	58	HER/UNK	90K	1	Hi-Res S	None

^{*} Z34 left device failed 5 months subsequent to participation in this study. Reimplantation was successful.

^{**} Z36 right device failed. Reimplantation, 9 months prior to participation, was successful.

¹ EVA=enlarged vestibular aqueduct, NIH = noise-induced hearing loss, HER = hereditary, MEN = meningitis, UNK = unknown

TABLE 2

Mean slope and standard error for ECAP, EABR, and loudness growth functions.

	R E3	L E3	R E13	LE13
ECAP	N= 9	N= 9	N= 9	N= 9
Slope ($\mu\text{V}/\mu\text{A}$)	0.82	0.76	0.93	0.95
SE ($\mu\text{V}/\mu\text{A}$)	0.16	0.12	0.21	0.17
EABR	N=10	N=10	N=8	N=9
Slope ($\mu\text{V}/\mu\text{A}$)	0.0025	0.0024	0.0017	0.0014
SE ($\mu\text{V}/\mu\text{A}$)	0.0006	0.00055	0.00056	0.0003
Loudness	N=10	N=10	N=9	N=9
Slope (units/ μA)	0.11	0.11	0.11	0.10
SE (units/ μA)	0.022	0.014	0.017	0.015

TABLE 3

Mean R^2 and standard error for ECAP, EABR, and loudness growth functions.

	R E3	L E3	R E13	LE13
ECAP	N= 9	N= 9	N= 9	N= 9
R^2	0.9459	0.9594	0.9311	0.9558
SE	0.0194	0.0096	0.0220	0.0088
EABR	N=10	N=10	N=8	N=9
R^2	0.8139	0.7853	0.6751	0.5684
SE	0.0903	0.0921	0.1216	0.1011
Loudness	N=10	N=10	N=9	N=9
R^2	0.9411	0.9315	0.9314	0.9331
SE	0.0168	0.0142	0.0156	0.0148