Published in final edited form as:

Ear Hear. 2010 October ; 31(5): 679–692. doi:10.1097/AUD.0b013e3181e1d19e.

Effect of stimulus and recording parameters on spatial spread of excitation and masking patterns obtained with the electrically evoked compound action potential in cochlear implants

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Abstract

Objectives—Spread of excitation within the cochlea in response to electrical stimulation can be measured with the electrically evoked compound action potential (ECAP). Different spread-of-excitation measurement techniques have been reported in the literature. One method uses a fixed stimulus location while varying the recording electrode along the length of the implanted array. This results in a relatively coarse estimate of spatial spread (SS) along the cochlea. Another method uses a forward-masking paradigm to evaluate the relative overlap of stimulated neural populations between electrodes. Both the probe and recording electrodes are fixed in location while a masker stimulus is systematically applied across electrodes. This method, which yields a more precise estimate of spatial excitation patterns, is termed spatial masking (SM). Five experiments were conducted to examine potential effects of stimulus and/or recording parameters on SS and SM patterns. Experiment 1 examined whether SS patterns were systematically broader than SM patterns across electrodes and subjects. Experiments 2 and 3 evaluated the effects of stimulus level on SS and SM patterns, respectively, to determine whether increased stimulus level systematically resulted in broader patterns. Experiment 4 evaluated whether recording electrode location affected SM patterns, and Experiment 5 evaluated whether SM patterns varied significantly across repeated trials within a test session.

Design—Data were collected for 27 ears in 26 adult and teenage subjects [N=6 ears with Advanced Bionics CII, N=8 ears with Advanced Bionics HiRes 90K, N=10 ears with Nucleus 24R(CS), N=3 ears with Nucleus 24RE(CA) Freedom]. A standard forward-masking subtraction paradigm was used for all ECAP measures. For SS patterns, the masker and probe were fixed on the same electrode at the same level while the recording electrode varied across the remaining electrodes in the array. For SM patterns, the probe and recording locations were fixed while the masker location varied across all electrodes except the recording electrode.

Results—In Experiment 1, SS patterns were broader than SM patterns. Subjects with Advanced Bionics devices exhibited relatively broad patterns for both measures, whereas Nucleus subjects typically exhibited narrower SM functions relative to SS functions. In Experiments 2 and 3, there was a significant effect of stimulus level on the spread of both SS and SM patterns in roughly one-third of measures in each experiment. In Experiment 4, there was a significant effect of recording electrode location on the width/ spread of SM patterns for only 11.5% of comparisons. In Experiment

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5, there were no significant differences in SM amplitudes across repeated trials for 94% of comparisons, which suggests that ECAP measures are highly robust within a test session.

Conclusions—Results showed that SS functions were generally broader than SM functions, which suggests that SS measures reflect volume conduction of the ECAP response along the length of the cochlea. Differences in the spread of SM functions across devices are likely due to differences in modiolar proximity between the respective electrode array designs. Stimulus level had a more significant effect on the spread of SM functions than recording electrode location. Finally, ECAP measures were shown to be highly stable across repeated measurements within a test session; however, repeatability was not assessed across sessions or over extended time intervals.

Keywords

cochlear implant; electrically evoked compound action potential; spread of excitation; spatial masking

INTRODUCTION

Spread of neural excitation within the cochlea can be measured with the electrically evoked compound action potential (ECAP) in cochlear-implant (CI) recipients using a forward-masking paradigm (e.g., Cohen et al., 2003; Abbas et al., 2004; Hughes & Abbas, 2006a). Several recent studies have attempted to relate ECAP patterns to various psychophysical measures to evaluate the use of the ECAP as a potential predictor of perceptual outcomes for CI users, such as psychophysical forward masking or electrode pitch ranking (Cohen et al., 2003; Cohen et al., 2004; Hughes & Abbas, 2006a; Hughes, 2008; Hughes & Stille, 2008). One difficulty when comparing ECAP and psychophysical measures is that different stimuli are typically used to elicit each measure. Single pulses are used to generate ECAP excitation patterns, whereas pulse trains are commonly used for psychophysical forward masking (e.g., Cohen et al., 2003; Cohen et al., 2004; Hughes & Stille, 2008) or pitch ranking (e.g., Hughes & Abbas, 2006a; Hughes, 2008). Therefore, the current levels used to elicit ECAP and psychophysical measures are likely to be different, due to the differences in temporal integration and loudness percepts between the two types of stimuli. Further, ECAPs are recorded from an intracochlear electrode that is usually located near the stimulating electrode. Previous studies have shown that location of the recording electrode affects the measured ECAP amplitude (Abbas et al., 1999; Frijns et al., 2002; Cohen et al., 2004), whereas psychophysical measures are not confounded by this issue. Therefore, it is important to understand how stimulation and recording parameters affect the robustness of ECAP patterns, particularly if ECAP measures are to be related to perceptual measures. The present study therefore evaluated the relative effects of stimulus level and recording location on ECAP spatial spread and spatial masking patterns to determine how these variables might influence comparisons with psychophysical measures for CI users.

Stimulus and recording parameters can be manipulated to generate different types of ECAP spatial excitation or masking patterns in the cochlea. One method is to fix the location of the stimulus and systematically vary the location of the recording electrode. This method results in a coarse measure of spatial spread of excitation, which likely reflects volume conduction of the voltage associated with neural discharge in the vicinity of the stimulated electrode (i.e., the voltage from the ECAP response is conducted along the length of the cochlea; Abbas et al., 2004; Cohen et al., 2004). The largest ECAP amplitudes are typically obtained for recording electrodes near the stimulating electrode, with a gradual reduction in amplitude as the recording electrode location is moved away from the stimulus site (Abbas et al., 1999; Frijns et al., 2002; Havens et al., 2003; Cohen et al., 2004). In some cases, excessive stimulus artifact can preclude ECAP measurement if the recording electrode is too close (or adjacent) to the

stimulating electrode (Abbas et al., 1999; Frijns et al., 2002). Abbas et al. (1999) reported similar ECAP amplitudes in Nucleus 24M recipients for recordings made equidistant from the stimulating electrode in either a basal or apical direction. In contrast, Frijns et al. (2002) reported larger ECAP responses when the recording electrode was apical to the stimulating electrode in Advanced Bionics CII recipients. They attributed this result to the tapered cross-sectional area of the cochlea toward the apex, which positions apical electrodes closer to the modiolus. Commercial software default settings for the ECAP recording electrode are typically two positions apical to the stimulating electrode. Based on Frijns et al. (2002), this should ideally result in the largest ECAP recordings.

A second, more precise method to evaluate ECAP spatial excitation patterns uses a forward-masking subtraction paradigm, in which a probe pulse is delivered to a fixed electrode and a masker is systematically varied across the remaining electrodes in the array (Cohen et al., 2003; Abbas et al., 2004; Eisen & Franck, 2005; Hughes & Abbas, 2006a; Hughes & Stille, 2008). These measures use a fixed recording electrode location, typically two electrode positions apical to the probe. The change in ECAP amplitude as a function of masker location reflects the relative overlap of neural populations recruited by the masker and probe. In the subtracted trace, the largest ECAP amplitude usually occurs when the masker and probe are on the same electrode (i.e., greatest overlap), with decreasing amplitude as the masker is moved farther from the probe. Amplitudes of zero represent no measurable overlap, and thus no interaction between masker and probe stimuli.

In the literature, both of the ECAP measures described above have been referred to as spatial spread of excitation. In this paper, the first method (varied location of recording electrode) will be referred to as spatial spread (SS) and the second method (varied location of the masker electrode) will be referred to as spatial masking (SM). When the two methods have been compared, SS patterns tend to be broader than SM patterns (Abbas et al., 2003; Cohen et al., 2004). SM patterns have also been shown to more closely approximate psychophysical forward-masking patterns (Cohen et al., 2003, 2004; Hughes & Stille, 2008).

The effect of stimulus level on SS and SM patterns has been evaluated for relatively small groups of CI subjects, with mixed results. Havens et al. (2003) reported similar shapes of SS patterns for high, medium, and low stimulus levels in an unreported number of subjects with the Clarion CII device. In contrast, Cohen et al. (2004) reported significant effects of current level for 6 of 12 electrodes in four Nucleus 24M subjects. Details were reported for only one subject, who generally had broader patterns for higher stimulus levels. For SM patterns, Abbas et al. (2004; Nucleus 24M subjects) and Eisen and Franck (2005; Advanced Bionics CII and Nucleus 24 devices) showed broader patterns for higher levels. In contrast, Cohen et al. (2004) reported no significant effect of level on the width of the SM function at 50% of the peak amplitude for two different levels (80% and 50% of the loudness at most-comfortable level) for Nucleus 24M subjects.

In the present study, five experiments examined effects of stimulus and recording parameters on SS and SM patterns in a relatively large group of CI recipients. Experiment 1 compared SS and SM patterns to determine whether SS patterns were systematically broader than SM patterns across electrodes and subjects. In Experiments 2 (SS) and 3 (SM), the effect of stimulus level was evaluated to determine whether increased level systematically resulted in broader patterns. In Experiment 4, the effect of recording electrode location on SM patterns was evaluated. Finally, Experiment 5 evaluated whether or not there was significant amplitude variation of SM patterns over repeated trials within a session. Results from these experiments will assist with interpretation of results and help optimize future experimental design for studies that compare ECAP SS or SM patterns to psychophysical measures. It is important to understand the effects of stimulus and recording parameters on these types of ECAP measures

because the stimuli and method of measurement are typically different from those used for psychophysical measures.

MATERIALS AND METHODS

Subjects

Data were collected for 27 ears in 26 subjects: N=6 ears with Advanced Bionics CII, N=8 ears with Advanced Bionics HiRes 90K (Advanced Bionics Corp., Sylmar, CA); N=10 ears with Nucleus 24R(CS), N=3 ears with Nucleus 24RE(CA) Freedom (Cochlear Ltd., Lane Cove, Australia). Data were collected for both ears in one subject who was bilaterally implanted, designated in Table 1 as R3 and F1. Two additional Nucleus subjects had bilateral CIs (R6 and F4, designated in Table 1 with asterisks); however, only the ears listed were tested for this study. Twenty-three subjects were adults and three were teenagers. Age at implant ranged from 6.3 to 77.3 years (mean: 46.4 years). Duration of implant use at the time of participation ranged from 0.4 to 12.4 years (mean: 3.1 years). Duration of deafness prior to implantation ranged from 0.2 to 50 years (mean: 14.2 years). Additional demographic information is listed in Table 1. Although speech perception was not assessed as part of this study, open-set word scores were available for 16 of the present subjects who had simultaneously participated in another study in our laboratory (Hughes & Stille, 2008). Performance for those subjects ranged from 5% to 83% on the Consonant-Nucleus-Consonant monosyllabic word test (Peterson & Lehiste, 1962), which indicates that the performance levels for subjects participating in this study are representative of the general CI population.

Electrode impedances were measured for all subjects prior to data collection. The normal impedance range (monopolar) is 1–30 kohms for the Advanced Bionics devices, and 1.5–30 kohms for Nucleus Contour devices. All electrodes were functioning within normal limits, with the exception of open circuits for the following subjects: C15 on electrode 16; R1 on electrodes 10, 13, 15, 17, and 20; and F2 on electrode 8. Electrodes with open circuits were not used for stimulation or recording in this study. Table 1 lists experiments in which each subject participated. Not all subjects participated in all experiments due to various reasons (i.e., time constraints, moved away prior to study completion, small-magnitude ECAPs that precluded participation in the experiments that required data collection with various stimulus levels). Minimal inclusion criteria for participation in this study were that subjects had to have measurable ECAP responses at or near their maximum loudness comfort level. ECAP amplitudes at these levels ranged from approximately 50–1100 μ V across subjects, demonstrating large variability in nerve survival and/or electrode proximity to surviving auditory neurons. Approval for this study was obtained from the Boys Town National Research Hospital's Institutional Review Board (protocol 03-07XP).

Equipment Setup

For subjects with Nucleus devices, ECAPs were obtained using the Nucleus NRT [v. 3.0; for 24R(CS) devices] or Custom Sound EP [for 24RE(CA) Freedom devices] commercial software (Cochlear Ltd., Lane Cove, Australia). For subjects with Advanced Bionics devices, ECAPs were obtained using the Bionic Ear Data Collection System (BEDCS, v. 1.16.191), which is an experimental research platform (Advanced Bionics Corp., Sylmar, CA). All subjects were tested with a laboratory speech processor and headset. For subjects with the Nucleus 24R(CS), a SPrint body-worn processor was interfaced with either the Portable Programming System or the Processor Control Interface. For subjects with the Nucleus 24RE(CA), a Freedom processor was interfaced with the programming Pod. For subjects with Advanced Bionics devices, a Platinum Series Processor was interfaced with a Clinical Programming Interface (CPI II).

Stimuli and Procedure

Masker and probe stimuli each consisted of a single cathodic-leading biphasic current pulse that was either 25 or 50 μsec /phase with an inter-phase gap of 8 μsec (Nucleus) or 10 μsec (Advanced Bionics). For the initial subjects (C2 and R3), 25- μsec /phase pulses were used. Default pulse width was subsequently changed to 50- μsec /phase to allow adequate headroom for current amplitude increases while avoiding voltage compliance limits. The same pulse width was used across a parameter change within a subject. For Nucleus subjects, the following default parameters were used: 80-Hz stimulation rate, monopolar stimulation relative to the extracochlear ball electrode (MP1) and recording relative to the extracochlear case electrode (MP2), 60-dB gain (50 dB for Freedom), and 500- μsec masker-probe interval (400- μsec for Freedom). The number of averages varied from 50–200, depending on the overall signal-to-noise ratio of the ECAP waveforms. For Advanced Bionics subjects, the following parameters were used: 20-Hz stimulation rate, monopolar stimulation (re: reference electrode on the implant case), monopolar recording (re: implant case electrode for CII subjects or extracochlear ring electrode for 90K subjects), and 500- μsec masker-probe interval. The number of averages varied from 60–100, depending on the overall signal-to-noise ratio of the ECAP waveforms.

ECAPs were obtained using a standard forward-masking subtraction paradigm described in detail elsewhere (e.g., Cohen et al., 2003; Abbas et al., 2004; Hughes & Abbas, 2006a). Figure 1 illustrates the stimulus and recording configurations for the SS (Fig. 1A) and SM (Fig. 1B) patterns. For SS patterns, the stimulating electrode and current level were fixed for the masker and probe (equal level for both pulses), while the recording electrode varied systematically across all remaining electrodes. For SM patterns, the probe was fixed in level and location, the recording electrode was fixed in location (typically two electrode positions apical to the stimulated electrode), and the masker electrode and level varied systematically across all electrodes except the recording electrode.

Stimulus levels were determined based on the behavioral dynamic range of the stimulus used to elicit the ECAP. With both BEDCS and NRT, ten sweeps of the four-part ECAP stimulus set (i.e., probe alone, masker plus probe, masker alone, system signature; see Abbas et al., 2004) were delivered in an ascending manner. Step size for Nucleus subjects was typically 5 CL (current-level units, which represent a log-based current scale; see Kwon & van den Honert, 2006). Step size for Advanced Bionics subjects varied individually, also using a similar log-based step size (see Hughes & Stille, 2009). For this procedure, participants were asked to indicate when they first heard the sound (T) and when the sound was loud but not uncomfortable (C). Behavioral dynamic range was calculated as the difference between these two levels (C – T). Presentation levels for ECAP measures varied according to specific experiments, as described further in the Results. For experiments in which stimulus level was not a varied parameter, however, masker and probe were typically presented at 80% of the behavioral dynamic range for that electrode, calculated as:

$$(C - T) * 0.8 + T \quad (1)$$

Masker and probe levels were always equal when delivered to the same electrode. When the masker was delivered to an electrode other than the probe, current level was a consistent portion of the behavioral dynamic range for that electrode, calculated as for the probe level (e.g., 70%, 80%, or 90% of the behavioral dynamic range for that electrode).

For all but Experiment 5, data were collected for three probe electrodes per subject, representing basal, middle, and apical locations. Basal-to-apical electrode numbering is 1–22 for Nucleus and 16–1 for Advanced Bionics devices. For Nucleus subjects, probe electrodes were typically 7, 11, and 16. For Advanced Bionics subjects, probe electrodes were typically 12, 9, and 5.

The extreme ends of the array were not used for probe electrodes so that trends could be observed on either side of the probe.

Data Analysis

ECAP data were read into a custom analysis program written in Matlab (Mathworks Inc., Natick, MA). The standard subtraction procedure was applied: probe-alone trace minus the masker-plus-probe trace plus the masker-alone trace minus the system signature (e.g., Abbas et al., 2004). Peak-to-peak amplitudes were measured from the negative trough (N1) to the following positive peak/plateau (P2). For SS patterns, ECAP amplitudes were plotted as a function of recording electrode location. For SM patterns, ECAP amplitudes were plotted as a function of masker electrode location. Data from Advanced Bionics subjects are reported in millivolts (mV), whereas data from Nucleus subjects are reported in microvolts (μ V), because those are the units provided by the respective software. In figures with electrode number on the abscissa, electrodes are numbered from base (left) to apex (right). Following each manufacturer's numbering convention, electrode 1 is most basal in Nucleus devices whereas electrode 16 is most basal in the Advanced Bionics devices. Statistical analyses were performed with SigmaPlot 8.0 (SPSS Inc., Chicago, IL), SigmaStat 3.0 (SPSS Inc., Chicago, IL), and JMP 8.0 (SAS Institute Inc., Cary, NC).

RESULTS

Experiment 1: SS versus SM patterns

The goal of Experiment 1 was to determine whether ECAP SS patterns were significantly broader than SM patterns. Comparisons were made for a basal, middle, and apical probe electrode in each of 25 subjects ($N = 12$ Advanced Bionics, $N = 13$ Nucleus; see Table 1), with the exception of the middle electrode for R6 and the apical electrode for R5¹. The same probe level was used for both functions within a subject. For SM patterns, the masker level was the same percentage of the behavioral dynamic range as the probe. For each set of functions, a two-tailed t test was performed to determine whether the mean of the SS function was significantly greater than the mean of the SM function². This method was used instead of comparing the widths of the two functions at a specified normalized amplitude (as in Cohen et al., 2003; Hughes & Abbas, 2006a, 2006b) because (1) the functions were not normalized and (2) it is possible for two functions to have similar widths at a single specified point on the function (e.g., 75% of the maximum amplitude), but have significantly different shapes overall (see Fig. 7 in Hughes & Abbas, 2006a). Further, Bonferroni corrections were not applied due to the increased risk of a Type II error for the number of comparisons made here (Benjamini & Hochberg, 1995, as cited in Donaldson et al., 2009).

Figure 2 illustrates six representative examples for basal, middle, and apical probe electrodes (across columns) for Advanced Bionics and Nucleus recipients (top and bottom rows, respectively). Subject number and probe electrode (P) are indicated in each panel. SS patterns (open circles) typically produced broader patterns than SM patterns (filled circles). Subjects with Advanced Bionics devices exhibited relatively broad patterns for both measures, whereas Nucleus subjects typically exhibited narrower SM than SS functions. Asterisks next to the probe electrode numbers in Fig. 2 represent statistically significant differences ($p < 0.05$). Only two subjects (C12 and R5) showed no significant differences between SM and SS functions for all three electrode regions tested. The remaining 23 subjects exhibited significant

¹For R6, different stimulus levels were used for SS and SM patterns for the middle electrode, so they could not be compared. R5 had no measurable ECAP response for the apical electrode.

²Paired t tests could not be used because the data could not be paired (note different x-axis labels for each of the two functions in Figs. 2 and 3).

differences for one or more electrode regions tested. Overall, significant differences were observed for 47 of the 73 (64%) comparisons across the 25 subjects. For basal electrodes, 76% (19 of 25) of the comparisons were significant; for middle electrodes, 54% (13 of 24) were significant; and for apical electrodes, 63% (15 of 24) were significant. The majority of significant differences occurred for Nucleus subjects: 81% (30 of 37 electrodes), compared with 47% (17 of 36) for Advanced Bionics subjects.

To obtain a more general comparison between SM and SS functions, ECAP amplitudes were normalized within each subject and then averaged across subjects. Figure 3 shows average normalized SM (filled circles) and SS (open circles) functions for the three probe electrode locations. The top and bottom rows show data for Advanced Bionics (ABC) and Nucleus (NUC) subjects, respectively. Probe electrode and the number of subjects included in the calculation for each function are indicated on each graph. When the number of subjects differed for SM and SS functions within a panel, values for SM are listed first.

For each subject, SM patterns were normalized to the amplitude obtained with the masker and probe on the same electrode, because this is the condition in which the maximum ECAP amplitude is expected. SS patterns were normalized to the amplitude obtained when recording from the electrode two positions apical to the probe, which is the default recording location. Thus, the normalization point for both SM and SS functions was typically the condition in which masker and probe were on the same electrode, measured two positions apically³. The two normalization points represent the same stimulus and recording configuration; however, they do not align vertically in Fig. 3 because the abscissa labels differ for SM (masker electrode) and SS (recording electrode) functions. In several cases (particularly for Nucleus subjects), excessive artifact precluded SS measurements from the default location; therefore, those data could not be normalized or included in the group analysis.

For each device type, a two-way analysis of variance (ANOVA) was used to examine the effects of probe electrode and measure on the mean normalized ECAP amplitude across each function. For Nucleus subjects, SS functions were significantly broader than SM functions for all three electrode regions ($p < 0.001$). For Advanced Bionics subjects, SS patterns were significantly broader for basal ($p = 0.002$) and middle ($p = 0.017$) probe electrodes, but not for apical probes ($p = 0.12$). For both device types, there was no significant interaction between probe electrode and measure, and no significant differences across probe electrodes for either SM or SS measures. To further compare the breadth of SM and SS functions, standard deviations were computed for amplitude histograms generated for each of the 12 functions in Fig. 3. A linear regression revealed significantly larger standard deviations for SM functions than for SS functions ($f(1,10) = 41.68$, $p < 0.0001$). With this metric, sharper functions (i.e., SM) yield larger standard deviations because the range of amplitudes across electrodes is larger. In summary, SS patterns were, overall, broader than SM patterns.

Experiment 2: Effect of level on SS patterns

The goal of Experiment 2 was to determine whether relative stimulus level affects the overall width or spread of SS patterns. Within subjects, SS patterns were compared across several stimulus levels in the upper portion of the behavioral dynamic range (e.g., 70%, 80%, and 90%). Relatively high levels were chosen because ECAP thresholds tend to be higher than behavioral thresholds obtained with the same stimulus (Potts et al., 2007). Further, because SS patterns are supra-threshold measures, it is typically necessary to use levels in the upper portion of the behavioral dynamic range to obtain measurable ECAPs. Behavioral dynamic ranges for

³On an individual basis, however, SM functions could not always be recorded from the default position of two electrodes apical to the probe. In those cases, the recording position was adjusted until a measurable ECAP could be obtained.

the ECAP stimulus (averaged across electrodes within each subject) ranged from 203 μA (C6) to 1030 μA (C14) in Advanced Bionics subjects and from 35 CL (R11) to 93 CL (R7) in Nucleus subjects. Three Advanced Bionics subjects (C1, C6, and C15) had relatively small behavioral dynamic ranges (under 300 μA) compared to the rest of the group, and four Nucleus subjects (R3, R5, R11, and F1) had relatively small dynamic ranges (under 40 CL).

Data were obtained for a basal, middle, and apical probe electrode in each of 18 subjects ($N = 9$ Advanced Bionics, $N = 9$ Nucleus; see Table 1), with the exception of the basal electrode for C6 and the middle and apical electrodes for R11 (no measurable ECAP at the highest level). For most subjects, SS patterns were obtained for masker/probe levels fixed at 70%, 80%, and 90% of the behavioral dynamic range⁴. For each SS function, masker and probe were delivered to the same electrode at equal current levels. To evaluate relative amplitude differences across levels, each SS pattern was normalized to the amplitude obtained for the recording electrode that was used for the SM patterns (typically two electrodes apical to the stimulus electrode). A one-way repeated-measures (RM) ANOVA was used to determine whether statistical differences ($p < 0.05$) existed across levels, followed by pairwise multiple comparison procedures (Tukey tests) to identify statistically significant pairs. Paired t-tests were used when only two levels were compared.

Figure 4 shows individual examples of normalized SS functions for basal, middle, and apical probe electrodes, using the same format as Figure 2. The arrow in each panel indicates the electrode to which the masker/probe stimulus was applied. Asterisks indicate a statistically significant difference for one or more comparisons within the set. Overall, only one subject (R6) showed no significant effect of level across all three electrode regions tested. The remaining 17 subjects showed significant differences within one or more electrode regions tested. Significant differences were observed for 64 of the 166 (39%) comparisons across the 18 subjects. For basal electrodes, 40% (21 of 52) of the comparisons were significant; for middle electrodes, 45% (25 of 56) were significant; and for apical electrodes, 31% (18 of 58) were significant. The occurrence of significant differences was similar for both devices: 38% (35 of 93) of comparisons for Advanced Bionics subjects, compared with 40% (29 of 73) for Nucleus subjects.

Experiment 3: Effect of level on SM patterns

This experiment determined whether relative stimulus level affected the shape or breadth of SM patterns. First, SM patterns were compared across several levels in the upper portion of the behavioral dynamic range, similar to Experiment 2 for SS patterns. Data were obtained for a basal, middle, and apical probe electrode in 18 subjects ($N = 9$ Advanced Bionics, $N = 9$ Nucleus; see Table 1, Experiment 3A), with the exception of the basal electrode for C6 (no measurable ECAP response). For most subjects, SM patterns were obtained for masker levels at 70%, 80%, and 90% of the behavioral dynamic range⁵. To evaluate relative amplitude differences across levels, each SM pattern was normalized to the amplitude obtained with masker and probe on the same electrode. A one-way RM ANOVA determined statistical differences ($p < 0.05$) across levels. Pairwise multiple comparisons (either Tukey or Holm-Sidak) identified statistically significant pairs.

Figure 5 shows individual examples of normalized ECAP SM functions for basal, middle, and apical probe electrodes, using the same format as Fig. 4. Masker/probe levels are indicated in each panel. Arrows indicate the fixed probe electrode location. Asterisks indicate a statistically

⁴For subject R12 levels were 80%, 90%, and 100% because no response could be obtained at 70%. R2 data were not collected for 70%. For five subjects (C4, C10, R3, R4, R11), masker levels were 80% plus or minus a fixed current level (e.g., $80\% \pm 5$ CL).

⁵For subject R12, levels were 80%, 90%, and 100% due to lack of response at 70%. For subjects C4, C10, R3, R4, R6, and R11, masker levels were 80% plus or minus a fixed current level (e.g., $80\% \pm 5$ CL).

significant difference for one or more comparisons within the set. In many cases, SM patterns had larger normalized amplitudes and thus broader patterns for higher levels, compared to lower levels (e.g., C4, probe 12). Some subjects, however, showed no difference in SM patterns across levels (e.g., C12, probe 9). Overall, only one subject (C1) showed no significant effect of level across all three electrode regions tested. The remaining 17 subjects showed significant differences within one or more electrode regions tested. Across electrodes and subjects, significant level effects were observed for 59 of 172 comparisons (34%). For basal electrodes, 37% (19 of 51) of comparisons were significant; for middle electrodes, 32% (18 of 57) were significant; and for apical electrodes, 34% (22 of 64) were significant. The number of significantly different comparisons was similar for both devices: 33% (28 of 86) for Advanced Bionics, compared with 36% (31 of 86) for Nucleus subjects.

In the second portion of this experiment, SM patterns for masker levels at a fixed percentage of the dynamic range (e.g., 80%) were compared with SM patterns for masker levels relative to ECAP threshold for each masker electrode. Because ECAP thresholds do not always fall within a consistent percentage of the behavioral dynamic range, the shape or spread of SM patterns may be affected by these relative level differences. Data were obtained from a basal, middle, and apical probe electrode in eight subjects (N = 4 Advanced Bionics, N = 4 Nucleus; see Table 1, Experiment 3B). An individual example is shown in Fig. 6. Figure 6A depicts the behavioral dynamic range for subject R2, probe electrode 7, obtained with the stimulus used to elicit the ECAP (thick solid lines indicate T and C levels). ECAP thresholds (squares) fall in the middle portion of the behavioral dynamic range for basal masker electrodes, at roughly one-third of the dynamic range for middle electrodes, and just above T for apical electrodes 21 and 22. The filled and open circles in Fig. 6A indicate the masker levels used to obtain the two corresponding SM patterns in Fig. 6B. Filled circles represent masker levels at 80% of the behavioral dynamic range for each masker electrode, which was the standard method used for most SM patterns reported in this study. Open circles represent masker levels calculated relative to ECAP threshold using the following three formulas to determine stimulus levels for each masker electrode ($M_{ECAP\Theta}$). First, it was necessary to determine the percentage (n ; expressed as a decimal) of the dynamic range between ECAP threshold and C for the probe electrode ($C_p - ECAP\Theta_p$) that yielded the same current level that was calculated as 80% of the behavioral dynamic range for the probe electrode ($P_{80\%}$), or

$$(C_p - ECAP\Theta_p) * n + ECAP\Theta_p = P_{80\%} \quad (2)$$

Solving for n yields:

$$n = (P_{80\%} - ECAP\Theta_p) / (C_p - ECAP\Theta_p) \quad (3)$$

This method ensures that the level on the probe electrode is the same for both the “80 % behavioral dynamic range” and the “re: ECAP threshold” conditions. Finally, n percent of the dynamic range between ECAP threshold and C for each masker ($C_M - ECAP\Theta_M$) was calculated to determine the level for each masker electrode ($M_{ECAP\Theta}$):

$$M_{ECAP\Theta} = (C_M - ECAP\Theta_M) * n + ECAP\Theta_M \quad (4)$$

Figure 6B shows the difference between the raw amplitudes for SM patterns obtained with maskers at a consistent percentage of the behavioral dynamic range (80%) versus at a consistent percentage of the range between ECAP threshold and behavioral C levels for subject R2. These two functions were significantly different ($p = 0.035$, paired t test). As shown in Fig. 6A, masker

levels for the two methods differed most between E10-E15 and E21-E22, with higher levels for the “80% behavioral dynamic range” condition. As a result, the corresponding SM pattern (filled circles) exhibited higher ECAP amplitudes for most of those same electrodes.

Figure 7 shows representative examples of normalized SM functions for six of the 24 electrodes tested in eight subjects. Arrows indicate the fixed probe electrode. Masker levels for the “fixed % dynamic range” condition were 80%, except for C6 and C13, who required levels at 90% for measurable ECAPs. Each SM pattern was normalized to the amplitude obtained with the masker and probe on the same electrode to compensate for minor amplitude changes associated with test-retest variability (examined further in Experiment 5) for the masker-equals-probe-electrode condition. In other words, when the masker and probe were delivered to the same electrode, the current level was the same for both functions and therefore the ECAP amplitudes should have been the same. The normalization referenced both functions at the same point (i.e., probe electrode) to aid comparisons across the two functions.

Although only normalized ECAP amplitudes are shown in Fig. 7, both raw and normalized ECAP data were evaluated to determine whether SM patterns differed across the two masker-level methods. For raw ECAP amplitudes, paired t tests showed significant differences ($p < 0.05$) for five electrodes across three subjects (P12 and P9 for C13, P5 for C14, and P7 and P11 for R2), which represents 21% (5 of 24) of the total comparisons. For the normalized data (shown in Fig. 7), significant differences were found for three electrodes across two subjects (P12 for C14, P7 and P11 for F1), which represents 12.5% (3 of 24) of the comparisons.

Experiment 4: Effect of recording location on SM patterns

As shown in Experiment 2 for SS patterns, the relative position of the recording electrode can significantly affect the measured ECAP amplitude. Experiment 4 examined whether recording electrode location would significantly affect the shape or spread of SM patterns for a fixed level. Data were obtained for a basal, middle, and apical probe electrode in 18 subjects (except for R12 on the basal electrode due to time limitations). In general, the following recording electrode locations were attempted: ± 1 , ± 2 , and ± 4 electrode positions relative to the probe electrode for Advanced Bionics subjects, or ± 2 , ± 4 , ± 6 electrode positions for Nucleus subjects (due to closer inter-electrode spacing relative to the Advanced Bionics devices). Deviations from these values were often necessary, given individual differences in effects of stimulus artifact on the recorded responses. For some subjects, it was not possible to record responses within 2–3 electrode positions relative to the probe; whereas for other subjects, recordings could be obtained at an electrode adjacent to the probe. It was therefore not possible to collapse data across subjects for analysis.

Figure 8 depicts a series of SM patterns from different recording electrodes for P9 from subject C4. Raw (not normalized) data are shown to illustrate how recording electrode position affected overall ECAP amplitudes. In this case, the largest amplitudes were obtained for recording E7 (default recording position), E8, and E10. The overall amplitude of the functions decreased for recording electrodes farther from the probe. For recording electrodes equidistant from the probe, amplitudes were generally larger when recorded from the apical side (e.g., E8 vs. E10 and E5 vs. E13).

Figure 9 shows individual examples of normalized ECAP SM patterns for basal, middle, and apical probe electrodes. Recording electrode is the parameter, as indicated in each figure legend. Arrows in each panel indicate the fixed probe electrode location. Each SM pattern was normalized to the amplitude obtained with the masker and probe on the same electrode to evaluate the relative shape (or spread) of functions across recording electrode conditions. Asterisks indicate a statistically significant difference for one or more comparisons in the set. Overall, the data tended to follow one of three different trends. First, many SM patterns had

larger amplitudes on the basal side of the probe when the recording electrode was located basal to the probe. Similarly, larger amplitudes occurred on the apical side of the probe when the recording electrode was also located apical to the probe (see C4, P9 and P12; R7, P7; R6, P11; F2, P7). In these cases, a one-way RM ANOVA showed no significant effect of recording location because the overall spread of the functions did not change; the functions essentially pivoted about the probe electrode. These results are consistent with data in Figs. 2–4, which showed decrements in ECAP amplitude with increased separation between the stimulus and recording electrodes for SS functions. The second trend was that recording electrode location significantly affected the overall shape or spread of the SM patterns. Three examples of this in Fig. 9 are indicated with an asterisk next to the probe electrode number. Significant effects of recording location ($p < 0.05$, one-way RM ANOVA) were observed for only 50 of 433 (11.5%) total comparisons obtained from the 18 subjects. When recording electrodes were equidistant from the probe, SM patterns were generally broader for the apical recording electrode (e.g., subject C8, P5, recording E1 vs. E9). Patterns also tended to be narrower when recording from an electrode adjacent to the probe compared to a non-adjacent electrode (e.g., subject R6, P16, recording E17). The third trend was that there was no significant effect of recording location on the shape or relative location of the edges (i.e., no pivoting about the probe electrode) of the SM patterns (e.g., subject C6, P5; subject R2, P11).

Experiment 5: Robustness of SM patterns over repeated trials

Studies that have compared ECAP measures with psychophysical measures typically report a single trial for ECAP measures, as opposed to averages of several trials for psychophysical measures. This practice is based on the assumption that there is little variability in ECAP measures across trials, but this has not been systematically evaluated. This experiment examined whether ECAP SM patterns differed significantly across repeated recordings within a single test session. If no significant differences exist across repeated measures within a session, then it would be reasonable to continue with the current practice of comparing a single-trial ECAP measures to multi-trial averages of psychophysical measures. However, if significant differences do exist, then future studies designed to compare ECAP SM patterns to psychophysical measures should incorporate repeated trials for ECAP measures, as is done for psychophysical measures.

Twelve subjects participated (see Table 1). SM patterns were obtained for one randomly chosen probe electrode (i.e., basal, middle, or apical) per subject. Three to four successive measures were obtained for each subject, except for C14⁶. Figure 10 shows raw ECAP data from all subjects. Only two of the 12 subjects showed significant differences (one-way RM ANOVA) between a subset of trials, as indicated by asterisks and brackets in the figure legends. For C14, the mean amplitude for trial 1 was significantly smaller than for the subsequent two trials ($p < 0.001$). There was no significant difference in amplitude between trials 2 and 3. For F1, the mean amplitude for trial 1 was significantly larger than for trial 3 ($p = 0.002$). Across all trials and subjects, 45 of 48 comparisons (94%) were not statistically significant, which suggests that ECAP SM patterns are quite stable across repeated measurements.

DISCUSSION

Experiment 1: SS versus SM patterns

In Experiment 1, SS and SM patterns were compared to determine whether SS patterns were systematically broader than SM patterns across electrodes and subjects. For SS patterns, the peaks of the functions generally occurred within 1–2 electrodes of the stimulated electrode.

⁶For C14, the first trial was obtained at the beginning of the test session, and then two SM functions for a medial and basal probe electrode were collected for a different experiment in this study before collecting trials 2 and 3.

For SM patterns, the peaks typically occurred when the masker and probe were on the same electrode. Both patterns showed a decrease in ECAP amplitude as the recording (SS patterns) or masker (SM patterns) electrode was located farther from the probe. For SS functions, broader and smoother patterns are expected because the voltage associated with neural discharge in the vicinity of the stimulated electrode is presumably conducted along the length of the cochlea through the surrounding fluid and tissue (Abbas et al., 2004; Cohen et al., 2004). The measured voltage decreases because of larger physical separations between stimulus and recording sites; the geometry of the cochlea likely has an effect as well (see Kral et al., 1998). Therefore, the SS functions only represent the decay in the measurement of an ECAP generated at one specific place in the cochlea (masker/probe electrode), so these functions are not likely to be sensitive enough to reveal uneven patterns of nerve survival along the length of the cochlea (Dingemanse et al., 2006). For SM patterns, narrower functions are expected because the decay in ECAP amplitude as a function of masker location reflects the decreasing overlap between neural populations that are recruited by the masker and probe electrodes. As the masker and probe are separated spatially, there is less overlap of the respective stimulated neural populations, which results in a smaller ECAP in the subtracted trace (e.g., Abbas et al., 2004; Hughes & Abbas, 2006a). In this case, the recording electrode location is fixed, so it does not influence the measured responses (Mens, 2007). Therefore, SM patterns are more likely to reflect uneven nerve survival patterns as demonstrated by non-monotonicities or less smoothly-shaped patterns, compared with SS patterns (see for example the basal portion of the SM versus SS functions for F4, P7 in Fig.2). Functionally, SS patterns are useful for assessing the conduction or decay of the ECAP response along the length of the cochlea, whereas SM patterns are useful for assessing the combination of stimulus current spread and neural recruitment patterns along the length of the cochlea. SM patterns are also more useful for relating to psychophysical forward-masking patterns using similar methodology (e.g., Cohen et al., 2003; Hughes & Stille, 2008), relating to electrode pitch discrimination (Hughes & Abbas, 2006a; Hughes 2008), detecting local patterns of nerve survival (e.g., Abbas et al., 2004) or detecting electrode foldovers (Grolman et al., 2008).

Group data showed that SS patterns were significantly broader than SM patterns, which is in general agreement with Abbas et al. (2003) and Cohen et al. (2004). The exception was for the apical region for Advanced Bionics subjects, where the difference was not statistically significant (see Fig. 3). The majority of significant differences between the two functions occurred for Nucleus subjects (81% of comparisons), compared with Advanced Bionics subjects (47%). As shown in Figs. 2 and 3, SS patterns were similar across devices, but SM patterns tended to be narrower for Nucleus subjects. This result may be due to differences in the dimensions and positions of the respective electrode arrays. Both the Nucleus Contour and the Advanced Bionics HiFocus arrays consist of medial-facing electrode contacts. However, the Contour array has a pre-curved design to facilitate perimodiolar electrode placement, whereas the HiFocus arrays are relatively straight with a more lateral scalar position when not coupled with the electrode positioner (only subject C1 had a positioner; van der Beek et al., 2005; Finley et al., 2008). Perimodiolar devices have been shown to yield narrower SM patterns than straight arrays (Cohen et al., 2003; Hughes & Abbas, 2006b), presumably due to lower current requirements and thus less current spread for smaller electrode-nerve distances. The difference in SM patterns between the two devices was most apparent in the apical electrodes (see Fig. 3), which is consistent with previous reports of the Contour occupying a more perimodiolar position toward the apex (Balkany et al., 2002; Saunders et al., 2002). Despite differences in electrode design, perhaps the similarity of SS patterns across devices occurs because the spatial selectivity of excitation patterns is independent from the measurement of volume conduction patterns. In other words, electrode design/placement appears to affect the selectivity of neural recruitment patterns (i.e., SM patterns), but seems to have little influence on how the voltage from the resulting ECAP decays along the length of the cochlea (SS patterns).

Experiments 2 and 3: Effect of level on SS and SM patterns

In Experiments 2 and 3, the effect of stimulus level on SS and SM patterns, respectively, was evaluated to determine whether increased stimulus level systematically resulted in broader patterns. The results showed stimulus level had a significant effect for about one-third of SM (34%) and SS (39%) patterns. For SS patterns, this represents a lower incidence than that reported by Cohen et al. (2004), who showed significant effects of level for 6 of 12 electrodes in four subjects⁷.

For SM patterns, the present results are generally consistent with previous studies that have demonstrated broader patterns for higher stimulus levels (Abbas et al., 2004; Eisen & Franck, 2005). Cohen et al. (2003), however, reported no significant effect of stimulus level on the width of SM functions for group data, although they did point out individual cases where increased stimulus level resulted in broader functions. Despite methodological differences across studies, it is clear that stimulus level can have significant effects on the overall amplitude and spread of SM patterns in at least a subset of subjects.

In a study comparing ECAP SM patterns with psychophysical spatial forward-masking patterns, Hughes and Stille (2008) used maskers at equal loudness levels for both measures, and found broader patterns for the ECAP measures. Because pulse trains were used for the psychophysical measures, lower current levels were needed to achieve the same relative loudness level compared with the single pulses used for ECAP measures. Results from the present study support the existing evidence that broader ECAP patterns can result from higher stimulus levels. This is an important issue to consider when relating physiological and psychophysical measures when different stimuli are used.

The present results also showed that the shape or spread of SM patterns can vary depending on whether maskers are presented at a level relative to the behavioral dynamic range or relative to the ECAP thresholds (see Figs. 6 and 7). This is particularly relevant when ECAP thresholds fall at different percentages of the behavioral dynamic range across the electrode array within a subject (see for example Hughes et al., 2000, Fig. 5; Potts et al., 2007). If masker levels are determined based on the behavioral dynamic range alone, a larger ECAP will result if the ECAP threshold falls at a lower compared to a higher percentage of the behavioral dynamic range. As shown in Fig. 6, higher masker levels resulted in larger ECAP amplitudes and broader SM functions. These results are similar to those reported by Abbas et al. (2004), who measured SM functions for masker levels set relative to behavioral comfort levels (which varied significantly across the electrode array) versus a fixed current level. They found a broader pattern for the fixed-level masker, which was higher than the current levels based on behavioral comfort levels.

These results are consistent with greater current spread at higher levels and subsequent recruitment of additional neural populations that contribute to the measured ECAP response. The amount of current spread will vary depending on the magnitude of the increase in stimulus level. For subjects with small behavioral dynamic ranges or whose ECAP thresholds are close to behavioral maximum comfort levels, it can be difficult to measure significant level effects for SS or SM patterns because only small increments in current level can be used. In general, the results from Experiments 2 and 3 showed that higher stimulus levels can produce broader patterns for both SS and SM functions; although no level effects were observed for two-thirds of the comparisons.

⁷In that study, current levels ranged from the upper loudness comfort for the ECAP stimulus down to just above ECAP threshold, which in most subjects would be a larger range of levels than was tested in the present study.

Experiment 4: Effect of recording location on SM patterns

The goal of Experiment 4 was to determine whether the recording electrode location had a significant effect on the shape or spread of SM patterns for a fixed stimulus level. The results showed that the location of the recording electrode significantly affected the width of the SM patterns in less than 12% of cases. In general, the results from Experiment 4 were consistent with those of Cohen et al. (2003), who compared SM patterns recorded from two electrode positions (apical vs. basal to the probe) in a small group of Nucleus subjects, and observed similar amplitudes and widths for the two recording positions. The current study extends those findings to additional recording electrode locations both apical and basal to the probe. In many cases, however, SM functions tended to pivot about the probe electrode depending on which side of the probe that the recording electrode was located (see Figs. 8–9). Specifically, larger normalized amplitudes were generally obtained for maskers that were on the same side of the probe as the recording electrode. These results are a product of reduced ECAP amplitudes for greater separations between stimulus and recording electrodes, as illustrated by the SS patterns in Figs. 2–4. It may therefore be worthwhile to average recordings obtained from both apical and basal sides of the probe when relating SM measures to psychophysical spatial excitation patterns (e.g., Hughes & Stille, 2009).

Experiment 5: Stability of SM patterns over repeated trials

Experiment 5 assessed the stability of ECAP SM functions by examining amplitude variations over repeated trials. Results showed that ECAP amplitudes were, in general, highly repeatable across sequential measurements within a session. Significant amplitude differences were found for only 3 of 48 comparisons (6%). For one subject (F1), the mean amplitude from trial 3 was significantly smaller than trial 1. This decrease may have been due to adaptation effects from prolonged stimulation. Schmidt Clay and Brown (2007) showed systematic decreases in ECAP amplitude over a five-minute period of constant stimulation presented at 80 Hz for a group of 21 Nucleus subjects. For Nucleus subjects in the present study, the probe repetition rate was also 80 Hz, and it typically took about six minutes to collect a single SM function. However, stimulation in the present study was not constant over the course of measuring a single SM function (i.e., the “series” function in the software was not used). Each waveform was collected separately, so there was typically a delay of a few seconds while the masker electrode and level parameters were changed. It is not clear how small breaks in stimulation might affect the overall excitability of the auditory neurons.

For subject C14, trial 1 yielded significantly smaller amplitudes than trials 2 and 3. Recall that trial 1 was collected at the beginning of the test session, whereas trials 2 and 3 were collected after two SM patterns for other electrodes. Because the smallest amplitudes were obtained for the first trial, these results are not consistent with the notion of adaptation over prolonged periods of stimulation (Schmidt Clay & Brown, 2007). C14 has an Advanced Bionics device, for which the stimulus repetition rate was much slower (20 Hz) than for Nucleus subjects. Lack of adaptation in this case is consistent with Schmidt Clay and Brown’s finding of little to no adaptation for Nucleus subjects for a repetition rate of 15 Hz. It should be emphasized, however, that the repeatability measures in this experiment only assessed the repeatability of SM functions within a single data collection session and not across longer time intervals. Further studies are needed to assess variance in ECAP amplitudes for repeated measures within a single data collection session that are not successively measured, as well as across sessions spaced across concurrent days or longer time intervals.

CONCLUSIONS

The primary purpose of this study was to evaluate the effects of stimulus and recording parameters on SS and SM patterns obtained with the ECAP. In general, stimulus and recording

parameters had significant effects within most individual subjects, although not necessarily for all three electrode regions or for all comparisons within a region. First, SS functions were generally broader than SM functions. This is consistent with evidence that SS measures reflect volume conduction of the ECAP response along the length of the cochlea, whereas SM functions reflect the relative overlap of neural populations recruited by the masker versus probe. Subjects with Nucleus devices generally exhibited larger differences between SS and SM measures than subjects with Advanced Bionics devices, which is likely due to differences in intrascalar electrode array placement between the two devices. Second, stimulus level had a more significant effect on the spread of SM functions (roughly one-third of comparisons) than recording electrode (11.5% of comparisons). Although recording electrode location did not typically affect the width or overall spread of SM functions, it did affect the relative locations of the edges of the resulting patterns by yielding larger amplitudes for masker electrodes that were on the same side (basal or apical) as the probe (i.e., the functions tended to pivot about the probe electrode). Finally, ECAP measures were shown to be highly stable across sequential repeated trials, which suggests that there is little need for averaging several measurements within a test session as is typical for psychophysical measures. Results from these experiments provide important information about the variance underlying SS and SM patterns, which is particularly useful for studies that might relate these types of ECAP measures to psychophysical measures.

Acknowledgments

This research was supported by NIH/NIDCD R03 DC007017 and P30 DC04662. The authors thank Kelly Barrow and Erin Castioni for assistance with data collection and analysis, Adam Goulson for assistance with figure preparation, Donna Neff for editorial comments, Dan Valente for statistical assistance, and Charlie Finley and two anonymous reviewers for valuable feedback on earlier drafts of this manuscript.

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Fig. 1.

Schematic illustrating the stimulus and recording configurations for (A) spatial spread (SS) and (B) spatial masking (SM) patterns. For SS patterns, stimulus level and electrode location were fixed for masker and probe stimuli while recording electrode was varied across the array, excluding the stimulating electrode. For SM patterns, probe stimulus level and electrode location were fixed, recording electrode was fixed (typically two electrode positions apical to the probe), and masker location varied across the array, excluding the recording electrode.

Fig. 2. Individual examples of raw ECAP amplitudes for spatial masking (SM; filled circles) and spatial spread (SS; open circles) patterns as a function of masker or recording electrode, respectively. Examples of basal, middle, and apical probe electrodes are in the left, center, and right columns, respectively. Top and bottom rows represent Advanced Bionics and Nucleus subjects, respectively. Subject number and probe electrode (P) are indicated on each panel. Asterisks next to probe electrode numbers indicate statistically significant differences between SM and SS functions ($p < 0.05$).

Fig. 3.

Mean (± 1 SD) normalized ECAP amplitudes across subjects for SM (filled circles) and SS (open circles) functions for basal (left), middle (center), and apical (right) probe electrode locations. Top and bottom rows show data for Advanced Bionics (ABC) and Nucleus (NUC) subjects, respectively. Probe electrode (P) and number of subjects included for each function (N) are noted on each panel. When the number of subjects differed for the two functions within the same panel, the value for SM is listed first. Asterisks next to probe electrode numbers indicate that SS functions were significantly broader than SM functions.

Fig. 4.

Individual examples illustrating the effect of stimulus level on SS patterns. Data are arranged as in Fig. 2, with stimulus level as the parameter. Arrows indicate the location of the stimulus. Normalized ECAP amplitudes are plotted as a function of recording electrode for each masker/probe level. Asterisks next to probe electrode labels indicate significant differences between one or more level comparisons for that subject.

Fig. 5.

Individual examples illustrating the effect of stimulus level on SM patterns. Data are arranged as in Fig. 4. Arrows indicate the location of the fixed probe. Normalized ECAP amplitudes are plotted as a function of masker electrode for each masker/probe level.

Fig. 6.

A: An example from one subject illustrating the behavioral dynamic range across electrodes (thick solid lines; bottom is threshold and top is maximum comfort). Filled circles represent masker levels at 80% of the behavioral dynamic range for each masker electrode. Open circles represent masker levels calculated relative to ECAP threshold [see text for formulas used to determine (M_{ECAP0})]. Filled squares represent ECAP thresholds. B: Raw ECAP amplitudes for SM patterns obtained with the respective masker levels (open and closed circles) indicated in panel A.

Fig. 7.

Normalized SM functions for a subset of subjects for masker levels referenced to behavioral dynamic range (filled circles) or ECAP threshold (open circles). Data are plotted similar to Fig. 6B for basal, middle, and apical electrodes. Top and bottom rows represent Advanced Bionics and Nucleus subjects, respectively. Asterisks indicate statistically significant differences between the two functions. Arrows indicate the fixed probe electrode.

Fig. 8. Individual example of SM functions for different recording electrodes, as listed in the figure legend. The vertical solid line indicates the probe electrode position. ECAP amplitudes have not been normalized to illustrate the overall change in amplitude with more distal recording sites.

Fig. 9. Individual examples illustrating the effect of recording location on normalized SM patterns. Data are arranged as in Fig. 5, with recording electrode as the parameter. Asterisks next to probe electrode labels indicate significant differences between one or more level comparisons for that subject.

Fig. 10.

Raw SM functions for all 12 subjects with repeated trials as the parameter. Asterisks next to pairs of trials in the figure legends indicate statistically significant differences between functions (see text).

Table 1

Subject demographic information. +p = subject has an electrode positioner. R = right ear, L = left ear, CNC = Consonant-Nucleus-Consonant test. Asterisks denote subjects with bilateral CIs; data were only collected for the ear listed. Years post CI represents the time from initial stimulation to the start of participation in this study.

Subject	Internal Device and Electrode Array	Ear	Duration Deafness (yrs)	Age at CI (yrs)	Years Post CI	CNC Words % Corr	Experiments Participated In					
							Exp1	Exp2	Exp3A	Exp3B	Exp4	Exp5
C1	Clarion CII HF 1 +p	R	16.0	18.4	5.6	21%	x	x	x	x	x	x
C2	HiRes 90K HF 1J	L	0.5	69.2	0.9	39%	x					
C3	HiRes 90K HF 1J	R	16.7	18.7	1.1		x					
C4	HiRes 90K HF 1J	R	19.0	57.0	0.4	69%	x	x	x		x	
C6	Clarion CII HF 1J	L	21.0	64.4	1.8	67%	x	x	x	x	x	x
C7	Clarion CII HF 1	L	5.0	57.3	2.1	8%	x	x	x			
C8	Clarion CII HF 1J	R	0.3	55.7	1.9	75%	x	x	x		x	x
C9	HiRes 90K HF 1J	R	4.0	41.9	1.0	37%					x	
C10	HiRes 90K HF 1J	R	14.0	51.9	0.6	5%	x	x	x			
C11	HiRes 90K HF 1J	R	15.0	58.2	4.7						x	x
C12	HiRes 90K HF 1J	R	38.6	40.6	1.1		x	x	x			
C13	Clarion CII HF 1	L	20.0	77.3	5.4		x			x	x	x
C14	Clarion CII HF 1	R	0.2	6.3	5.8		x	x	x	x	x	x
C15	HiRes 90K HF 1J	L	34.0	39.3	3.2		x	x	x		x	
R1	Nucleus 24R(CS)	R	4.0	60.9	6.6	46%	x					
R2	Nucleus 24R(CS)	R	2.0	51.7	3.8	83%	x	x	x	x	x	x
R3	Nucleus 24R(CS)*	R	50.0	56.2	3.3	42%	x	x	x	x	x	
R4	Nucleus 24R(CS)	L	1.0	41.9	2.6	68%	x	x	x		x	
R5	Nucleus 24R(CS)	R	16.0	49.3	4.8	78%	x				x	
R6	Nucleus 24R(CS)*	R	0.8	44.4	12.4	17%	x	x	x		x	x
R7	Nucleus 24R(CS)	R	5.0	62.3	0.9	39%	x	x	x		x	x
R10	Nucleus 24R(CS)	R	2.0	61.9	2.5	35%	x					
R11	Nucleus 24R(CS)	L	15.0	17.2	2.1		x	x	x	x		
R12	Nucleus 24R(CS)	R	8.6	12.0	5.4		x	x	x			

Subject	Internal Device and Electrode Array	Ear	Duration Deafness (yrs)	Age at CI (yrs)	Years Post CI	CNC Words % Corr	Experiments Participated In				
							Exp1	Exp2	Exp3A	Exp3B	Exp4
F1	Nucleus 24RE(CA)*	L	50.0	60.7	0.9		x	x	x	x	x
F2	Nucleus 24RE(CA)	R	8.5	60.3	0.5		x	x	x	x	x
F4	Nucleus 24RE(CA)*	L	15.4	17.5	1.1		x				x