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Identifying cochlear implant channels with poor electrode-neuron interface: partial tripolar, single-channel thresholds and psychophysical tuning curves

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Abstract

Objectives—The goal of this study was to evaluate the ability of a threshold measure, made with a restricted electrode configuration, to identify channels exhibiting relatively poor spatial selectivity. With a restricted electrode configuration, channel-to-channel variability in threshold may reflect variations in the interface between the electrodes and auditory neurons (i.e., nerve survival, electrode placement, tissue impedance). These variations in the electrode-neuron interface should also be reflected in psychophysical tuning curve measurements. Specifically, it is hypothesized that high single-channel thresholds obtained with the spatially focused partial tripolar electrode configuration are predictive of wide or tip-shifted psychophysical tuning curves.

Design—Data were collected from five cochlear implant listeners implanted with the HiRes 90k cochlear implant (Advanced Bionics). Single-channel thresholds and most comfortable listening levels were obtained for stimuli that varied in presumed electrical field size by using the partial tripolar configuration, for which a fraction of current (σ) from a center active electrode returns through two neighboring electrodes and the remainder through a distant indifferent electrode. Forward-masked psychophysical tuning curves were obtained for channels with the highest, lowest, and median tripolar ($\sigma=1$ or 0.9) thresholds. The probe channel and level were fixed and presented with either the monopolar ($\sigma=0$) or a more focused partial tripolar ($\sigma \geq 0.55$) configuration. The masker channel and level were varied while the configuration was fixed to $\sigma = 0.5$. A standard, three-interval, two-alternative forced choice procedure was used for thresholds and masked levels.

Results—Single-channel threshold and variability in threshold across channels systematically increased as the compensating current, σ , increased and the presumed electrical field became more focused. Across subjects, channels with the highest single-channel thresholds, when measured with a narrow, partial tripolar stimulus, had significantly broader psychophysical tuning curves than the lowest threshold channels. In two subjects, the tips of the tuning curves were shifted away from the probe channel. Tuning curves were also wider for the monopolar probes than with partial tripolar probes, for both the highest and lowest threshold channels.

Conclusions—These results suggest that single-channel thresholds measured with a restricted stimulus can be used to identify cochlear implant channels with poor spatial selectivity. Channels having wide or tip-shifted tuning characteristics would likely not deliver the appropriate spectral information to the intended auditory neurons, leading to suboptimal perception. As a clinical tool, quick identification of impaired channels could lead to patient-specific mapping strategies and result in improved speech and music perception.

Keywords

cochlear implants; partial-tripolar electrode configuration; psychophysical tuning curves

Introduction

The design of multi-channel cochlear implants takes advantage of the tonotopic organization of the cochlea, mapping the spectral information in an acoustic signal to an array of stimulating electrodes. In response to a stimulus, the spatial distribution of auditory nerve fibers activated by each channel contributes to the perception of that stimulus. Previous modeling, physiology, and psychophysical studies have suggested a number of factors that can affect the tonotopic extent of auditory nerve activation (e.g., modeling – Hanekom, 2005; physiological - Bierer and Middlebrooks, 2002; psychophysical - Pfingst and Xu, 2004). Perhaps the best understood of these factors is electrode configuration (Jolly et al., 1996; Kral et al., 1998), which determines how current flows between electrodes for a given implant channel. Poor surgical placement of the implant (Cohen et al., 2003; Wardrop et al., 2005a; Wardrop et al., 2005b), electrode insertion depth (Skinner et al., 2007; Finley et al., 2008; Gani et al., 2007; Kos et al., 2007), and fibrous and bony tissue growth around the electrode array (Spelman et al., 1982; Hanekom, 2005) may also have profound effects on current flow in the cochlea. Any of these conditions, or a combination of them, may increase the effective distance between an electrode and its closest responsive auditory neurons and thus degrade the selectivity of that electrode. Another condition that may increase the electrode-to-neuron distance is the variable patterns of spiral ganglion degeneration (Hinojosa and Marion, 1983; Nadol et al., 2001). If such impaired electrodes could be readily identified, the clinical mapping procedure could be tailored to minimize their adverse impact on listening performance. The present study demonstrates that implant channels exhibiting relatively wide psychophysical tuning patterns – implying an impairment of spatial selectivity – may be detected by measuring thresholds using a spatially focused electrode configuration.

Modern cochlear implants primarily use the monopolar (MP) electrode configuration which consists of an active intracochlear electrode and a remote, extracochlear return. Based on electrostatic principles, this configuration produces a relatively broad electrical field in the cochlea (Jolly et al., 1996; Kral et al., 1998). More restricted electrical fields require an arrangement of two or more intracochlear electrodes to act as current sinks and sources. Examples include bipolar (BP), which is used clinically, quadrupolar or tripolar (TP) (Litvak et al., 2007; Jolly et al., 1996; Kral et al., 1998), and various phased-array configurations (e.g., van den Honert and Kelsall, 2007). Phased-array configurations sharpen electrical fields by counter-weighting several return electrodes relative to the active electrode. Physiological studies revealing the extent of activation in the auditory system to cochlear implant stimulation are generally consistent with electrostatic predictions. For instance, the TP configuration has been shown to be more tonotopically restricted than BP, which in turn is more restricted than MP (Kral et al., 1998; Bierer and Middlebrooks, 2002; Snyder et al., 2004; Snyder et al., 2008; Bonham and Litvak, 2008). Several lines of psychophysical evidence, including simultaneous channel interaction (Boex et al., 2003; de Balthasar et al., 2003; Bierer, 2007) and cross-channel masking (e.g., Chatterjee et al., 2006; Nelson et al., 2008), provide additional support for the improved spatial selectivity of focused configurations.

A recent study by Bierer (2007) suggests that the TP configuration is sensitive to factors within the cochlea that can degrade transmission of information to the auditory nerve. Thresholds obtained with the TP mode exhibited substantial variability from channel to channel. Somewhat less channel-to-channel variability was observed, on average, with the BP configuration, and the lowest variability in all subjects was observed with the MP configuration. One interpretation

of these findings is that those TP channels with elevated thresholds had a poor electrode-to-neuron interface, whether due to the loss of nearby spiral ganglion neurons, the placement of electrodes far from the osseous spiral lamina, or other factors; threshold perception for those channels could be reached only when the current was high enough to stimulate distant, but viable, portions of the spiral ganglion. In contrast, the smaller channel-to-channel variability observed with the MP configuration (and to a lesser degree than the BP configuration) was presumably due to its broader electrical field, which could stimulate distant neurons with only a small increase in current. The Bierer study further demonstrated that listeners with poorer word recognition were those with highly variable channel-to-channel thresholds with TP. However, no attempt was made to implicate any particular high-threshold TP channel as contributing to a functional impairment. The present study was designed to explore if such a relationship exists by comparing TP threshold measures and psychophysical tuning curves.

In acoustic hearing, psychophysical tuning curves (PTCs) are used to evaluate the frequency selectivity of the auditory system. Moore and colleagues (e.g., Moore and Alcantara, 2001) measured PTCs in hearing impaired subjects to assess the location and extent of cochlear “dead regions”, defined as an area of inner hair cell loss and/or spiral ganglion neuron damage. The PTCs were obtained using narrowband sounds of varying center frequency to mask a pure tone probe with a fixed frequency and level. In normal hearing listeners, the tip of each PTC closely approximated the probe frequency. In contrast, for hearing impaired listeners, the PTC tip at some probe frequencies was shifted basally or apically, consistent with the activation of auditory neurons at the edge of a dead region. Moore concluded that PTCs are a sensitive diagnostic tool for identifying irregularities in hearing across frequencies, even when pure-tone audiograms do not reveal a localized deficit.

Studies of cochlear implant listeners suggest that psychophysical tuning curves are also sensitive to localized cochlear factors affecting electrical hearing. Nelson and colleagues (2008) observed tip-shifted as well as broader tuning curves in some subjects. Analogous to the acoustic forward masking studies of Moore, they interpreted these PTC shapes as possibly reflecting localized spiral ganglion loss. However, only one channel was evaluated per subject, so changes in tuning properties across the array could not be assessed. In other studies, in which PTC or forward masking patterns were measured on multiple channels for each subject, significant channel-to-channel variability of tuning width and shape was observed, especially with a focused configuration (Chatterjee et al., 2006; Hughes and Stille, 2008). However, a direct relationship between tuning properties and single-channel thresholds was not explored. As discussed above, thresholds measured with the TP configuration also exhibit significant variability across the implant array of an individual listener. If high TP thresholds and tip-shifted or broad tuning reflect the same underlying cochlear conditions, then some correlation between these metrics might be expected. For example, the additional current required for a high-threshold TP channel to achieve perception (compared to a channel with a lower threshold) implies that neurons relatively distant to that channel's nominal place along the cochlea would be stimulated, due to longitudinal current spread. If the channel is the probe channel in a forward masking task, then at least some remote channels would make effective maskers, leading to broad or tip-shifted tuning curves. In addition, the restricted current spread of the TP configuration should make it an effective probe stimulus for measuring PTCs, which, in theory, are more sensitive to local factors if the extent of auditory nerve activation is limited (Moore and Alcantara, 2001; Kluk and Moore, 2006; Nelson et al., 2008).

Despite the potential advantage of the TP configuration to identify channels with a poor electrode-neuron interface, its practical application is limited because of its relatively high current requirements, a trade-off that has been well documented (Spelman et al., 1995; Kral et al., 1998; Mens and Berenstein, 2005; Bierer, 2007). A relatively novel electrode configuration, partial tripolar (pTP), has been proposed as one way of balancing current spread and current

level requirements (Mens and Berenstein, 2005; Jolly et al., 1996; Litvak et al., 2007). pTP is a hybrid of the MP and TP configurations, whereby a fraction of the return current is delivered to the flanking electrodes while the remainder flows to the distant extracochlear ground. A fraction of zero is equivalent to MP (all current is directed to the extracochlear electrode), while a fraction of one is TP (no current is directed to the extracochlear electrode) (Fig. 1). In the present study, single-channel pTP thresholds were measured using the largest current fraction that allowed threshold measurements across all channels for each subject. To test the hypothesis that a focused configuration can predict which channels have impaired spatial selectivity, psychophysical tuning curves were obtained for probe channels corresponding to the lowest, median, and highest pTP threshold channels for each subject. The effect of configuration on PTC characteristics was tested by applying both the pTP and MP configurations for the probe channel stimulus. Together, these methods offer a promising approach to identify cochlear implant electrodes that may be functionally impaired by spiral ganglion loss, poor electrode placement, or other factors.

General Methods

Subjects

Five adult cochlear implant listeners, four females and one male, participated in this study. The subjects, ranging in age from 30 to 74 years, were all native speakers of American English who had become deaf post-lingually. All participants wore a HiRes90k implant with a HiFocus 1J electrode array (Advanced Bionics Corp., Sylmar, CA), having a center-to-center electrode distance of 1.1 mm and all had at least 9 months of experience with their implants. Details about individual subjects can be found in Table I. The speech perception scores shown in Table I are from the most recent standard clinical visit (within three months of the beginning of the experiment) for each subject. The subjects made between 8 and 13 visits to the laboratory (two to four hour long visits) to complete the data collection. Each participant provided written consent, and the experiments were conducted in accordance with guidelines set by the Human Subjects Division of the University of Washington.

Stimuli

Biphasic, charge-balanced (cathodic phase first on the active electrode) pulses were presented with 102 μ s per phase and at a rate of 980.4 pulses/second. The active electrode and the return electrodes that complete the current loop are called a “channel”. Channel numbers denote the position of the active electrode on the implant array, and for this experiment, ranged from 2 (apical) to 15 (basal).

The electrode configurations used include monopolar (MP), tripolar (TP), and partial tripolar (pTP) at various current fractions (see Fig. 1). The MP configuration consists of a single active intracochlear electrode and an extracochlear return electrode. The TP electrode configuration consists of an intracochlear active electrode, with the return current divided equally between each of the two nearest flanking electrodes. The pTP configuration is similar, but only a fraction of the return current, represented by ‘ σ ’, is delivered to the flanking electrodes; the remainder flows to the distant extracochlear ground. Therefore, a σ of 0 is equivalent to MP (all current is directed to the extracochlear electrode), and a σ of 1 is equivalent to TP (no current is directed to the extracochlear electrode). In this paper, MP and TP channels are often referred to as pTP channels with fractions of 0 and 1, respectively.

The stimuli were delivered to the implant using a clinical interface controlled by the Bionic Ear Data Collection System, version 1.15.158 (BEDCS, Advanced Bionics Corp., Sylmar, CA). All stimulation levels used were within the current levels supported by the implant. Based on the clinically measured impedance values, the maximum compliance limits were calculated

at the beginning of each test session (Advanced Bionics, personal communication). The compliance limit was defined as the maximum voltage supported by the device (8 V) divided by the impedance.

A personal computer, which was used to run the BEDCS software, communicated with the clinical interface via a dedicated Platinum Series Processor. The same computer was used for online data collection via subject response using a computer mouse. Subjects were given practice sessions when new tasks were introduced until they became familiar with the task. They did not receive trial-by-trial feedback.

Data analysis and plotting was mainly performed in units of decibels (re. 1 mA) throughout this study, because the proportional changes in current between conditions are emphasized. The dynamic range was also highly variable from channel to channel and from subject to subject, making a logarithmic scale more suitable for comparisons.

Single-Channel Thresholds

For each subject, thresholds on every channel were obtained for a 204 ms pulse train using three configurations: MP, pTP at a fixed current fraction of $\sigma = 0.5$, and the largest common pTP fraction for which a threshold could be obtained on all fourteen channels (either $\sigma = 1$ or 0.9). For clarity, this latter configuration will be referred to as “TP”, even when the fractional current is not strictly 1. (For one subject (S24), this fraction was 1; for all others, the fraction was 0.9). The term “pTP”, unless specified, will be reserved for channels having a current fraction intermediate to the most restricted ($\sigma \leq 0.9$) and the most broad ($\sigma = 0$, MP).

The lowest, median, and highest threshold channels obtained with the TP configuration for each subject were identified for further testing. Thresholds were measured for this subset of channels for several pTP fractions. All thresholds were measured with an adaptive two-down one-up, three-interval, three-alternative forced-choice procedure, which converged on the 70.7 percent correct point on the psychometric function (Levitt, 1971). Each run started at a level estimated to be suprathreshold, and subjects responded using a mouse to indicate the interval that contained the signal. Twelve reversals (i.e., changes in the direction of the signal level) were measured for each trial, and the levels for the last eight were averaged and taken as threshold. For the first two reversals, the signal was adjusted in 2dB steps; for the other 10 reversals, it was adjusted in 0.5 dB steps.

For each condition, at least two runs were collected and averaged. If the threshold of two runs differed by more than 1 dB, a third run was collected and all three runs were averaged. Generally, the third run's threshold was between those of the first two runs. The standard deviation for the last eight reversals from each run was measured; if the value exceeded 1 dB the subject was given a break and threshold was subsequently re-measured. Additionally, because large numbers of trials were also an indication of subject fatigue, the total number of trials per run was limited to 75. To reduce subject fatigue, conditions (e.g. thresholds, MCL) were alternated within each testing session as much as possible.

Most Comfortable Level (MCL)

Accurate thresholds and MCLs were important for setting stimulus levels on the masker channels during the PTC procedure, which is described in the following subsection. The MCL was determined by presenting a pulse train just above threshold (204 ms pulse train, $\sigma = 0.5$) and asking the subject to adjust the level by clicking one of two options labeled “up” and “down.” The subject was asked to set the level to the subjective rating of “loud but comfortable,” corresponding to 7 on the 1-10 clinical loudness rating scale (Advanced Bionics). The level was changed in 1 dB steps until the subject clicked the “down” button; thereafter it

was changed in 0.5 dB steps. At least two runs were collected and averaged for each MCL condition. If the two measured MCLs differed by more than 1dB, a third run was completed, and all three runs were averaged. For two electrodes in S23, MCL could not be reached because the current level for maximal loudness perception exceeded the compliance limits of the device. In those cases, the maximum compliance limit was used as the MCL and grey symbols are indicated in the figures.

Psychophysical Tuning Curves (PTCs)

Psychophysical tuning curves were measured using a forward masking paradigm in which the masker was a 204 ms pulse train, with the configuration fixed at a pTP fraction of $\sigma = 0.5$. The masker threshold and MCL levels were then used to set the range of possible stimulus levels for each channel. Thresholds obtained in the first experiment with a pTP fraction of $\sigma = 0.5$ determined the lower limit, while the measured MCL determined the upper limit.

The probe electrodes for each subject were those with the highest, lowest, and median single-channel TP thresholds (thresholds based on the largest pTP fraction possible, either 0.9 or 1). The probe, a 10.2 ms pulse train fixed at 3 dB above threshold, was presented 9.18 ms after the masker (see Fig. 2). Two configurations were used for the probe: MP ($\sigma = 0$) and the largest pTP fraction that would accommodate a current level 3 dB above threshold without exceeding the compliance limit. (For most subjects, the pTP fraction for the more restricted probe configuration was smaller than the one used to measure single-channel TP thresholds (i.e. less than 0.9).) The two types of probe stimuli will be referred in this paper as “MP” and “pTP”. The probe presentation level was calculated as 3dB above the probe-only threshold using the same pTP fraction, where threshold was measured as described previously except that a 10.2 ms pulse train was used.

The level of the masker was adjusted to determine how much masking was required to just mask the probe. The masked thresholds were obtained using a procedure similar to the one described above for the probe, an adaptive, two-up one-down, three-alternative forced-choice tracking procedure. The masker was presented in all three intervals, while the probe was presented randomly, but with equal probability, in only one of the three intervals. The subject was asked to indicate which interval sounded “different”. For each probe channel, the sequence of testing began with the masker presented on the same channel as the probe. The masking channel was then changed to other channels successively more distant from the probe channel. If masker threshold reached masker MCL in any condition, an indication that masking could not be achieved, this channel was determined to be the edge of the tuning curve. The apical and basal edges of each tuning curve were obtained in most conditions except when the probe channel was near the end of the electrode array. For some subjects for completeness, if time allowed, masked thresholds were obtained for channels beyond the edge of the tuning curve (i.e., every other masker electrode) until the basal and apical ends were reached. The masker level was constrained at or below the MCL. Masker-alone threshold and MCL measurements were interleaved with PTC masking measurements to reduce the fatigue of the participants.

In four subjects, additional PTCs were obtained with the probe level fixed at 1.5 or 2 dB above the probe-alone threshold and the probe configuration limited to $\sigma = 0$. All other stimuli and procedures were the same as for the PTCs measured with a 3-dB probe-level.

Quantifying PTCs

PTC data are shown in raw form as a function of masker level in decibels relative to one mA (see Figures 4 and 8) and normalized to the percentage of the masker-alone dynamic range (see Figures 5 and 9). A unique aspect of this study is the consistent use of a restricted masker configuration of $\sigma = 0.5$, which allows for comparisons of changes in tuning properties that

can only be a result of the varying probe configuration. The fixed masker configuration also allows for the analysis of data normalized to percentage of masker-alone dynamic range, which reduces the effect of channel-to-channel variability in masker-alone levels. For instance, in some cases for which the MCL was relatively high and the PTC was relatively shallow (S22 highest threshold channel) the shape of the tuning curve is hard to discern. The normalized data were used to accurately identify the tip and data points to be analyzed from the PTCs.

To compute the slopes of the apical and basal sides of the PTCs, first the tip of the tuning curve (i.e., the lowest masker level required to mask the probe) was identified using the normalized masker levels. Once the tip was identified, the level for which the curve crossed 80% of masker dynamic range was used for the endpoint in either direction. Then, using the raw data points from the tip through the endpoint, a least-square error line was obtained and the slope was calculated from that line in decibels per millimeter. In the few cases where the tuning curve was shallow such that the data did not fall below 80%, the minimum was used as the tip and the curve was fit to the point where the data reached masker-alone MCL. In addition, the depths of the PTCs were taken as the difference between the minimum and maximum masker levels measured in dB rel. 1 mA. Finally, the widths of the PTCs reported in millimeters were measured at 50% above the tip of the normalized PTCs.

Results

Single Channel Thresholds

Figure 3 plots individual channel threshold data for each subject (rows). The data are plotted in two ways. The left column shows the threshold across all available channels for 3 different pTP fractions, while the right column shows the thresholds for the lowest, median, and highest threshold channels as a function of pTP fraction. In the left column the ordinate shows thresholds in units of dB re. 1 mA and the abscissa shows CI channel number from apical to basal. The symbols represent three pTP fractions denoted by σ ; 1) the largest fraction possible for that subject (as indicated in the figure legend, either $\sigma=0.9$ or $\sigma=1.0$), 2) a fraction of $\sigma = 0.5$, and 3) a fraction of $\sigma = 0$, which corresponds to MP. Note that the grey triangle for S23 indicates that the compliance limit was reached, so this data point was below the true threshold for that channel. The level at the compliance limit, however, was higher than all other thresholds for this subject; therefore it was taken as the highest threshold channel. The vertical dashed lines identify the channels selected for further testing; the channels with the highest, median and lowest thresholds obtained using TP. The thresholds systematically decreased as a function of pTP fraction; those obtained with TP were highest and those obtained with MP were the lowest (t-test, $\sigma \geq 0.9$ versus $\sigma = 0.5$, $p < 0.05$; $\sigma \geq 0.9$ versus $\sigma = 0$, $p < 0.05$; $\sigma = 0.5$ versus $\sigma = 0$, $p < 0.05$). Channel-to-channel variability was quantified within a subject as either the standard deviation of the unsigned difference between thresholds of adjacent channels (Bierer, 2007) or the mean of the unsigned difference in thresholds of adjacent channels (Pfingst and Xu, 2004). Both measures were included because the two measures emphasize different aspects of the data. The variability measure using standard deviation takes into account the expected channel-to-channel differences emphasizing local variability while the mean emphasizes the absolute magnitude of the differences. A systematic decrease in variability as a function of pTP fraction was observed, with the greatest variability for $\sigma = 0.9$ or 1.0 and the least for $\sigma = 0$ (see Table 2) (channel-to-channel variability based on both standard deviation and mean; paired t-test, $\sigma \geq 0.9$ versus $\sigma = 0.5$, $p < 0.005$; $\sigma \geq 0.9$ versus $\sigma = 0$, $p < 0.005$; $\sigma = 0.5$ versus $\sigma = 0$, $p > 0.05$).

In the right column of Fig. 3, the data are plotted with threshold on the ordinate and pTP fraction on the abscissa. The different symbols represent the lowest, median, and highest threshold channels measured with TP. For each channel plotted, threshold generally increased systematically with pTP fraction, consistent with the expected narrowing of electrical field

size. The slopes of the least-square error fits (solid lines) were computed for each of the three channels and are listed in Table 3. The channels with the lowest thresholds (measured with TP) have shallow slopes with increasing σ . In contrast, the high threshold channels have steep slopes. Note that for subjects S22 and S26, the thresholds measured for the lowest channels remained relatively constant despite the focusing of the electrode configuration.

Forward-masked psychophysical tuning curves

Forward-masked psychophysical tuning curves (PTCs) were measured for each subject and for the experimental electrodes identified by single-channel thresholds; those with the highest and lowest threshold and sometimes the median (denoted by the vertical dashed lines in Fig. 3). The masker stimulus was always presented with a pTP fraction of $\sigma = 0.5$ while the probe stimulus was either $\sigma = 0$ or $\sigma \geq 0.55$ as denoted in the figure legend. Figure 4 illustrates PTCs for all subjects for the lowest (left column), median (middle), and the highest (right column) pTP threshold channels (see figure legend). The data represent the masker level required to just mask the fixed-level probe stimulus (ordinate), across individual masker channels (abscissa), and the different probe configurations are indicated by the symbols. The solid gray lines indicate the range of possible stimulation levels for the masker stimulus ($\sigma = 0.5$), representing the masker-alone threshold (lower bound) and masker-alone most comfortable level (MCL) (upper bound). The bold lines represent the best-fit line of the data used to calculate the slope, yielding a metric to quantify the sharpness of the tuning curves (slope data are plotted in Fig. 6). Note that for S23 the grey symbols represent the two channels for which the masker-alone MCL was above the maximum current level possible for that subject.

The difference between threshold and MCL defines the dynamic range. In Figure 5 the data are plotted as a function of masker-alone percent dynamic range (threshold (0%) to MCL (100%)) to further characterize the shape of the PTCs and to facilitate comparisons across subjects and channels. This normalization of the data is appropriate when the masker stimulus is the same for all of the sets of data within a given subject. As in Fig. 4, the symbols indicate the probe configurations used. The width of the PTC was measured at half maximum, as indicated by the horizontal lines (width data are plotted in Figure 7). Note that for the lowest threshold channel of S23 (left), only the apical side of the tuning curve could be measured because the probe channel was the most basal channel. In this case the width was measured from the probe channel to the edge of the curve at half-maximum and then doubled. For S24, high threshold channel, $\sigma = 0$ probe (right panel) the curve did not achieve a level of half-maximum on the apical side of the curve. In that case the width is measured to the end of the electrode array and likely underestimates the width. For all other cases the curves achieved a level of half-maximum on both sides of the curve. Note that width calculations for the median channels were not included for S24 and S26 because the curves were incomplete or not obtained. Also note that for S9 highest threshold channel and S24 low and high threshold channels a secondary peak is observed. One possible explanation for the secondary tips is cross-turn stimulation. Because the secondary tips are always basal to the probe electrode, these tips could not be a result of stimulating fibers of passage from more apical parts of the cochlea.

Figure 6 summarizes the slope calculations of the tuning curves in Figure 4. The left and right columns plot the slopes for the apical and basal sides of the tuning curves, respectively. The negative apical slopes are inverted. The top and middle rows plot the slopes for the $\sigma = 0$ and $\sigma \geq 0.55$ configurations, respectively. Each subject is represented by a symbol and the fill of the symbol indicates the lowest (open), median (grey) and highest (filled) pTP threshold channel (connected by dashed lines for a given subject). The slope of the tuning curves becomes progressively shallower from the lowest to highest threshold channel for both probe configurations. That trend is more pronounced for the apical than the basal side of the tuning curve. (Spearman rank correlation coefficient for the apical slope: MP probe, $r = -0.66$, $p =$

0.013, pTP probe, $r = -0.775$, $p = 0.002$; basal slope: MP probe, $r = -0.22$, $p = 0.5$, pTP probe, $r = -0.469$, $p = 0.124$). The least-square error fits are shown by solid lines. (For the basal slopes, the line fits were performed after removing the outlying data points for subject S24. However, the correlation statistics include data from all subjects). A comparison of slopes between the two configurations is plotted in the lower row of panels with the $\sigma = 0$ data on the abscissa and $\sigma \geq 0.55$ on the ordinate. Slopes were steeper for the $\sigma \geq 0.55$ pTP condition for both the apical (Wilcoxon signed rank test, $p < 0.05$) and basal ($p < 0.01$) sides of the PTCs.

Figure 7 plots the PTC widths (left column) and depths (right column) measured for $\sigma = 0$ (top row) and for $\sigma \geq 0.55$ (middle row). The depths of the PTCs were taken as the difference between the minimum and maximum masker levels measured in dB re. 1mA. Conventions are as in Fig. 6. These results demonstrate the trend that widths measured for the highest threshold channel were wider and depths were smaller than the lowest threshold channel (Spearman rank correlation coefficient for PTC width: MP probe, $r = 0.47$, $p = 0.105$, pTP probe, $r = 0.476$, $p = 0.10$; PTC depth: MP probe, $r = -0.495$, $p = 0.072$, pTP probe, $r = -0.455$, $p = 0.102$). In addition, the widths were narrower for PTCs measured with pTP compared to $\sigma = 0$ or MP (bottom row of Fig. 7; Wilcoxon signed rank test, width, $p < 0.005$). However, no trend was observed in the depth measure of PTCs with changes in partial-tripolar fraction (depth, $p > 0.1$).

Although the correlation analysis revealed statistical significance for only a subset of the PTC metrics as a function of TP threshold (see top two rows of Figs. 6 and 7), for individual subjects the PTCs were always wider and had shallower apical slopes for the highest threshold channels (Wilcoxon signed rank test, apical slope: MP probe, $p = 0.031$, pTP probe, $p = 0.031$; width: MP probe, $p = 0.031$, pTP probe, $p = 0.09$). The basal slope was shallower for 3 out of 4 subjects and the PTC depth was shallower for 4 out of 5 subjects for the highest threshold channels (Wilcoxon signed rank test, basal slope: MP probe, $p = 0.125$, pTP probe, $p = 0.062$; depth: MP probe, $p = 0.031$, pTP probe, $p = 0.09$). If the PTC metrics and thresholds are normalized relative to the mean for each subject, reducing the across subject variability, the trends described above are more pronounced. However, the data are not normalized because the relationships with the absolute TP thresholds are more clinically relevant.

Psychophysical tuning curves with low-level probe stimuli

A second series of PTCs were obtained using a lower level probe stimulus to clarify the possible influence of probe level on tuning properties. For example, in Figures 4 and 5, some of the PTCs were shallow, which made slope, width and depth calculations difficult. This effect was likely related to the relatively high probe level of 3 dB above threshold; a high probe level requires higher masker levels. In this second experiment, we measured PTCs with a fixed probe level of 1.5 dB above threshold (or 2 dB for S9) for the lowest and highest threshold channels in four subjects. For this series the probe channel was not varied but was fixed to $\sigma = 0$. Figure 8 plots each individual subject's PTC measured with the probe fixed at 1.5 dB above threshold (indicated with filled circles) along with the previous PTC data collected with the probe fixed at 3 dB above threshold for comparison (unfilled circles). The results indicate that with a lower level probe (1.5 or 2 dB-above threshold), the tip of the tuning curve occurs lower in the dynamic range, meaning that less masker was required to just mask the probe. As for the previous set of PTCs the slopes of the apical and basal sides were calculated and are shown with bold lines (see Figure 10 for slope results).

Figure 9 represents the PTCs for lower-level probe stimuli with the data normalized to percentage of masker-alone dynamic range in decibels. In all cases but one (S23 low threshold channel) the tip of the tuning curve is lower in the dynamic range for the 1.5 dB than the 3-dB probe level. As was done previously, the width of the PTCs was calculated at half-maximum (see Figure 10).

Figure 10 shows the summary data from the second experiment. Top panels show the apical (left) and basal (right) slopes of the PTCs for the lowest and highest threshold channels for a 1.5-dB probe stimulus. The least-square error fits are shown by the solid lines. The slopes were steeper for the lowest compared to the highest threshold channel, more so for the apical side than the basal side of the PTC (Spearman rank correlation coefficient for apical slope: $r = -0.857$, $p = 0.007$; basal slope: $r = -0.714$, $p = 0.071$; width: $r = 0.643$, $p = 0.086$; depth: $r = -0.5$, $p = 0.207$). The lower panels plot the width (left) and depth (right) of the PTCs for those channels. The widths were larger for the highest threshold channel and the depths were smaller.

Discussion

To summarize, the results of the present study indicate that cochlear implant channels with high thresholds, when measured with a restricted electrode configuration, have relatively wide or tip-shifted psychophysical tuning curves (S9 and S24). This relationship between single-channel thresholds and tuning curve metrics suggests that the high thresholds observed for some channels are the result of a poor interface between those channels and nearby spiral ganglion neurons. These preliminary findings suggest that the measurement of single-channel thresholds using a restricted electrode configuration like TP or pTP could be a simple yet effective clinical tool to identify impaired electrodes.

Single-channel thresholds

This study demonstrated a systematic increase in threshold level and threshold variability with more focused stimulation (see Fig. 3), extending the previous findings of studies comparing MP and BP (Pfungst and Xu, 2004; Pfingst et al., 2004) and/or TP (Mens and Berenstein, 2005; Bierer, 2007). The authors of those studies hypothesized that the electrodes with high thresholds were likely interfacing poorly with nearby spiral ganglion neurons. A close examination of the data from the present study supports this theory. Specifically, it would be expected that electrodes having a good electrode-to-neuron interface would be relatively unaffected by pTP current fraction, because viable neurons are sufficiently close that the electrical field does not need to be broad to achieve a threshold level of activation. Indeed, for subjects S22 and S26 threshold did not change appreciably as a function of pTP fraction for the channel having the lowest TP threshold (see Fig. 3, right column). In contrast, electrodes that are not in close proximity to viable neurons would require a lot of additional current to achieve threshold (i.e. to activate more distant neurons) when using the TP configuration, because the electrical field broadens slowly with current; only a small amount of additional current would be necessary for the MP configuration to activate the same distant neurons. In the present study, at least half of the electrodes for each subject exhibited a substantial difference between TP and MP thresholds (Fig. 3, left column). In two subjects (S9 and S24), nearly all electrodes had this property. Thus, “good” electrode-neuron interfaces, based on the above description, were not prevalent in our population of cochlear implant subjects.

Psychophysical tuning curves

If a high TP threshold is indeed due to a poor electrode-neuron interface, as hypothesized above, then a psychophysical tuning curve applied to such a channel should demonstrate some deficit in spectral/spatial selectivity. Because a high-threshold probe channel would be activating spiral ganglion neurons that are displaced longitudinally along the cochlea, the best masking channels would also be displaced, leading to tip-shifted or wide tuning curves (i.e. poor selectivity). The two major findings of the present study are consistent with this proposed mechanism: 1) PTCs were wider, with shallower slopes and depths, for the highest TP threshold channels; and 2) PTCs were sharper with a TP probe configuration.

Pair wise comparisons of implant channels tested in the same subject showed that the channel with the highest TP threshold consistently exhibited poorer spatial selectivity. With the more restricted pTP probe, apical and basal slopes were generally shallower and tuning curve widths were greater for the high-threshold channel. Interestingly, these PTC properties also exhibited differences when an MP probe was used. Furthermore, when the subject data were pooled and the median-threshold channels included, apical slope was significantly and inversely correlated with TP threshold, while the other tuning curve metrics showed similar trends but were not statistically significant. Together, these results demonstrate the strong relationship between high tripolar thresholds and low spatial selectivity, implying that such channels are interfacing poorly with nearby auditory neurons. In contrast, thresholds measured with the monopolar configuration would not be predictive of spatial selectivity, because of the uniformity of MP thresholds within and across subjects.

Previous studies examining forward masked tuning properties have reported variability across subjects and, when multiple channels were tested in individual subjects, variability among channels. A recent study by Hughes and Stille (2008) compared PTCs of channels based on their apical to basal position in the cochlea. They did not find tuning properties to be affected by channel location. Our study supports this finding. Specifically, in the five subjects who participated in this study, one subject's highest threshold channel was located basally, one was apical, and three were in the middle part of the array. Thus, the source of channel-to-channel variability in tuning properties was likely not related to cochlear position. Rather, much of the variability in this and previous studies may be explained by the nature of the electrode-to-neuron interface, as assessed by TP threshold.

Another goal of the present study was to demonstrate if restricted electrode configurations produce narrower psychophysical tuning curves than the monopolar configuration, given the inconsistent findings reported by previous investigators with forward masking patterns (Shannon, 1990; Boex et al., 2003; Cohen et al., 2003; Chatterjee et al., 2006; Kwon and van den Honert, 2006) and psychophysical tuning curves (Nelson et al., 2008). A major source of variability in the previous studies may have been how the channels were selected: either one channel was chosen in the middle of the array, or several channels were chosen to be distributed along the cochlea (e.g. apical, middle, or basal). As suggested by the present results, other factors of variability among channels may have obscured a modest effect of electrode configuration on the masking patterns. In the present study, the channels were selected based on single-channel threshold patterns measured with TP. Significantly sharper tuning was observed for the pTP probe configuration, with no observable trend with the longitudinal cochlear position. On the other hand, low-threshold TP channels showed a stronger effect of configuration than high-threshold channels. Another difference is that in this study a potentially more restricted configuration, partial tripolar, was used for the probe channel. In all of the previous studies mentioned above, the masker and probe configurations were varied in tandem, making comparisons of configuration effect more tentative. Because the configuration changes in the present study were applied only to the probe stimulus (masker was fixed to $\sigma = 0.5$), the changes in tuning (i.e. wider tuning with MP than pTP) were primarily a reflection of probe configuration.

Acoustical versus electrical psychophysical tuning curves

Acoustic studies have used PTCs extensively to identify putative cochlear dead regions (e.g., Moore and Alcantara, 2001). These studies have demonstrated relatively wide tuning for areas of presumed cochlear dead regions, as well as shifts in the location of tuning curve tips away from the probe frequency. The wider tuning curves likely reflected the loss of the active mechanism normally provided by outer hair cells. A shift in tip location was interpreted as off-place activation of the nearest area of healthy inner hair cells and/or spiral ganglion neurons

(e.g., Moore and Alcantara, 2001). In the present study, we observed similar effects, with relatively wide electrical tuning curves obtained from channels having a putatively poor electrode-neuron interface as identified by high TP thresholds. In the case of cochlear implant listeners, we presume that the increase in width of tuning does not reflect a loss of outer hair cells. Rather, it's a result of the greater current spread necessary to activate the nearest viable neurons, which may be distant from the probe electrode. Not only were PTCs wider for the highest threshold channels, but shifts in tip location were observed for two of the five subjects (S9 and S24, see Figs. 4, 5, 8, and 9). Tip shifts did not occur for any subjects for their low-threshold channels.

In acoustic hearing, an increase in probe level results in wider psychophysical tuning curves because at low levels the non-linear outer hair cells dominate the cochlear response (e.g., Huss and Moore, 2003) while at higher stimulus levels passive mechanical processes dominate (Nelson and Fortune, 1991; Nelson and Donaldson, 2001). In contrast, we did not observe a consistent effect of probe level for individual channels (see Figs. 8 and 9), in support of the findings of Nelson and colleagues (Nelson et al., 2008). Therefore, the wider tuning properties for high-threshold TP channels can not be explained by the relatively high probe levels required. Additional evidence against a probe level effect is apparent from a close inspection of the MP probe data. Specifically, for S9 and S26, approximately the same MP probe level was used for the low- and high-threshold TP channels, yet the PTCs in each subject were clearly wider for the high-threshold channel.

Clinical implications

The results of the present study, along with previous studies showing substantial channel-to-channel variability in single-channel thresholds, suggest that implant channels are not equivalent in sensitivity or spectral resolution. These findings may be relevant to the existing clinical techniques used to map cochlear implant channels. For example, if an audiologist could identify channels with a poor electrode-neuron interface based on TP thresholds, he or she might consider removing those channels from the patient's speech processing strategies, even if the sound-processing strategy uses the MP configuration. On close examination of the data, plotting PTC metrics as a function of TP threshold (Figs. 6, 7, and 9), it seems that a TP threshold greater than approximately -15 dB relative to 1 mA corresponds with broad PTCs. That finding could potentially be applied clinically as a screening tool to identify electrodes with poor spatial selectivity.

Also, if a restricted configuration is preferred, the audiologist could optimize each channel for the most restricted pTP fraction that allows for reasonable thresholds and complete growth of loudness. Although recent studies have shown only modest improvements in spectral resolution and speech-in-noise tasks when using pTP stimulation strategies (Mens and Berenstein, 2005; Berenstein et al., 2008), additional improvement might have been obtained if the pTP parameters had been optimized for each channel.

In addition to these findings, the lower current level requirements with pTP compared with true TP or BP configurations reduces one of the major limitations of using focused electrode configurations in sound processing strategies. The use of the pTP configuration also reduces the previous limitation of reduced growth of loudness by allowing stimulus levels to reach MCLs within the compliance limits of the device.

Future Directions

Measuring psychophysical tuning curves in a clinical setting is not practical because of time constraints in clinical practice and possible patient fatigue. However, it might be feasible to measure TP or pTP thresholds to make mapping decisions in a clinical setting. Future

experiments will also explore the use of evoked potentials in the prediction of impaired cochlear implant channels.

Studies that examine spread of excitation patterns for individual channels (PTC shape or masking patterns) often do not relate those measures to speech perception (Chatterjee et al., 2006; Kwon and van den Honert, 2006). Those authors suggest that a relationship is unlikely because the one or two channels tested in each subject are not representative of the implant as a whole. However, a relationship between speech perception and the tuning properties of individual channels might be found if the most and least spatially selective channel of each listener could be identified. The present study suggests that single-channel TP thresholds would be an effective tool for identifying such channels. Unfortunately, speech perception was not explored in the present study, because all of the subjects had excellent speech scores that were similar to one another (see Table 1). Future studies will seek to include subjects with a range of speech perception abilities.

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References

- Berenstein CK, Mens LH, Mulder JJ, et al. Current steering and current focusing in cochlear implants: Comparison of monopolar, tripolar, and virtual channel electrode configurations. *Ear Hear* 2008;29(2):250–260. [PubMed: 18595189]
- Bierer JA. Threshold and channel interaction in cochlear implant users: Evaluation of the tripolar electrode configuration. *J Acoust Soc Am* 2007;121(3):1642–1653. [PubMed: 17407901]
- Bierer JA, Middlebrooks JC. Auditory cortical images of cochlear-implant stimuli: Dependence on electrode configuration. *J Neurophysiol* 2002;87(1):478–492. [PubMed: 11784764]
- Boex C, Kos MI, Pelizzone M. Forward masking in different cochlear implant systems. *J Acoust Soc Am* 2003;114(4 Pt 1):2058–2065. [PubMed: 14587605]
- Bonham BH, Litvak LM. Current focusing and steering: Modeling, physiology, and psychophysics. *Hear Res* 2008;242(12):141–53. [PubMed: 18501539]
- Chatterjee M, Galvin JJ 3rd, Fu QJ, et al. Effects of stimulation mode, level and location on forward-masked excitation patterns in cochlear implant patients. *J Assoc Res Otolaryngol* 2006;7(1):15–25. [PubMed: 16270234]
- Cohen LT, Richardson LM, Saunders E, et al. Spatial spread of neural excitation in cochlear implant recipients: Comparison of improved ecap method and psychophysical forward masking. *Hear Res* 2003;179(12):72–87. [PubMed: 12742240]
- de Balthasar C, Boex C, Cosendai G, et al. Channel interactions with high-rate biphasic electrical stimulation in cochlear implant subjects. *Hear Res* 2003;182(12):77–87. [PubMed: 12948604]
- Finley CC, Holden TA, Holden LK, et al. Role of electrode placement as a contributor to variability in cochlear implant outcomes. *Otol Neurotol* 2008;29(7):920–928. [PubMed: 18667935]
- Gani M, Valentini G, Sigrist A, et al. Implications of deep electrode insertion on cochlear implant fitting. *J Assoc Res Otolaryngol* 2007;8(1):69–83. [PubMed: 17216585]
- Hanekom T. Modelling encapsulation tissue around cochlear implant electrodes. *Med Biol Eng Comput* 2005;43(1):47–55. [PubMed: 15742719]

- Hinojosa R, Marion M. Histopathology of profound sensorineural deafness. *Ann N Y Acad Sci* 1983;405:459–484. [PubMed: 6575668]
- Hughes ML, Stille LJ. Psychophysical versus physiological spatial forward masking and the relation to speech perception in cochlear implants. *Ear Hear* 2008;29(3):435–452. [PubMed: 18344869]
- Huss M, Moore BC. Tone decay for hearing-impaired listeners with and without dead regions in the cochlea. *J Acoust Soc Am* 2003;114(6 Pt 1):3283–3294. [PubMed: 14714809]
- Huss M, Moore BC. Dead regions and noisiness of pure tones. *Int J Audiol* 2005a;44(10):599–611. [PubMed: 16315451]
- Huss M, Moore BC. Dead regions and pitch perception. *J Acoust Soc Am* 2005b;117(6):3841–3852. [PubMed: 16018486]
- Jolly CN, Spelman FA, Clopton BM. Quadrupolar stimulation for cochlear prostheses: Modeling and experimental data. *IEEE Trans Biomed Eng* 1996;43(8):857–865. [PubMed: 9216159]
- Kluk K, Moore BC. Detecting dead regions using psychophysical tuning curves: A comparison of simultaneous and forward masking. *Int J Audiol* 2006;45(8):463–476. [PubMed: 17005489]
- Kos MI, Boex C, Guyot JP, et al. Partial withdrawal of deeply inserted cochlear electrodes: Observations of two patients. *Eur Arch Otorhinolaryngol* 2007;264(11):1369–1372. [PubMed: 17562059]
- Kral A, Hartmann R, Mortazavi D, et al. Spatial resolution of cochlear implants: The electrical field and excitation of auditory afferents. *Hear Res* 1998;121(12):11–28. [PubMed: 9682804]
- Kwon BJ, van den Honert C. Effect of electrode configuration on psychophysical forward masking in cochlear implant listeners. *J Acoust Soc Am* 2006;119(5 Pt 1):2994–3002. [PubMed: 16708955]
- Levitt H. Transformed up-down methods in psychoacoustics. *J Acoust Soc Am* 1971;49(2):467. [PubMed: 5541744]
- Litvak LM, Spahr AJ, Emadi G. Loudness growth observed under partially tripolar stimulation: Model and data from cochlear implant listeners. *J Acoust Soc Am* 2007;122(2):967–981. [PubMed: 17672645]
- Mens LH, Berenstein CK. Speech perception with mono- and quadrupolar electrode configurations: A crossover study. *Otol Neurotol* 2005;26(5):957–964. [PubMed: 16151343]
- Moore BC, Alcantara JI. The use of psychophysical tuning curves to explore dead regions in the cochlea. *Ear Hear* 2001;22(4):268–278. [PubMed: 11527034]
- Nadol JB Jr, Shiao JY, Burgess BJ, et al. Histopathology of cochlear implants in humans. *Ann Otol Rhinol Laryngol* 2001;110(9):883–891. [PubMed: 11558767]
- Nelson DA, Donaldson GS. Psychophysical recovery from single-pulse forward masking in electric hearing. *J Acoust Soc Am* 2001;109(6):2921–2933. [PubMed: 11425134]
- Nelson DA, Donaldson GS, Kreft H. Forward-masked spatial tuning curves in cochlear implant users. *J Acoust Soc Am* 2008;123(3):1522–1543. [PubMed: 18345841]
- Nelson DA, Fortune TW. High-level psychophysical tuning curves: Simultaneous masking with different noise bandwidths. *J Speech Hear Res* 1991;34(2):374–378. [PubMed: 2046361]
- Pfingst BE, Xu L. Across-site variation in detection thresholds and maximum comfortable loudness levels for cochlear implants. *J Assoc Res Otolaryngol* 2004;5(1):11–24. [PubMed: 14605920]
- Pfingst BE, Xu L, Thompson CS. Across-site threshold variation in cochlear implants: Relation to speech recognition. *Audiol Neurotol* 2004;9(6):341–352. [PubMed: 15467287]
- Rattay F, Leao RN, Felix H. A model of the electrically excited human cochlear neuron. II. Influence of the three-dimensional cochlear structure on neural excitability. *Hear Res* 2001;153(12):64–79. [PubMed: 11223297]
- Shannon RV. Forward masking in patients with cochlear implants. *J Acoust Soc Am* 1990;88(2):741–744. [PubMed: 2212298]
- Skinner MW, Holden TA, Whiting BR, et al. In vivo estimates of the position of advanced bionics electrode arrays in the human cochlea. *Ann Otol Rhinol Laryngol Suppl* 2007;197:2–24. [PubMed: 17542465]
- Snyder RL, Bierer JA, Middlebrooks JC. Topographic spread of inferior colliculus activation in response to acoustic and intracochlear electric stimulation. *J Assoc Res Otolaryngol* 2004;5(3):305–322. [PubMed: 15492888]

- Snyder RL, Middlebrooks JC, Bonham BH. Cochlear implant electrode configuration effects on activation threshold and tonotopic selectivity. *Hear Res* 2008;235(12):23–38. [PubMed: 18037252]
- Spelman FA, Clopton BM, Pfingst BE. Tissue impedance and current flow in the implanted ear. Implications for the cochlear prosthesis. *Ann Otol Rhinol Laryngol Suppl* 1982;98:3–8. [PubMed: 6814331]
- Spelman FA, Pfingst BE, Clopton BM, et al. Effects of electrical current configuration on potential fields in the electrically stimulated cochlea: Field models and measurements. *Ann Otol Rhinol Laryngol Suppl* 1995;166:131–136. [PubMed: 7668604]
- van den Honert C, Kelsall DC. Focused intracochlear electric stimulation with phased array channels. *J Acoust Soc Am* 2007;121(6):3703–3716. [PubMed: 17552721]
- van den Honert C, Stypulkowski PH. Physiological properties of the electrically stimulated auditory nerve. II. Single fiber recordings. *Hear Res* 1984;14(3):225–243. [PubMed: 6480511]
- Wardrop P, Whinney D, Rebscher SJ, et al. A temporal bone study of insertion trauma and intracochlear position of cochlear implant electrodes. I: Comparison of nucleus banded and nucleus contour electrodes. *Hear Res* 2005a;203(12):54–67. [PubMed: 15855030]
- Wardrop P, Whinney D, Rebscher SJ, et al. A temporal bone study of insertion trauma and intracochlear position of cochlear implant electrodes. II: Comparison of spiral clarion and hifocus II electrodes. *Hear Res* 2005b;203(12):68–79. [PubMed: 15855031]

Figure 1.

Schematic of electrode configurations. The current path from active to return electrode(s) is represented by the arrows. The magnitude of current at the active electrode, $-i$, indicates that biphasic pulses were delivered cathodically first. For monopolar (top), the return current is delivered to an extracochlear return electrode located in the temporal bone, for TP (middle) the return current is equally divided and delivered to the two flanking intracochlear electrodes. For pTP (bottom), a fraction (σ) of the return current is directed to the extracochlear return electrode.

Figure 2.

Schematic of forward masking paradigm showing masker/probe amplitude (dB re. 1 mA) as a function of time (ms). The masker was a 204 ms pulse train that varied in stimulus level but was fixed with a pTP fraction of $\sigma = 0.5$. The masker pulse train preceded the 10.2 ms probe pulse train by 9.18 ms. The probe configuration was either $\sigma = 0$ or the largest sigma possible for each subject. The probe was fixed in level to 3 dB above threshold, unless otherwise specified. The masker varied in level to reach masked threshold, the amount of masking necessary to just mask the probe. The inset shows the biphasic pulses that made up both the masker and probe pulse trains. Pulses were 102 μ s/phase presented at a rate of 918 pulses per second (interpulse interval of 0.8 ms). The inset shows two biphasic pulses from the pulse train.

Figure 3.

Single-channel thresholds across subjects and configurations. In the left column, each panel plots the single-channel detection thresholds for a given subject (indicated in the top left corner). The abscissa represents cochlear implant channel from apical to basal and the ordinate represents detection threshold in decibels relative to 1 mA. Electrode configuration is indicated by symbols and for the triangles is different for each subject. The vertical dashed lines indicate the lowest, median and highest threshold channels obtained with the largest pTP fraction for each subject. In the right column, each panel plots the single-channel detection thresholds for a given subject as a function of partial tripolar fraction (σ) on the abscissa. Symbols indicate the stimulus channel based on the threshold for the largest pTP fraction possible (corresponding

to the vertical dashed lines in the left panels). The dashed lines are the least-squared error calculations for each channel.

Figure 4.

Forward-masked psychophysical tuning curves (PTCs) for all subjects plotted using the raw masker levels, which were measured as the masker level that just masked detection of the probe (ordinate in decibels (left) and mA (right)). Subject is indicated in the top of the left panels. The left, middle, and right panels are PTCs for the lowest, median and highest threshold channels, respectively (as indicated in Fig. 3). The shaded grey lines represent masker-alone threshold and most comfortable level. Symbols indicate the probe configuration and vertical dashed lines indicate the probe channel. The bold lines indicate the slope of the best fit line from the estimated tip of the PTC to the point where the data crosses 80% of the masker-alone dynamic range. The lines were extended for ease of viewing.

Figure 5.

Forward-masked psychophysical tuning curves (PTCs) for all subjects plotted using the masker levels relative to the percentage of masker-alone dynamic range in dB (masker-alone MCL – masker-alone threshold) (ordinate). Conventions are as in Fig. 4. Each row plots PTCs for a given subject, indicated in the top of the left panels. The left and right panels represent low- and high-threshold probe channels, respectively. The width was measured at half-maximum indicated by the horizontal line.

Figure 6.

Summary of PTC slope calculations. Symbols represent subject number and fill represents threshold (open = lowest, gray = median, and black = highest). Data from a given subject are connected by a dashed line. The negative apical slopes are inverted. Top row plots the slope of the $\sigma = 0$ PTCs in dB/mm (ordinate) as a function of pTP threshold for the apical (left) and basal (right) sides of the curves. The least-square error best fit line is shown in bold. Middle row plots the slope of the $\sigma \geq 0.55$ PTCs. Conventions are as in the top row. Lower row plots PTC slopes for $\sigma = 0$ (abscissa) versus $\sigma \geq 0.55$ probe (ordinate) for the apical (left) and basal (right) sides of the curves.

Figure 7.

Summary of PTC width and depth calculations. Symbols represent subject number and fill represents threshold (open = lowest, gray = median, and black = highest). Data from a given subject are connected by a dashed line. The left column plots PTC width in mm and the right column is PTC depth in dB. Top row plots widths and depths of the $\sigma = 0$ PTCs as a function of pTP threshold. The least-square error best fit line is shown in bold. Middle row plots the widths and depths of the $\sigma \geq 0.55$ PTCs. Conventions are as in the top row. Lower row plots PTC widths and depths for $\sigma = 0$ (abscissa) versus $\sigma \geq 0.55$ probe (ordinate).

Figure 8.

Lower probe level PTCs using raw masker level in dB re. 1 mA. Conventions are as in Fig. 4. Each row plots PTCs for a given subject, indicated in the top of the left panels. The left and right panels plot low- and high-threshold probe channels, respectively. The fill of the symbol represents the probe level, either filled (1.5 or 2 dB above threshold) or open (3 dB above threshold).

Figure 9.

Lower probe level PTCs using percentage of masker-alone dynamic range in dB. Conventions are as in Fig. 5. Each row plots PTCs for a given subject, indicated in the top of the left panels. The left and right panels represent low- and high-threshold probe channels, respectively. The fill of the symbol represents the probe level, either filled (1.5 or 2 dB above threshold) or open (3 dB above threshold).

Figure 10.

Summary of lower probe level PTC slopes, widths and depths calculations. Data from a given subject are connected by a dashed line. Top row plots the apical (left) and basal (right) PTC slopes in dB/mm as a function of pTP threshold (abscissa). Note that the negative apical slopes are inverted. The lower row plots the PTC width (left) and the PTC depth (right) as a function of pTP threshold (abscissa). The bold lines indicate the least-square error best fit to the data.

Table 1

Subject Information

Subject Number	Sex	Age (years)	Duration of Severe Hearing Loss (years)	Duration of CI Use	Etiology of Hearing Loss	HINT Sentences in Quiet	CNC Words in Quiet	CNC Phonemes in Quiet
S9	F	64	24	3 years	Hereditary	99%	48%	75%
S22	F	67	12	9 months	Hereditary	92%	68%	76%
S23	M	62	19	1.5 years	Noise Exposure	94%	68%	85%
S24	F	74	2	1 year	Unknown	100%	54%	73%
S26	F	30	2	1.8 years	Atypical Menieres Disease	99%	56%	78%

CNC = Consonant Nucleus Consonant test from the Minimum Speech Test Battery for Adult Cochlear Implant Users, House Ear Institute and Cochlear Corporation, 1996

Table 2

Channel-to-channel variability (dB) based on the difference in standard deviation of thresholds (top) and the mean thresholds (bottom).

Subject	$\sigma = 0$	$\sigma = 0.5$	$\sigma = 0.9$ or $\sigma = 1.0$
S9 (standard deviation) S9 (mean)	1.0286	0.9495	2.6670
	0.8191	0.7119	2.0124
S22 (standard deviation) S22 (mean)	1.3099	2.9038	3.7743
	1.1291	2.2681	3.2159
S23 (standard deviation) S23 (mean)	2.3073	2.0740	3.6723
	1.8604	1.4813	2.6450
S24 (standard deviation) S24 (mean)	0.7814	1.5513	3.4750
	0.6260	1.0837	2.4756
S26 (standard deviation) S26 (mean)	1.0656	1.8880	3.3835
	0.8902	1.3836	2.8406

Table 3

Slope of the threshold versus fraction functions (dB/fraction) across subjects

Subject number	Lowest threshold channel	Median threshold channel	Highest threshold channel
S9	9.39	16.89	18.39
S22	1.16	4.40	18.56
S23	9.86	9.40	15.27
S24	8.94	14.90	21.15
S25	1.45	5.75	15.96