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Preliminary results of the relationship between the binaural interaction component of the electrically evoked auditory brainstem response and interaural pitch comparisons in bilateral cochlear implant recipients

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Abstract

Objectives—The purpose of this study was to investigate the relationship between electrophysiologic measures of the binaural interaction component (BIC) of the electrically evoked auditory brainstem response (EABR) and psychophysical measures of interaural pitch comparisons in Nucleus bilateral cochlear implant users.

Design—Data were collected for ten postlingually deafened adult cochlear implant users. Each subject conducted an interaural pitch-comparison task using a biphasic pulse train with a pulse rate of 1000 pulses per second (pps) at high stimulation levels. Stimuli were presented in a two-interval, two-alternative forced-choice procedure with roving current variations. A subgroup of four subjects repeated the task at low stimulation levels. BICs were measured using loudness balanced, biphasic current pulses presented at a rate of 19.9 pps for each subject by pairing the electrode 12 (out of 22 intracochlear electrodes) in the right ear with each of 11 electrodes spaced across the electrode array in the left ear. The BIC was measured at high stimulation levels in ten subjects and at low stimulation levels in seven subjects. Because of differences in stimulation rate used in BIC measures and interaural pitch comparisons, the actual stimulation levels were different in these two measures. The relationship between BIC responses and results of interaural pitch comparisons was evaluated for each of the individual subjects as well as at the group level. Evaluation was carried out separately for results obtained at high and low stimulation levels.

Results—There was no significant correlation between results of BIC measures and interaural pitch comparisons on either the individual or group levels. Lower stimulation level did not improve the relationship between these two measures.

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Conclusions—No significant correlations between psychophysical measures of interaural pitch comparisons and electrophysiologic measures of the BIC of the EABR were found. The lack of correlation may be attributed to methods used to quantify the data, small number of subjects retested at low stimulation levels, as well as central processing components involved in the interaural pitch-comparison task.

Keywords

auditory evoked potential; bilateral cochlear implantation; auditory brain stem response; electrical stimulation

INTRODUCTION

Bilateral cochlear implantation has been provided to many individuals with severe to profound hearing loss in an attempt to restore binaural advantages experienced by normal-hearing listeners. The electrode array of a cochlear implant (CI) consists of a group of electrodes placed along the longitudinal axis of the cochlea. Studies have shown that stimulating different electrodes can elicit different pitch percepts that generally correspond to the tonotopic organization of the cochlea (Townshend et al., 1987; Nelson et al., 1995; McDermott and McKay, 1997). Some investigators have used interaural pitch comparisons to aid in interaural electrode pairing (e.g. Long et al., 2003). Results of these studies showed that interaural electrode pairs that were matched in pitch did not always show optimal interaural time difference (ITD) sensitivity.

For devices that do not use current steering technology, the electrical current delivered by each electrode creates an electric field that stimulates the surrounding neural tissue. Instead of being distinct, the electric fields created by different electrodes typically overlap with each other. The overlap in electric fields means that there is also likely to be interactions between neural populations stimulated by different electrodes (spatial spread of neural excitation). Wide spread of neural excitation may reduce the number of effective channels of a multichannel CI due to the lack of across-fiber independence. The number of available pitches related to place of stimulation depends on the number of actually effective channels. Theoretically, a patient with wide spread of excitation may have worse electrode discrimination and pitch ranking ability than a patient who has limited spread of neural excitation.

The relationship between pitch ranking ability and the degree of spatial spread of neural excitation in monaural hearing has been investigated in several studies, with mixed results (Busby et al., 2008; Hughes, 2008; Hughes and Abbas, 2006; Hughes and Stille, 2008, 2009). Some studies have found a significant correlation (Hughes and Stille, 2008, 2009; Hughes, 2008), whereas others have found no correlation (Hughes and Abbas, 2006; Busby et al., 2008). In these studies, the electrophysiologic spread of excitation (SOE) function (an index of spatial spread of neural excitation) was obtained by measuring the electrically evoked compound action potential (ECAP) using a forward masking technique. Busby et al. (2008) investigated the relationship between pitch ranking and the SOE functions in nine Nucleus Freedom CI users for dual and single electrode stimulation. The SOE functions were measured at three positions of the electrode array: apical, middle, and basal. They did not find any significant correlations between the pitch ranking ability and the SOE function for either condition. Hughes and Abbas (2006) studied the relationship between these two measures in ten Nucleus 24 recipients. The slope of the psychometric pitch ranking functions was compared with the width of the SOE functions that were obtained from the same ear. They also found that the pitch ranking ability did not correlate well with the width of the SOE functions. However, Hughes and Stille (2008) found a significant correlation between the width of SOE functions and the psychophysical forward masking pattern. They attributed the discrepancy between these studies to the differences in methodology, stimulation modes, device types, and processing strategies across studies.

The condition in bilateral CI users may be more complicated due to the possibility of different amounts of spread of neural excitation in two ears. Theoretically, interaural electrode pairs with large differences in relative position of the stimulation electrodes in the two ears (i.e. interaural offset) may be judged to be matched in pitch by patients with wide spread of neural excitation, which may partly account for the limited success of interaural pitch comparisons in matching interaural electrode pairs. To date, the relationship between interaural pitch comparisons and the spread of neural excitation has not been investigated for binaural processing.

The Binaural Interaction Component (BIC) of the Auditory Brainstem Response (ABR) reflects electrophysiologic activity of the binaural neurons central to the cochlear nucleus that is the substrate for psychoacoustic function of sound localization and lateralization. The BIC of the ABR reflects neural activity from three levels within the brain stem: the superior olivary complex, the nuclei of lateral lemniscus and the inferior colliculus (Moore, 1991). One way of obtaining the BIC of the ABR is to subtract the binaural ABR response from the sum of the two monaural ABR responses. The theory is that if stimulation of each ear individually results in activation of separate non-overlapping, independent neural networks, the response to binaural stimulation should be equal to the sum of the responses recorded with stimulation of the two ears separately. Any deviation from the sum would be evidence of binaural interaction.

The BIC of the ABR, as elicited in response to an acoustic stimulus, consists of a vertex positive peak with the latency between 5 and 8 ms (McPherson and Starr, 1993; Dobie and Berlin, 1979; Wrege and Starr, 1981; McPherson et al., 1989). The amplitude of the BIC is small, estimated at approximately 0.5 – 0.8μV (McPherson and Starr, 1993; Dobie and Berlin, 1979; Wrege and Starr, 1981; McPherson et al., 1989; Riedel and Kollmeier, 2002a). However, larger BIC amplitudes are obtained for chirp stimuli than for click stimuli presumably due to the fact that the chirp stimulus results in increased neural synchronization (Riedel and Kollmeier, 2002b).

Several investigators have examined the relationship between perceptual features of binaural signals and the BIC of the ABR (Wrege and Starr, 1981; Furst et al., 1985, 1990; Jones and Van der Poel, 1990; McPherson and Starr, 1995; Ungan et al., 1997; Riedel and Kollmeier, 2002a, 2006). These studies have shown that when interaural level and/or time differences are increased, the amplitude of the BIC decreases and its latency increases. At the same time, the image of the perceived sound remains unitary and moves toward the ear with the louder and/or leading signal (Furst et al., 1985, 1990; Jones and Van der Poel, 1990; McPherson and Starr, 1995; Wrege and Starr, 1981; Riedel and Kollmeier, 2002a). The BIC is absent for ILDs greater than about 16 dB and for ITDs longer than 1.6 ms (McPherson and Starr, 1995). If binaural stimulation results in the perception of a single fused image that is not localized intracranially or is completely lateralized, the BIC is not recorded (McPherson and Starr, 1995). Up to date, effects of interaural frequency disparity of acoustic stimuli on the BIC of the ABR have not been systematically investigated.

The BIC of the electrically evoked ABR (EABR) has been recorded from bilateral CI users (Pelizzone et al., 1990; Firszt et al., 2005; Gordon et al., 2007). Pelizzone et al. (1990) and Firszt et al. (2005) recorded the BIC of the EABR from one interaural electrode pair in a group of post-lingually deafened, adult bilateral CI users at a stimulation level that resulted in equal loudness perception in the two ears. Results of these studies showed that the BIC consisted of a small negative peak followed by a positive peak with shorter latencies (approximately 3.8 ms) and larger amplitudes (approximately 1.1 μv) than those typically recorded from normal hearing listeners with acoustic stimuli. More recently, Gordon et al. (2007) recorded BICs from 40 children who used bilateral CIs. They found that the BICs recorded from children who received their CIs after a long period of unilateral CI use typically had longer latencies compared with similar responses recorded from children who had shorter periods of unilateral CI use. Results of these studies suggest that electrically evoked BICs can be recorded from both adult and pediatric bilateral CI users.

It is possible to use the BIC of the EABR to estimate the amount of overlap in neural responses that are elicited by stimuli delivered from interaural electrode pairs. The overlap is affected by spatial spread of neural excitation for bilateral stimulation with greater amount of overlap suggesting more spread of neural excitation. In order to do this, the BICs of the EABR are recorded for several interaural electrode pairs. Amplitude of the BIC is plotted as a function of the interaural electrode pair. In theory, BIC amplitudes should increase as the number of neurons activated by the bilateral input increases. Therefore, electrode pairs with similar intracochlear positions should yield greater BIC responses than electrode pairs with large interaural offsets due to the tonotopic organization of the auditory system. It is possible, however, that wide spread of neural excitation may result in the activation of the same group of auditory neurons despite the fact that the stimulus is delivered to one of several adjacent electrodes. Thus, wide spread of neural excitation will reduce the effect of electrode offset on the BIC responses. Consequently, the amount of spread of excitation could be derived from the width of the BIC versus electrode function, with the narrower function indicating less amount of spread.

The effect of interaural electrode pairing on the BIC of the EABR has been investigated in two studies. Smith and Delgutte (2007) studied effects of interaural electrode alignments on BICs of the EABR in cats. They showed that the amplitude of the BIC was maximal for interaural electrode pairs with the same relative cochleotopic position and decreased as the interaural offset increased. They demonstrated that the size of the BIC was reduced by approximately 50% as the interaural offset between the two stimulating electrodes exceeded approximately 1.5 mm. They also found that the neural activity recorded from the inferior colliculus in response to left and right monaural stimulation showed the largest overlap for interaural electrode pairs with the maximum BIC amplitude. He et al. (2010) investigated the effect of interaural electrode pairing on the BIC of the EABR in adult bilateral CI users. For each subject, electrode 12 in the right ear was fixed and was paired sequentially with 11 electrodes in the left ear. The BIC of the EABR was obtained for these 11 interaural electrode pairs. The effect of electrode alignment was studied at high stimulation levels in ten subjects and at relatively low stimulation levels in seven subjects. The high stimulation level was defined as the 90% point on the subject’s dynamic range or the highest stimulation level that did not result in myogenic artifacts. The dynamic range (DR) was defined as the difference in clinical units (CUs) between the lowest stimulation level that subjects could detect and the highest stimulation level that was judged by subjects to be “loud but comfortable”. For six subjects, the low stimulation level was defined as a level that was 10% higher than the BIC threshold on the subject’s dynamic range. For the seventh subject, the low stimulation level was defined as the 70% point of the dynamic range. At high stimulation levels, the data showed that BIC amplitude was not strongly affected by the relative position of the interaural stimulating electrodes. The BIC versus electrode functions for high stimulation levels were broad and did not exhibit a clear peak. At low stimulation levels, the BIC of the EABR decreased in amplitude as the interaural offset increased. Compared with the relative flat BIC amplitude versus electrode functions obtained at high stimulation levels, functions obtained at low stimulation levels were much narrower and generally described an inverted “V” shape for most of subjects. In addition, the data showed large individual variability in the amount of spread of neural excitations as indicated by the width of the BIC versus electrode functions.

This study describes results of an interaural pitch-comparison task that was obtained from the same group of listeners as reported in He et al. (2010). Although effects of stimulation level and electrode pairing on the BIC of the EABR were thoroughly described in He et al. (2010), results of interaural pitch-comparison task and its relationship with electrophysiologic measures of the BIC of the EABR have not been reported. The primary goal of this study was to determine whether there was a relationship between the electrophysiologically measured BIC of the EABR and the psychophysically measured interaural pitch comparisons. It was hypothesized that the bilateral CI users who had wide spread of neural excitations as indicated by broad BIC versus electrode functions would have difficulty in the interaural pitch-comparison task. In addition, stimulation level is known to affect both the amount of spatial spread of neural excitation (Chatterjee and Shannon, 1998; Cohen, 2003; Abbas et al., 2004; Chatterjee et al., 2006; Hughes and Stille, 2008; He et al., 2010), and pitch perception (Arnoldner et al., 2006, 2008) in CI users. The relationship between these two measures was investigated at both high and low stimulation levels. It was hypothesized that decreasing the stimulation level would improve the association between these two measures.

METHODS

Subjects

Ten adult bilateral Nucleus CI users participated this study. Two subjects were implanted bilaterally with Nucleus 24M device, four with the Nucleus 24 R Contour device, and four with the Nucleus 24RE device. The subjects ranged in age from 28 to 84 years, and their duration of severe to profound deafness ranged from 7 months to 28 years. Nine out of ten subjects received simultaneous bilateral cochlear implantation. One subject (E10) received the second implant in her left ear after two years of listening experience with her first CI in the right ear. She was implanted with the Nucleus 24RE device in both ears. At the time of testing, all subjects had at least six months of experience with their bilateral CIs. Detailed demographic data for all subjects are listed in Table 1. Informed consent was obtained in accordance with the University of Iowa Human Subjects Committee requirements.

Interaural Electrode Pairs and External Equipment

The electrode array of the Nucleus CI consists of 22 intracochlear electrodes that are numbered from 1 to 22 in a basal to apical direction. The letters “L” or “R” are used to indicate whether a specific electrode is in the left or right cochlea in this study. For example, R12 refers to the electrode 12 of the right CI. The electrode R12 was paired with 11 electrodes in the left side (L6, L8, L9, L10, L11, L12, L13, L14, L15, L16, and L18). Thus, eleven different interaural electrode pairs were tested. All electrodes were stimulated in a monopolar stimulation mode relative to the extracochlear ground electrode (MP1).

Electrical stimuli were generated and sent to each interaural electrode pair tested via direct computer control. Nucleus Implant Communication (NIC) routines (Cochlear Corp.) were used to bypass the speech processor interfaces. Two specially modified Nucleus L34 speech processors (Irwin and He, 2007) were used to synchronize the output of the two CIs and to ensure simultaneous stimulation to binaural electrode pairs.

Procedures

Electrophysiologic Measures of the BIC of the EABR—Details of the electrophysiologic measures are given in He et al. (2010) and are only briefly summarized here.

Stimuli and procedure: The stimulus was a gated train of biphasic, charge-balanced current pulses presented at a rate of 19.9 pulses per second (pps). Each pulse phase was 25 μs in duration and an 8-μs interphase gap separated the two phases. A trigger pulse, used to initiate averaging, was also generated just prior to the output of the individual pulses in the pulse train. The output of the two CIs was coordinated such that a stimulus pulse train could be presented to either ear alone or to both ears simultaneously.

For all ten subjects, a high level of stimulation was selected where the level of R12 was fixed at the 90% point of the individual's dynamic range measured for stimuli used for EABR measures (DR-P) or the highest stimulus level that elicited an EABR free of contamination of myogenic activities and/or vestibular nerve responses (van den Honert and Stypulkowski, 1986; Cushing et al., 2006). Levels of the 11 electrodes in the left ear were loudness-balanced to the level of R12. For seven subjects, a low level of stimulation was also selected. For six of these seven subjects, the low stimulation level of R12 was chosen as a level that was 10% higher on the subject's DR-P than the BIC threshold. For one subject (E55) the amplitude growth function of the BIC of the EABR was not recorded due to time constraints and the low stimulation level was chosen as 70% of her DR-P. Loudness balance procedures were repeated at these low stimulation levels.

Subjects were tested while seated in a reclining chair. During the electrophysiologic recording sessions, they were encouraged to sleep or to relax as much as possible. The positive electrode was placed on vertex (Cz), the ground electrode was placed on the forehead (Fpz), and the reference electrode was placed on a noncephalic site overlying the seventh cervical vertebra (C7). The EABR was measured in the left monaural, right monaural and synchronized bilateral stimulation modes for each of 11 interaural electrode pairs. At least three averaged EABR traces (based on 1000 sweeps) were recorded for each stimulation condition. The sequence of these recordings was pseudo-randomized on a trial-by-trial basis across electrodes and stimulation conditions in order to guard against the order effect.

Data Analysis: The BIC was computed by subtracting the bilaterally evoked EABR response from the sum of the two monaural EABR responses (Levine, 1981; Wrege and Starr, 1981; Jones and Van der Poel, 1990; Furst et al., 1985; Pelizzone, et al., 1990; Firszt et al., 2005). Figure 1 illustrates how the BIC was derived. A minimum of two replications of BIC responses were obtained for each interaural electrode pair. The average of these replications was used for amplitude measurements. The BIC response is biphasic with a small negative peak occurring approximately 3.3 ms after stimulus onset followed by a positive peak near 4 ms. Response amplitudes were measured in μV in two different ways. Peak-to-peak amplitude was measured as the difference in amplitudes between the positive peak and the preceding trough. An alternative measure of root mean square (RMS) amplitude was also computed. The RMS amplitude was defined as the square root of the arithmetic mean of the square of difference between the individual voltage measures recorded during the time window between 3 and 5.5 ms after stimulus onset and the average voltage computed over the same time window. The BIC threshold was defined as the lowest stimulation level that resulted in a visually detectable BIC response with an amplitude that was at least 50% larger than that of the noise floor. The electrode pair with the largest BIC amplitude (peak-to-peak or RMS) was defined as the best-matched electrode pair.

Psychophysical Measures of Interaural Pitch-Comparisons

Stimuli and procedure: The stimuli were generated using a custom computer program that utilized NIC subroutines (Cochlear Corp.). The stimulus was a 1000 pps fixed-amplitude, biphasic pulse train with a duration of 1000 ms. Each pulse in the pulse train had a duration of 25 μs/phase and an inter-phase gap of 8 μs. Behavioral dynamic range of this pulse train was measured for each selected electrode for all subjects using an ascending method of adjustment procedure and was referred as DR-PT in this study. All stimuli were presented in monopolar (MP1) mode. In order to reduce effects of stimulation level on results of interaural pitch comparison, stimuli were randomly presented at 80%, 90% and 100% of the DR-PT for each electrode for all ten subjects. For a subgroup of four subjects, the interaural pitch-comparison task was repeated at a lower stimulation level. Here, the stimuli were presented at three levels within the DR PT: the same percentage as the BIC threshold, and ±10% of DR-PT relative to BIC threshold.

In the interaural pitch-comparison task, the stimulus was presented to each electrode of the bilateral electrode pair in sequence. The right ear was always stimulated first and a two-interval, two-alternative forced-choice (2I, 2AFC) procedure was used to determine which of the stimuli presented to the two electrodes was perceived as being higher in pitch. Subjects were instructed to concentrate on pitch and ignore differences in loudness.

Before each presentation, a dialog box with the word “ready” showed up on the screen for 200 ms. Two stimulus bursts, each with a duration of 1000 ms, were then presented in sequence one to each ear. The time interval between stimuli was 500 ms. After each trial, the subject was prompted to identify which of the two stimuli was higher in pitch. Subjects were instructed to guess if they could not tell the difference in pitch between the two stimuli. Response time was subject driven and no feedback was given. The subject was able to listen to the stimulus pair again prior to responding if they so desired.

For each electrode pair, there were 10 trials at each of three stimulation levels. The order of trials was randomized across electrodes and stimulation levels. The interaural pitch-comparison results were calculated as the percentage of trials in which the stimuli presented to the electrode in the left ear was judged to be higher in pitch than the stimuli presented to the right-ear electrode.

Before data collection, three practice runs were completed in order to familiarize the listener with the task and response requirements. In one practice run, the stimuli were presented to an interaural electrode pair that was widely spaced and therefore easy to discriminate (e.g., electrode pair L6-R12). The other two runs included stimuli presented to electrode pairs that were more difficult to discriminate in terms of perceived pitch.

The pitch comparison test took about one hour to complete. Subjects were offered frequent breaks. Testing was spread out over two sessions for subjects who were tested at two different overall stimulation levels.

Data Analysis: Results of the interaural pitch-comparison task were plotted as a function of left ear electrode for each subject. A least squares procedures was used to fit the data for each subject with a logistic function of the form

$$P(x)=a/(1+e^{-b(x-x0)}) \tag{1}$$

Where *P* is the percentage of trials the stimulus presented to the left ear was judged to be higher in pitch than the stimulus presented to the electrode R12 (0–1), *a* is the upper limit of the performance, x_0 is the midpoint of the function, and b is the slope, with larger value represents steep functions.

The point on the psychometric function that corresponds to chance performance (the stimulus presented to the left ear was judged to be higher in pitch than the stimulus in the right ear 50% of the time) was determined. The electrode pair closest to this 50% point was defined as the “pitch-matched” electrode pair. The rate of change in pitch between adjacent electrodes was obtained by taking the first derivative of the psychometric function. These measures became more negative when the electrode pairs were more closely matched in pitch perception and approached to zero when the two electrodes being compared were perceived as being clearly different in pitch. Therefore, it is an inversion of perception of pitch change. This measure is referred to as the inverse perceptual pitch change (IPPC) in the present study. For each subject, the correlation between the BIC amplitudes and the IPPC results was evaluated using Pearson Product Moment Correlation tests. It was expected that the amount of neural excitation as measured by the BIC amplitude should correlate with the change in pitch perception as indicated by the IPPC results.

Data Modeling—Both the BIC amplitudes and the IPPC results were plotted as functions of left ear electrode for each subject. In order to smooth data and remove measurement noise, a least squares procedures was used to fit these data for each subject with a Gaussian function of the form

$$\mathrm{F(x)=A^{*}exp(-0.5^{*}-((x-x_{0})/B)\hat{}2)} \tag{2}$$

where F is the amplitude of the BIC response or the IPPC value, A determines the height of the function’s peak, x_0 is the position of the peak, and B determines the width of the function, with smaller values represent narrower functions. The widths of the fitted Gaussian functions of these two measures were compared using the Paired Sample T test for high stimulation levels and using the Wilcoxon Signed-Rank test for low stimulation levels. Pearson Product Moment Correlation tests were used to assess the relationship between the BIC amplitudes and the IPPC results at the group level for high stimulation levels by comparing the width of the fitted Gaussian functions of these two measures.

Figure 2 shows exemplary data obtained from subject E10b. Panel (a) shows the results of the interaural pitch-comparison task and the fitted psychometric function for this subject. The electrode pair R12-L11 was defined as the pitch-matched electrode pair based on psychometric function fit. Panel (b) shows the results of the IPPC measures (solid symbols) and the peak-to-peak amplitudes of the BIC responses (open symbols) plotted as functions of the left ear electrode for this subject. The dashed and solid line represents the Gaussian function fits for BIC amplitudes and results of the IPPC measures, respectively. The resulting correlation coefficient (*r* value) and the *p* value of the Pearson Product Moment Correlation test are shown in the graph.

RESULTS

Interaural Pitch Comparison

Figure 3 shows the results of the interaural pitch-comparison obtained from ten subjects at high stimulation levels. The abscissa shows the electrode in the left ear that was paired with electrode 12 in the right ear. The ordinate shows the proportion of comparisons where the left ear was judged to be higher in pitch. Each symbol represents an individual subject’s data, as indicated in the legend. Also shown is the fitted psychometric function for each subject (grey lines). The black symbols and thick line represent the group-averaged data for all ten subjects. All ten subjects perceived higher pitch as the stimulating electrode in the left ear progressed basalward in the cochlea. However, the results of interaural pitch-comparison task showed large individual variability. While some subjects (e.g., M35b and E23b) experienced a clear change in pitch perception as the stimulating electrode shifted along the cochleae, the perceived change in pitch was relatively subtle for other subjects (e.g., R40b and M58b). In general, psychometric function fits were good, accounting for 92%–98% of variance in these data. For most subjects, this function is sigmoidal. It is evident from Figure 3 that the steepness of the fitted psychometric functions as indicated by the slope varied considerably across subjects. The slope of psychometric function ranged from 1.84 to 12.12 percentage of trial/electrode with a mean of 6.32 percentage of trial/electrode (SD=3.47). Based on psychometric function fits, the electrode pairings judged to be most closely matched in pitch were: L14-R12 (subject R87b); L13-R12 (subjects M35b, M58b and E55b); L12-R12 (subjects E14b, R28b, R36b, E10 and E23b); and L11-R12 (subjects R40b).

Figure 4 shows results obtained at high and low stimulation levels for four subjects. Open symbols and dashed lines indicate data for high stimulation levels. Filled symbols and solid lines represent results for low stimulation levels. Results of a Wilcoxon Signed-Rank test indicated that there was no significant difference in slopes of psychometric functions obtained at high and low stimulation levels for these four subjects ($Z<0.001$, $p=1.00$). However, different pitch-matched electrode pairs were selected for high and low stimulation levels. Table 2 shows the pitch-matched electrode pairs that were chosen based on the psychometric function fits for high and low stimulation levels for these four subjects. Also shown is the amount of shift as quantified by the difference in the number of left ear electrodes with the minus sign indicating a shift toward basal end of the cochleae.

Spread of Neural Excitation and Pitch Ranking

The primary goal of this study was to examine the relationship between the results of the electrophysiologic measures of the BIC of the EABR and the psychophysical measures of interaural pitch-comparisons. Figure 5 (high stimulation level) and Figure 6 (low stimulation level) show the peak-to-peak amplitudes of the BIC responses (open symbols) and the results of IPPC measures (filled symbols) plotted as functions of left ear electrode for each of the individual subjects. The abscissa shows the electrode in the left ear that was paired with electrode 12 in the right ear. The left ordinate shows inverse perception pitch changes while the right ordinate represents the peak-to-peak amplitude of the BIC responses. Dashed and solid lines indicate the fitted Gaussian functions for the BIC amplitudes and the IPPC results, respectively. In general, the Gaussian function fits are good for the IPPC results at both stimulation levels, accounting for 93%–99% of variance in these data. However, the goodness of fit for the BIC amplitudes shows large individual variability, presumably due to noise of BIC measures – as discussed in He et al. (2010). The amount of variance accounted by the function ranges from 3% to 82% for peak-to-peak amplitude measured at high stimulation levels and ranges from 35%–70% for low stimulation levels. For the RMS amplitude measures, the amount of variance that is accounted by the Gaussian function ranges from 3% to 54% and from 35% to 67% for high and low stimulation level, respectively.

It is apparent from the data shown in Figure 5 that the fitted Gaussian function of the BIC amplitudes is much wider than the fitted function of the IPPC results for high stimulation levels. This observation is confirmed by the results of one-tailed Paired Samples T test (peak-to-peak amplitude: $t=-3.17$, $p<0.05$; RMS amplitude: $t=-4.90$, $p<0.05$). At low stimulation levels results of a Wilcoxon Signed Ranks test showed that there was no significant difference in the width of fitted functions of these two measures (peak-to-peak amplitude: $Z=-1.83$, $p=0.07$; RMS amplitude: $Z=-1.83$, $p=0.07$).

The relationship between the electrophysiologic measures of the BIC of the EABR and the psychophysical measures of interaural pitch comparisons was investigated at both the individual and group level. The assessment was carried out separately for peak-to-peak and RMS amplitude measures. The Pearson Product Moment Correlation test was used to assess the relationship between results of these two measures for each subject. The resulting correlation coefficient (*r* value) and the *p* value are shown in each graph of Figure 5 and 6. At high stimulation levels, two subjects (R36b and E10b) showed a significant positive correlation between the two measures. Four subjects (R28b, E14b, M58b and R40b) showed a weak to moderate positive correlation ($r=-0.21$, $r=-0.39$, $r=-0.51$, and $r=-0.14$, respectively). All other subjects showed a correlation in the opposite direction. However, these correlations didn't reach significance at the level of $p=0.05$. In order to further assess the relationship between these two measures at a group level, the widths of the fitted Gaussian function (B values) of peak-to-peak amplitudes and the IPPC results were compared. Results of a Pearson Product Moment Correlation test showed that the width of the fitted functions for these two measures were not correlated with each other ($r=-0.33$, $p=0.36$). At low stimulation levels, all four subjects showed a negative but non-significant correlation between the two measures ($p>0.05$). There is no evidence suggesting that the relationship between these two measures is different for different types of electrode array (straight, contour, or contour advanced).

The correlation between RMS amplitudes of BIC responses and the IPPC results was also evaluated using the Pearson Product Moment Correlation test for each subject. Results for high stimulation levels showed that only one subject (E55b) showed a significant correlation between the two measures ($r=-0.67$, $p<0.05$). Three subjects (R28b, E14b and R40b) showed a weak positive correlation ($r=-0.16$, $r=-0.21$, and $r=-0.12$, respectively). All other subjects showed a correlation in the opposite direction. These two measures were not correlated at the group level as showed by the result of a Product Moment Correlation test ($r=-0.40$, $p=0.247$). Similar to the results of the peak-to peak amplitude, there was a negative but non-significant correlation between the results of these two measures for low stimulation levels ($p>0.05$ for all subjects) on an individual basis. There was no apparent difference in the relationship of the two measures for different types of electrode array (straight, contour, or contour advanced).

The electrode pairs that had the largest BIC amplitudes (peak-to-peak or RMS amplitudes) and the electrode pairs that were best matched in pitch perception for ten subjects at high stimulation levels are listed in Table 3. Inspection of Table 3 suggests that there is no robust agreement among the electrode pairs chosen using different criteria for the majority of subjects. In order to more quantitatively compare these results, the left ear electrode was treated as the variable measured on an interval scale. Although the best matched electrode pair defined by BIC amplitudes or pitch perception is quite different at high stimulation level, results of repeated measures ANOVA showed that the difference was not statistically significant ($F_{2,18}=2.96$, $p=0.08$).

Figure 7 shows the best-matched electrode pair defined for four subjects who were tested at both high (left panel) and low (right panel) stimulation levels. Each symbol represents each subject's data. Inspection of Figure 7 suggests that reducing the stimulus level appears to improve the agreement among results obtained using different methods. However, results of Friedman Test showed that there was no significant difference in electrode pairs selected using different criteria for either high stimulation levels (Chi-Square=5.29, $p=0.07$) or low stimulation levels (Chi-Square =4, $p=0.14$).

DISCUSSION

This study investigated the relationship between the pitch ranking abilities and the amount of spread of excitation as estimated by the BIC versus electrode function. Results of the interaural pitch-comparison task showed that the basal electrodes were judged to be higher in pitch than more apical electrode by the subjects tested in this study, which is consistent with results reported in the literature (Townshend et al., 1987; Nelson et al., 1995; McDermott and McKay, 1997; Dawson et al., 2000; Laneau and Wouters, 2004; Donaldson et al., 2005). The logistic function was used to fit the results of the interaural pitch-comparison task for each subject. Our results showed that the general characteristics of the psychometric functions obtained in the present study are consistent with data previously reported by other investigators for a frequency discrimination task (He et al., 1998, 2007; Nelson and Freyman, 1986; Laneau and Wouters, 2004). The steepness of the slope varied somewhat across subjects. Some subjects (e.g., M35b) showed steep slopes, whereas other subjects had relatively shallow slopes (e.g., R40b). Our results also suggested that changing stimulation level could potentially affect pitch perception.

The primary goal of this study was to investigate the relationship between psychophysical measures of interaural pitch-comparisons and electrophysiologic measures of the BIC of the EABR. It was hypothesized that the bilateral CI users who had wide spread of neural excitations as indicated by the broad BIC versus electrode functions would have difficulty in the interaural pitch-comparison task. In general, our results showed no correlation between the two measures for either high or low stimulation levels.

The general lack of correlation between psychophysical measures of interaural pitch-comparisons and electrophysiologic measures of the BIC of the EABR for individuals in this study may be due to the dissimilarity between the two tasks and what they measure. The BIC of the EABR reflects the binaural processing at the brainstem level. It depends upon the spread of excitation within the cochlea and is an objective measure. The interaural pitch-comparison task used a different stimulus and assessed spatial/spectral resolution. That task, being a subjective measure, could be affected by processing mechanisms that occur beyond the auditory brainstem. Reiss et al. (2007) investigated the effect of experience on the electrical pitch sensation in 18 hybrid implant subjects at various stages of implant use, ranging from hook-up to five years of CI use. The hybrid implant is a shorter, thinner version of the traditional cochlear implant. It is designed to stimulate only the higher frequency regions of the cochlea leaving the low frequency regions unaffected. In that study, subjects estimated the perceived pitch when the most apical electrode was stimulated by matching it to the pitch of an acoustic tone presented sequentially to the non-implanted ear. High pulse rate stimuli (>800 pps) were used to eliminate the use of temporal cues. Results of this study showed that the perceived pitch could shift dramatically downward in frequency by as much as two octaves over a period of 60 months of implant use. Pitch sensations obtained at hook up were closer to those predicted based on electrode location in the cochlea. However, later pitch sensations were one to two octaves lower than those estimated by Greenwood’s frequency-position function (Greenwood, 1990). These findings were consistent with results reported by three other research groups (Dorman et al., 1994, 2007; Blamey et al., 1996; Boex et al., 2006; McDermott et al., 2009). Results of these studies indicate that user’s experiences can affect perceived pitch sensation over time and suggest that cortical processing plays a significant role in pitch determination. It should be noted that subjects who were tested in these studies had residual hearing in one ear and CI in the other ear. In contrast, most of subjects tested in the present study received simultaneous bilateral cochlear implantation. Therefore, they might experience less shift in the pitch matches between the two ears than subjects who participated in the studies referred to above.

McKay *et al.* (1999) investigated the effect of stimulation level on monaural electrode discrimination in four adult CI users. They showed a degradation of discrimination performance with a decreasing stimulation level. Based on their results, McKay *et al.* (1999) suggested that changes in the “peak” or “edge” of the excitation pattern were more important than the relative amount of non-overlap of two excitation patterns for electrode discrimination. It is possible that subjects tested in the present study were also comparing changes in “peaks” or “edges” of excitation patterns rather than the amount of non-overlap in neural responses from interaural electrode pairs when performing interaural pitch comparisons. The differences in what have been measured by the BIC of the EABR and the interaural pitch comparisons might account for the lack of correlation between these two measures.

Another potential reason for the lack of correlation between the BIC amplitude of the EABR and the electrode discrimination ability for subjects tested in this study may be due to different stimulation levels that were used for the two measures. The EABR measures were obtained using single-pulse stimuli presented at a rate of 19.9 Hz, whereas the stimuli that were used for the interaural pitch-comparison task were pulse train-stimuli. Consequently, the single-pulse stimuli were presented at a higher level than the pulse-train stimuli, as shown in Table A, Supplemental Digital Content 1, which may result in broader spread of neural excitation for the EABR measures. Unfortunately, our experimental setup does not allow us to investigate the hypothesis that the level difference may account for the observed lack of correlation.

It would be ideal if both measures were recorded using the same stimulus parameters. Unfortunately, a subset of subjects (n=4) could not derive pitch perception for single-pulse stimuli, which forced us to use pulse-train stimuli for the interaural pitch comparison task. Carlyon et al. (2010) recently showed that it was possible for CI users to derive pitch percepts for single pulses presented at rate of 12 Hz. It should be pointed out, however, that all four patients who were tested by Carlyon et al. had CIs in one ear and normal hearing in the other ear. The primary aim of their cochlear implantation was to alleviate tinnitus. These patients may have had a better “template” of pitch perception than our patients, which may account for the discrepancy between our experience and results showed in Carlyon et al. (2010).

Last, there were considerable variations across subjects in BIC amplitudes for both high and low level stimulation conditions. It is possible that there is a correlation between the BIC amplitude and electrode discrimination abilities within subjects, especially at low stimulation levels. However, the effect was not measured in this study because of large individual variability, the methods used to quantify the data, or the small number of subjects retested at low stimulation levels.

One caveat of the study is that the goodness of fit of Gaussian function for BIC amplitude was not robust for every subject, presumably due to the noise in BIC measures at high stimulation levels. Several factors might contribute to the measurement noise of the BIC responses, including cross-turn stimulation and vestibular evoked potentials. The cross-turn stimulation occurs when the stimulating electrodes excite auditory nerve fibers originating in more apical regions and running centrally in the modiolus at high stimulation levels. In this case, reduction in the stimulus level should have resulted in less noise in the BIC measurements. Consistent with this possibility, the goodness of fit of the Gaussian functions for BIC amplitudes improved at low stimulation level compared to the fits obtained at high stimulation levels.

Both interaural pitch comparisons and electrophysiologic measures of the BIC of the EABR have been suggested as possible tools to define the best-matched electrode pairs for bilateral CI users. There are pros and cons to both methods. The interaural pitch comparison technique is relatively time efficient compared with the electrophysiologic measures. However, studies have shown that this technique does not guarantee identification of electrode pairs with optimal sensitivity to interaural time differences (e.g, Long et al., 2003). Most importantly, it cannot be used for pediatric CI users. In contrast, electrophysiologic measures of the BIC of the EABR do not require active participation from subjects. Therefore, it can be performed for every CI user. However, the methods used in the present study are too time consuming to be used in clinical settings. The BICs were recorded from cooperative adult subjects and, even so, it took about eight hours to finish recording the EABR for all conditions. Although it is not necessary to obtain the BICs from 11 electrode pairs in order to find the electrode pair with the maximal BIC amplitudes, our data suggest that a minimum of two electrodes in each direction (basal and apical) are required. This means that three hours of testing time is required for the identification of one best-matched electrode pair. It could take even longer to obtain data from child CI users. Therefore, it might take multiple appointments to finish all the tests. Furthermore, it is still unknown whether the best ITD sensitivity will be obtained from the interaural electrode pairs with the largest BIC amplitudes. Thus, its clinical application appears limited this time.

CONCLUSIONS

The primary hypothesis was that there was a relationship between the electrophysiologic measures of the BIC of the EABR and the psychophysical measures of the interaural pitch comparisons. We hypothesized that reducing the stimulation level would improve the relationship between these two measures. In general, this study showed no relationship between the BIC amplitudes and results of interaural pitch comparison task for either high or low stimulation levels. The lack of correlation may be attributed to methods used to quantify the data, small number of subjects retested at low stimulation levels, as well as central processing components involved in the interaural pitch-comparison task.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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APPENDIX

Stimulation levels used in high and low level stimulation conditions are listed in Table A, Supplemental Digital Content 1.

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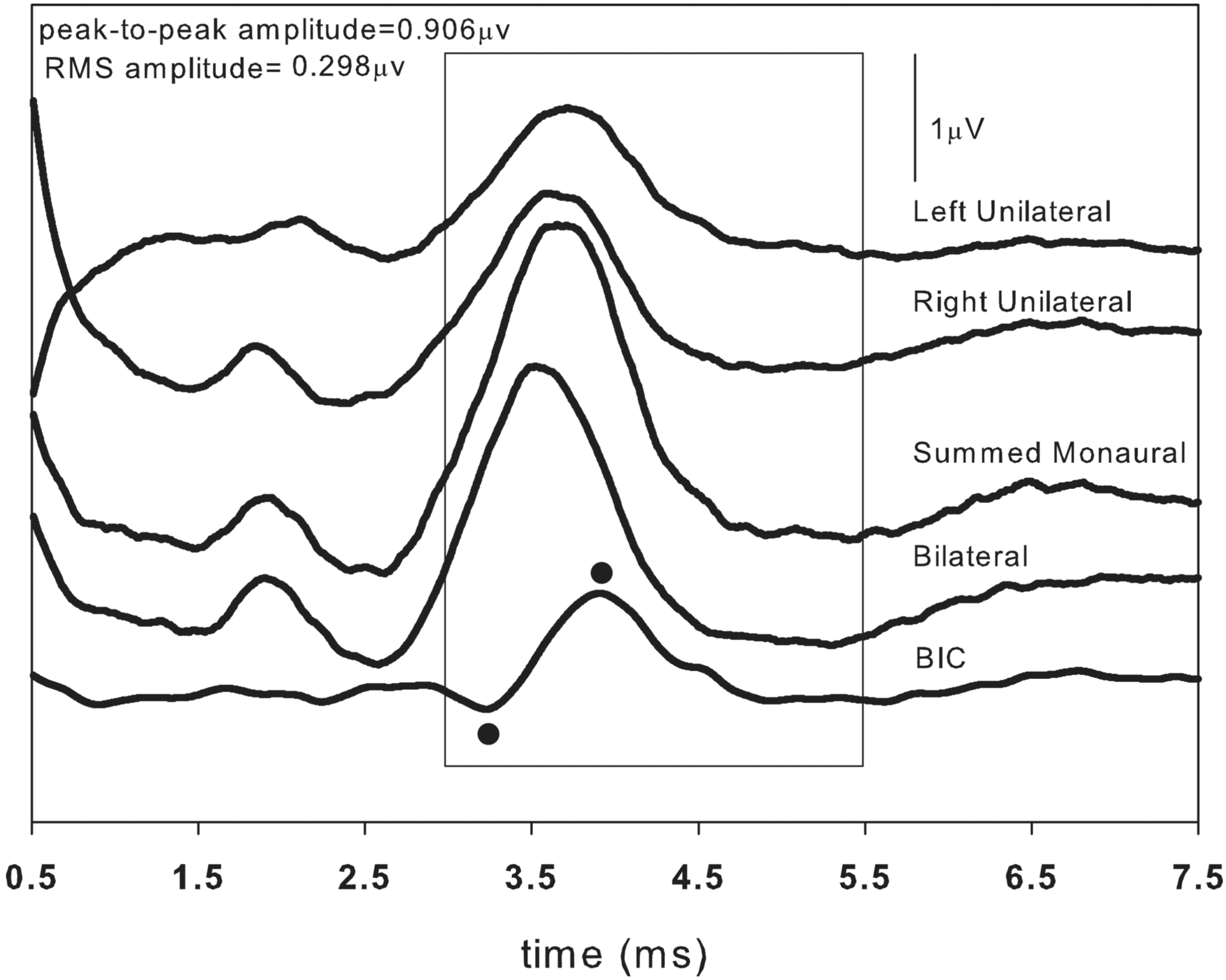

Figure 1.

EABRs recorded using unilateral and bilateral stimulation are shown. Also shown are the summed unilateral responses and the derived BIC. The dots indicate the points used to compute peak-to-peak amplitude of the BIC. The rectangular box indicates the time window over which the RMS amplitude is calculated. Results of peak to peak and RMS amplitude measures are indicated in the upper left corner of the graph.

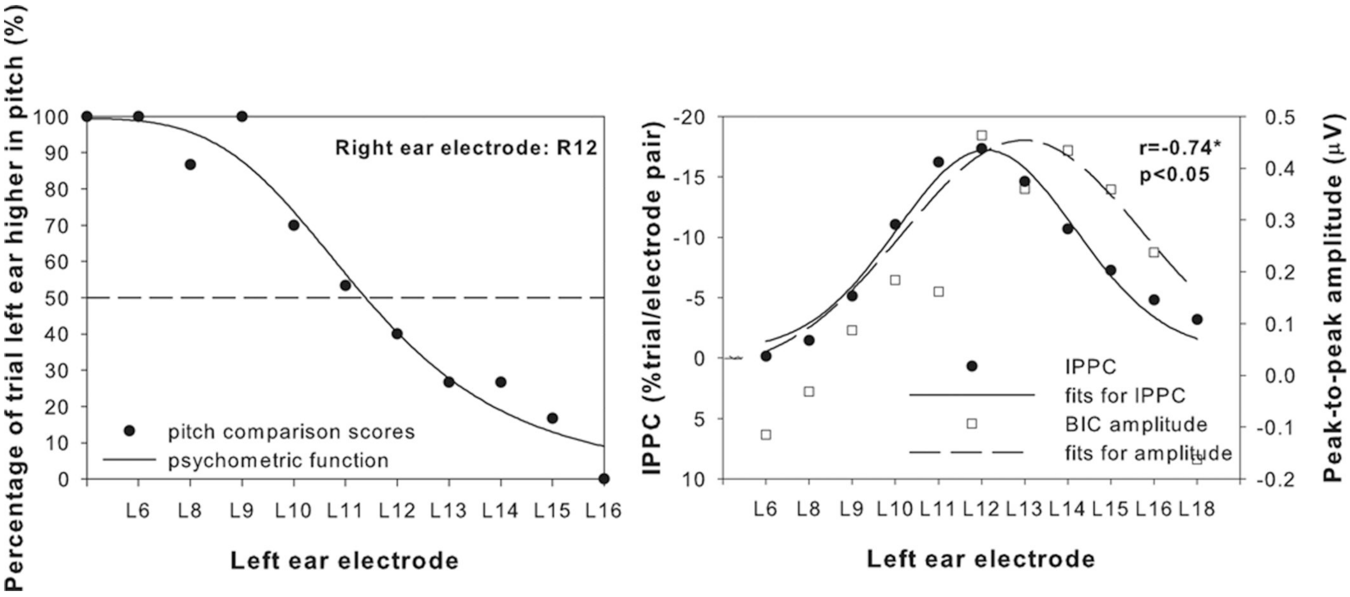

Figure 2.

An example illustrating the methodology used for data analysis in the present study. The data were obtained from subject E10b. The right ear electrode was fixed at electrode 12. Panel (a) shows the interaural pitch-comparison scores (symbols) plotted as a function of left ear electrodes and the psychometric function (solid line) fitted to these data. Panel (b) shows the inverse perceptual pitch change (IPPC) derived from the psychometric function. Also shown in panel (b) are the peak-to-peak amplitudes of BIC responses (open symbols) measured for each interaural electrode pair and the results of Pearson Moment Product Correlation test. Dashed and solid lines represent the fits of Gaussian function for the BIC amplitudes and the IPPC results, respectively.

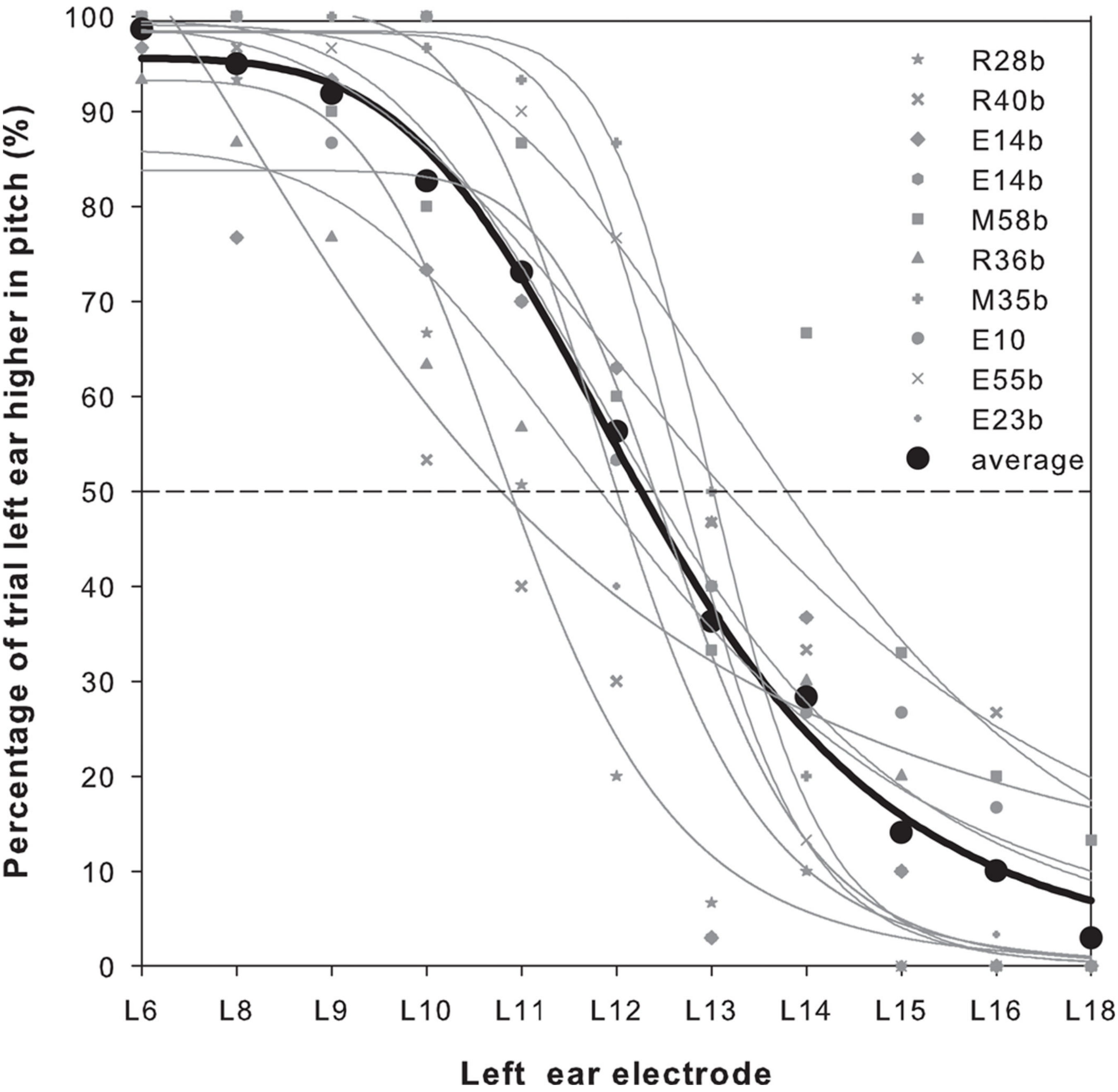

Figure 3.

Results of the interaural pitch-comparison task (symbols) and psychometric functions (grey lines) obtained from ten subjects at high stimulation levels. The black dots indicate the averaged interaural pitch-comparison scores for all subjects. The black thick line represents the psychometric function fitted to the averaged data. The horizontal dashed line indicates the 50% point on psychometric functions.

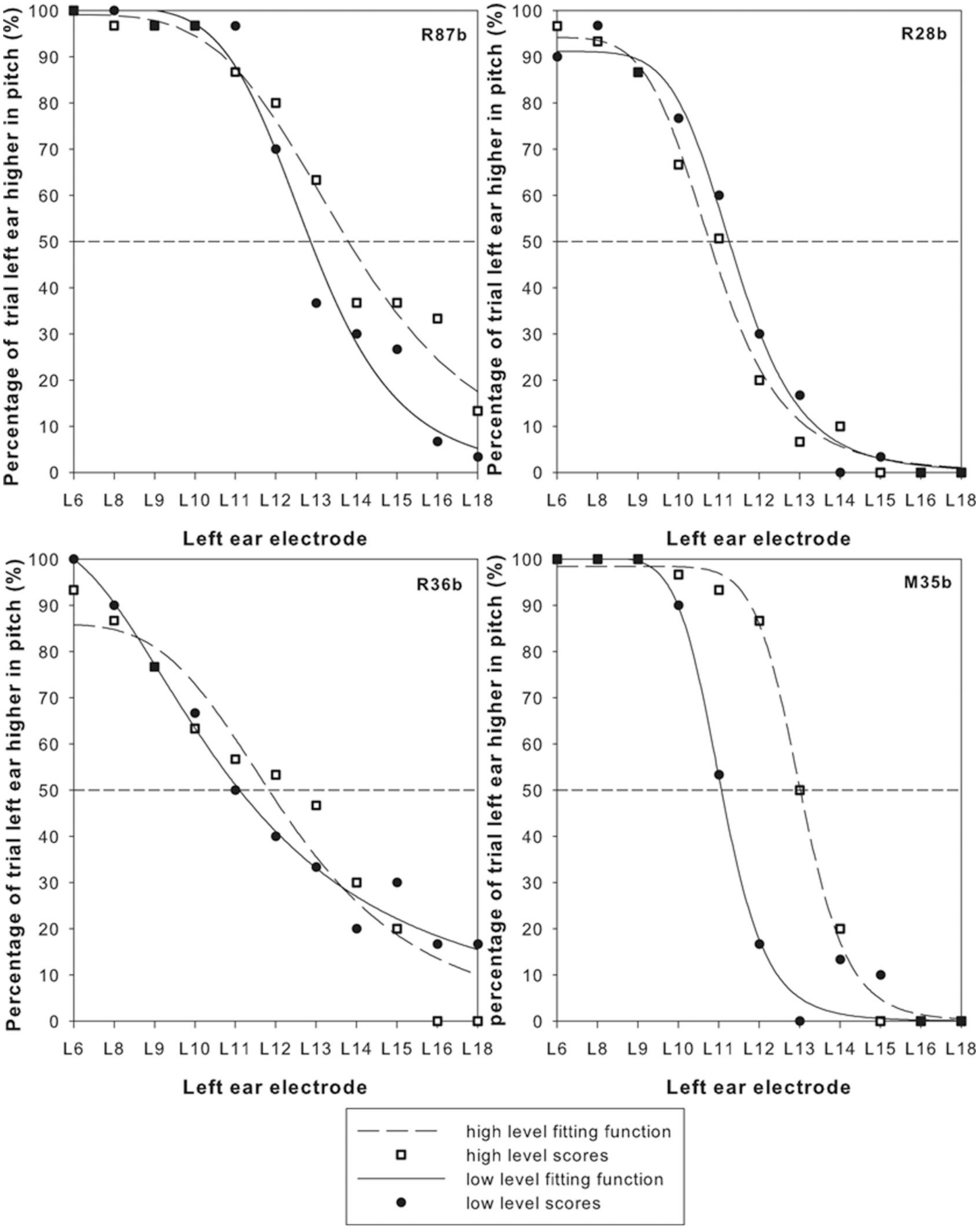

Figure 4.

Results of the interaural pitch-comparison task (symbols) and psychometric functions (grey lines) obtained from four subjects for high and low stimulation levels. Open symbols and dashed lines represent data obtained at high stimulation levels. Solid symbols and lines represent data obtained at low stimulation levels. The horizontal dashed line indicates the 50% point on psychometric functions. Subject number is indicated on each graph.

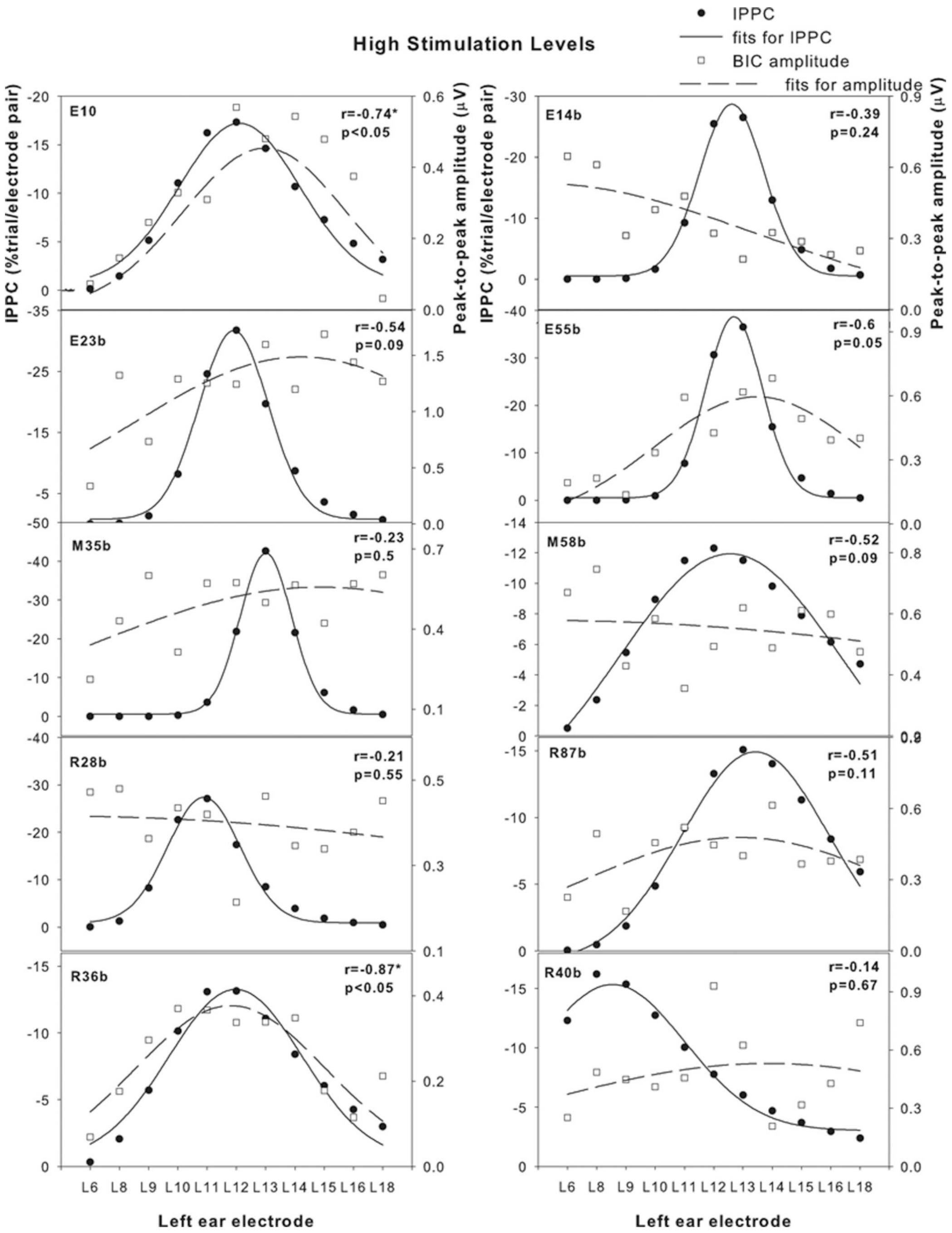

Figure 5.

Individual results showing results (open symbols) and fits of Gaussian function (dashed lines) for peak-to-peak BIC amplitudes and the inverse perceptual pitch change (IPPC) results (filled symbols and sold lines) plotted as the function of left ear electrode for high stimulation levels. Subject number, correlation coefficient (*r* value) and *p* value are indicated on each graph.

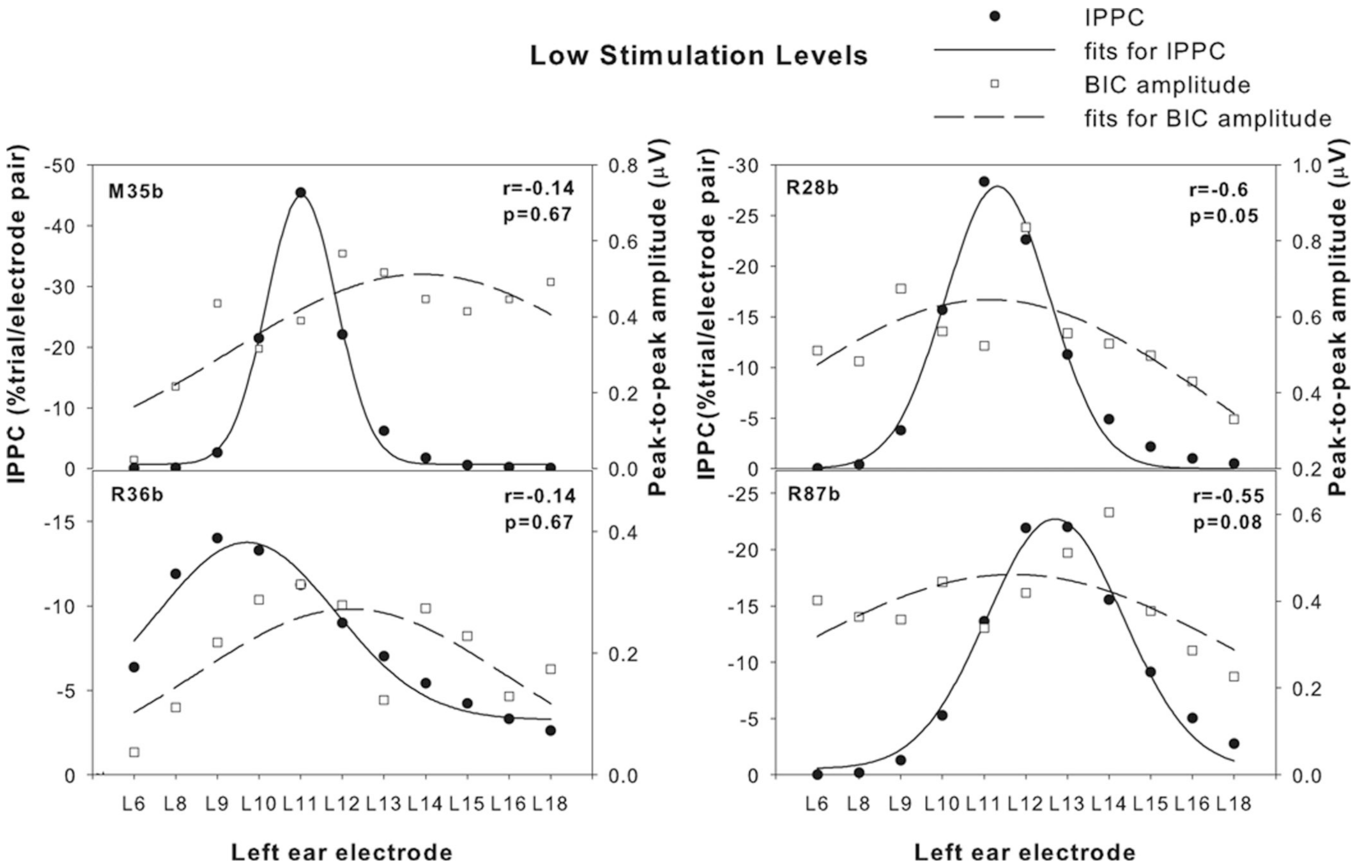

Figure 6.

Peak-to-peak amplitudes (open symbols) and fits of Gaussian function (dashed lines) as well as and the IPPC results (filled symbols) plotted as functions of left ear electrodes for four subjects at low stimulation levels. Each panel represents data from an individual subject. Subject number, correlation coefficient (*r* value) and *p* value are indicated on each graph.

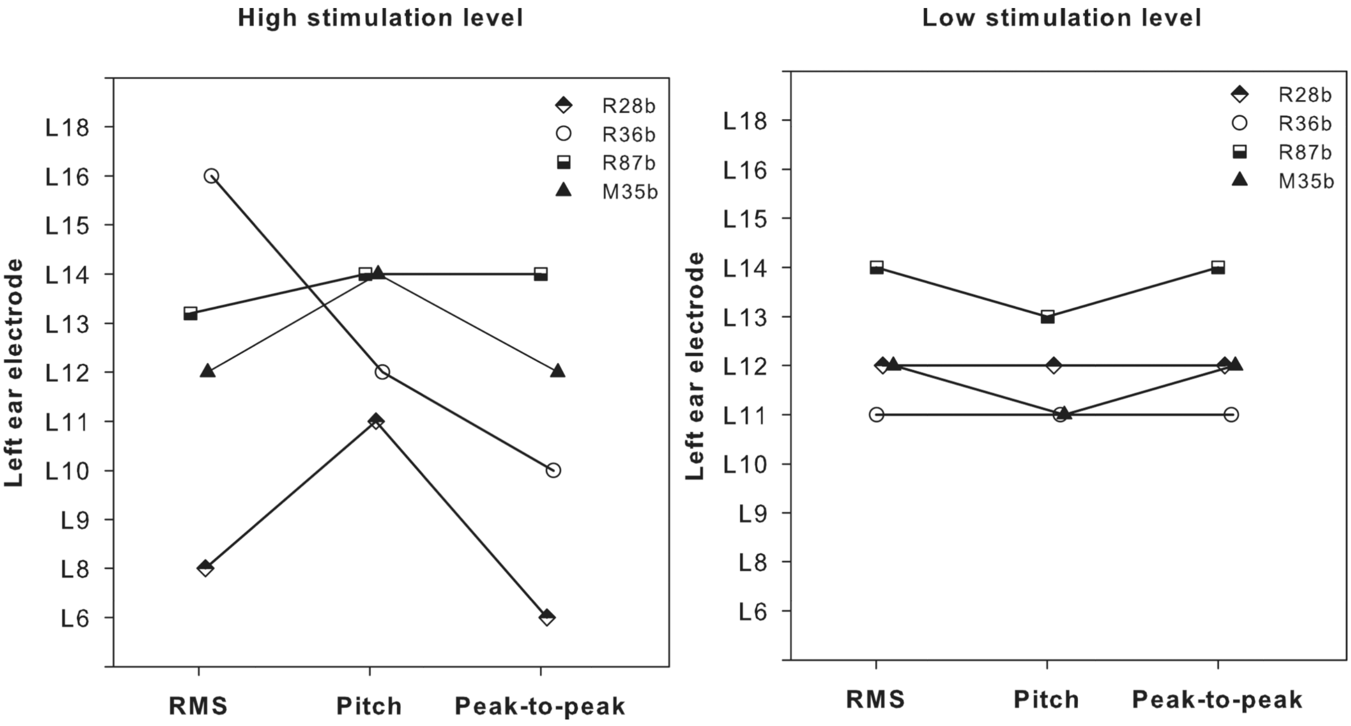

Figure 7.

The electrode pairs that have the biggest BIC amplitudes (peak-to-peak or RMS) or best matched in pitch for four subjects at low stimulation levels. Each type of symbols represents data from an individual subject. The methods used chose electrode pairs are indicated on the abscissa.

Table 1

General demographic information for ten subjects.

Subject number	Age	Gender	Bilateral severe or profound hearing loss (years)	Duration of bilateral implant use (months)	Etiology	Implant
R87b	28	M	0.6	32	Coggan's syndrome	24R (CA)
R28b	59	F	15	62	Unknown	24R (CS)
R40b	61	F	10	56	Enlarged Vestibular Aquaducts	24R (CS)
R36b	53	M	28	59	Unknown	24R (CS)
M58b	68	F	1	96	Meniere's disease	24M
M35b	79	M	1	108	Unknown	24M
E23b	84	F	5	24	Unknown	24RE (CA)
E55b	59	F	3	6	Hereditary	24RE (CA)
E10	49	F	14	28	Unknown	24RE (CA)
E14	73	F	10	22	Unknown	24RE (CA)

Table 2

The pitch-matched electrode pairs defined at high and low stimulation levels for four subjects.

	Pitch-matched electrode pair		Change in the pitch-matched electrode pair with reduced stimulation level
Subject number	**High stimulation levels**	**Low stimulation levels**	
R87b	L14-R12	L13-R12	−1
R28b	L12-R12	L11-R12	1
R36b	L12-R12	L11-R12	−1
M35b	L13-R12	L11-R12	−2

Table 3

Matched interaural electrode pairs defined based on results of interaural pitch comparison task, the peak-to-peak amplitude and the RMS amplitude measures of BIC responses obtained at high stimulation levels.

	Matched interaural electrode pairs based on		
Subject number	**Interaural pitch comparison**	**Peak to peak amplitude of the BIC**	**RMS amplitude of the BIC**
E10	L12-R12	L12-R12	L15-R12
E14b	L12-R12	L6-R12	L11-R12
E23b	L12-R12	L15-R12	L13-R12
E55b	L13-R12	L13-R12	L13-R12
M35b	L13-R12	L12-R12	L12-R12
M58b	L13-R12	L15-R12	L12-R12
R28b	L12-R12	L6-R12	L8-R12
R87b	L14-R12	L16-R12	L13-R12
R36b	L12-R12	L10-R12	L16-R12
R40b	L11-R12	L12-R12	L12-R12