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Research paper

Masking patterns for monopolar and phantom electrode stimulation in cochlear implants

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ABSTRACT

Phantom electrode (PE) stimulation consists of out-of-phase stimulation of two electrodes. When presented at the apex of the electrode array, phantom stimulation is known to produce a lower pitch sensation than monopolar (MP) stimulation on the most apical electrode. The ratio of the current between the primary electrode (PEL) and the compensating electrode (CEL) is represented by the coefficient σ, which ranges from 0 (monopolar) to 1 (full bipolar). The exact mechanism by which PE stimulation produces a lower pitch sensation is unclear. In the present study, unmasked and masked thresholds were obtained using a forward masking paradigm to estimate the spread of current for MP and PE stimulation. Masked thresholds were measured for two phantom electrode configurations (1) PEL = 4, CEL = 5 (lower pitch phantom) and (2) PEL = 4, CEL = 3 (higher pitch phantom). The unmasked thresholds were subtracted from the masked thresholds to obtain masking patterns which were normalized to their peak. The masking patterns reveal (1) differences in the spread of excitation that are consistent with the direction of pitch shift produced by PE stimulation, and (2) narrower spread of electrical excitation for PE stimulation relative to MP stimulation.

1. Introduction

In a cochlear implant, an array of intra-cochlear electrodes is used to deliver electrical stimulation to the auditory neurons. The most common configuration used in commercial strategies for electrical stimulation is known as monopolar (MP). In this configuration, the current flows between the primary (stimulating) electrode and a remote extra-cochlear ground electrode. Monopolar stimulation of longitudinally spaced electrodes produces pitch percepts that roughly correspond to the tonotopic organization of the cochlea. In addition to pitches generated by stimulation of physical electrodes, intermediate pitches can be generated using virtual channels (VCs) which consist of either simultaneous (Townsend et al., 1987; Wilson et al., 1994; Donaldson et al., 2005; Firszt et al., 2007; Koch et al., 2007; Landsberger and Srinivasan, 2009; Landsberger and Galvin, 2011) or sequential (McDermott and McKay, 1994; Kwon and van den Honert, 2006a; Landsberger and Galvin, 2011) dual-electrode stimulation. Through the use of VCs, even with the limited number of electrodes in an electrode array, current can be presented to any location between the most apical and most basal electrodes. However, VCs cannot provide stimulation beyond the locations represented by the apical and basal electrodes.

The range of pitches generated by an array of electrodes can be extended by phantom electrode (PE) stimulation (Wilson, 1993; Saoji and Litvak, 2010; Macherey et al. 2011; Macherey and Carlyon, 2012). In PE stimulation, two electrodes are stimulated simultaneously with out-of-phase stimulation. Current (i) is delivered to the primary electrode and compensating current ($i^*\sigma$) is delivered to the neighboring electrode. The relative amount of compensation (σ) ranges from 0 to 1. Wilson (1993) used PE stimulation ($\sigma = 0.2–0.8$) to generate a pitch sensation lower than that produced by MP stimulation of the most apical electrode. In this configuration, the apical electrode was used as the primary electrode and the neighboring basal electrode was used as the compensating electrode. In this article, this type of stimulation will be referred to as low-pitch PE (LP-PE) stimulation. Similarly, by using the most basal electrode as the primary electrode, and the neighboring apicalward electrode as the compensating electrode, Wilson (1993) demonstrated that PE stimulation can be used to generate a higher pitch sensation than that produced by the MP

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stimulation of the most basal electrode. This type of stimulation is referred to as high-pitch PE (HP-PE) stimulation in this article. Saoji and Litvak (2010) compared the pitch generated by LP-PE stimulation with that generated by the physical electrodes in MP mode and demonstrated that LP-PE stimulation can lower the pitch sensation by the equivalent of about 0.5–2 mm. As σ increases from 0 (MP stimulation) to 1 (Bipolar or BP stimulation), the pitch shift of PE stimulation relative to MP stimulation increases up to a certain level of σ (typically about $\sigma = 0.5$). Further increments in σ result in a reduction of pitch shift, presumably because of an increased influence from a side-lobe generated by the increasing magnitude of the current from the compensating electrode. For further details, refer to Saoji and Litvak (2010).

The mechanism by which LP-PE stimulation is able to generate a lower pitch sensation (and by which HP-PE stimulation is able to generate a higher pitch sensation) is not fully understood. The pitch shift produced by PE stimulation is attributed to the compensating electrode which alters the spread of excitation associated with the primary electrode. The out-of-phase current in PE stimulation is likely to push the electric current field and therefore spread of excitation away from the compensating electrode. Therefore, we propose three hypotheses for the pitch shift produced by PE stimulation. Fig. 1 shows a schematic illustration of the three hypothesis for MP (red solid line) and LP-PE (green dashed line) stimulation. Panel A shows a similar spread of excitation in the apical direction for MP and LP-PE stimulation but a narrower spread of excitation in the basal direction for PE stimulation. Here the compensating electrode is likely to restrict the spread of excitation to one side of the stimulating electrode (i.e., restricted in the direction of the compensating electrode). Panel B shows overall shift in the spread of excitation and the maxima produced by LP-PE stimulation relative to MP stimulation. Panel C shows a slight apical shift in spread of excitation and relatively larger sharpening in the spread of excitation for LP-PE stimulation as compared to that produced by MP stimulation. In this hypothesis, the LP-PE excitation can be described as a combination of hypothesis one and two where PE stimulation results in a more “lop-sided” spread-of-excitation.

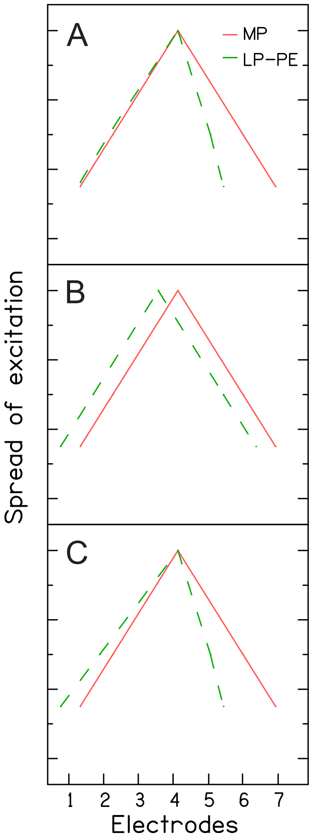

Fig. 1. This figure shows the schematic illustration of the three possible changes in the spread of excitation for low-pitch phantom electrode (LP-PE, green dashed line) stimulation relative to monopolar (MP, red solid line) stimulation. Panel A shows a narrow spread of excitation in the basal direction for LP-PE stimulation relative to MP stimulation. Panel B shows overall apical shift in the spread of excitation for LP-PE stimulation relative to MP stimulation. Panel C shows some narrow spread of excitation in the basal direction for LP-PE stimulation along with a slight apical shift as compared to MP stimulation. Electrode 1 is the most apical electrode.

Regardless of the mechanism, it seems likely that PE stimulation has the potential to extend the effective range of electrodes in patients who have already been implanted without an additional surgery. In patients who have yet to be implanted, one can surgically extend the range of place-pitch sensations evoked by a cochlear implant by making a deeper insertion of the electrode array. This approach is invasive and incurs additional surgical risk. In addition, deeper electrode insertion can lead to more insertion trauma in implant users and increase the possibility of apically located electrodes being pushed from scala tympani into the scala vestibuli. Skinner et al. (2007) reported that speech perception scores are negatively correlated with the number of electrodes being inserted into the scala vestibuli. If PE stimulation can push the current more apically or basally it can be used as a non-invasive method of extending the range of pitch sensations produced by the electrode array and therefore presumably a better encoding of the speech spectrum.

Potentially, a secondary property of PE stimulation could be that it produces a narrower spread-of-excitation than MP stimulation. It has been proposed that the broad current spread from MP stimulation creates channel interactions, which limit spectral resolution (Dorman and Loizou, 1997, 1998). Presumably, if the spread of current is reduced, channel interactions will also be reduced and spectral resolution will be improved. Stimulation modes which involve out-of-phase stimulation on at least two electrodes, such as BP, tripolar (TP), or quadrupolar virtual channel (QPVC) are considered to involve current focusing which reduces the spread of excitation relative to MP stimulation. PE stimulation, which consists of out-of-phase stimulation on two electrodes, is likely to share this property. However, larger current levels are needed to achieve comfortable loudness sensation with these modes of stimulation than with MP stimulation (Litvak et al., 2007; Berenstein et al., 2008; Bonham and Litvak, 2008; Landsberger and Srinivasan, 2009). Chatterjee and Shannon, 1998 have shown that an increase in current level results in an increase of spread-of-excitation. It is therefore likely that the reduction in current spread generated by these current focusing modes is counteracted by the increased current levels required by these stimulation modes. Kwon and van den Honert, 2006b showed no consistent change in reduction in spread of excitation between equally loud MP and BP stimuli. Landsberger et al. (2012) demonstrated a reduction in spread-of-excitation with partial tripolar stimulation in about half of the patients tested. Srinivasan et al. (2010) demonstrated a more consistent reduction in spread-of-excitation with QPVC stimulation relative to the conventional (non-current focused) VCs. As a result, it is plausible that at a fixed loudness, PE stimulation would result in a smaller spread of excitation than MP stimulation, although it is also plausible that they would have similar spreads of excitation. In the current manuscript, we propose that PE stimulation provides a narrower spread of excitation than MP stimulation at a fixed loudness, consistent with our first hypothesis as shown in Fig. 1, panel A.

To test the hypotheses about the differences in spread of excitation between MP and PE stimulation, psychophysical forward-masking patterns were measured for equally loud MP, LP-PE and HP-PE stimulation in the present study. For both PE stimulation conditions σ was set to a fixed value of 0.5 ($PE_{\sigma = 0.5}$). The psychophysical forward-masking paradigm has been used to characterize the spread of electrical excitation in cochlear implant users (Shannon, 1983; Nelson and Freyman, 1984; Tong and Clark, 1986; Lim et al., 1989; Cohen et al., 1996; Chatterjee and Shannon, 1998; Cohen et al., 2001; Boex et al., 2003). In this technique, the psychophysical forward-masking patterns are computed by measuring minimum detectable amplitude of a short probe stimulus both in isolation and following a longer-duration preceding masker. The masking pattern is defined as the difference between the masked and unmasked thresholds and is thought to estimate the degree of overlap of the neural elements excited by the probe and the masker (Moore, 1978).

2. Methods

2.1. Subjects

Eight cochlear implant users with CII or HiRes 90k implant and HiFocus electrode array from Advanced Bionics participated in this study (Table 1). The distance between the midpoint of one electrode to another is 1.1 mm for the HiFocus electrode array. The study protocol used to measure forward masking patterns for cochlear implant listeners was approved by the Western Institutional Review Board (WIRB®) for patients tested at Advanced Bionics and by the St. Vincent Medical Center Institutional Review Board for patients tested at the House Research Institute. Subjects S1, S2, and S3 were tested at Advanced Bionics and subjects C1, C3, C7, C14, and C19 at the House Research Institute.

2.2. Stimuli

All stimuli were composed of trains of charge-balanced, symmetric, anodic leading, biphasic pulses. The rate of stimulation was 1288 pulses per second. The pulses were biphasic (194 μs/phase). A wider pulse width of 194 μs/phase was used to allow one to achieve comfortable loudness level for PE stimulation without exceeding the maximum compliance voltage of the device (see below). The electrode attached to the case of the device on the CII or HR 90k implant was used as the distant ground.

One MP and two different PE maskers were used in this study. The MP and the PE maskers were presented on electrode 4 for all subjects. In one PE configuration, the adjacent basal electrode (electrode 5) was used as the compensating electrode for PE stimulation. In the other PE configuration, the adjacent apical electrode (electrode 3) was used as the compensating electrode along with primary electrode 4. The compensation for PE maskers was fixed to 0.5. The masker duration was 350-ms.

A low-pitch PE probe with adjacent basal electrode and compensation currents of $\sigma = 0.75$ was used to measure unmasked and masked thresholds. The σ value for the probe stimulus was different than the σ used for the masker stimuli to ensure that the probe had a distinctive sound as compared to the masker for all masked conditions. Also, a probe with PE configuration is likely to produce a narrower spread of excitation as compared to an MP probe and therefore allow one to investigate the spread of excitation from the masker in the region of probe electrode. The probe stimuli were 20 ms in duration, and had the same rate and pulse width as the masker stimuli. Probe thresholds were measured from electrodes 1 to 10. The masker and probe were separated by 4 ms. To facilitate comparison between masking patterns across different maskers, the stimulation configuration of the probe stimulus was kept constant. Fig. 2 shows a schematic representation of the forward masking paradigm. In that example, the low−pitch $PE_{\sigma = 0.5}$ masker is presented on electrode 4 and the low-pitch $PE_{\sigma = 0.75}$ probe is presented on electrode 5. In the Advanced Bionics device, the lower electrode numbers represent a more apical placement.

Table 1
Shows the details for 8 cochlear implant subjects.

Subject	Age	Implant use (yrs)	Implant/electrode
S1	58	9	CII/HiFocus
S2	39	9	CII/HiFocus
S3	86	6	CII/HiFocus
C1	78	12	CII/HiFocus
C3	55	5	HiRes 90K/HiFocus
C7	62	5	HiRes 90K/HiFocus
C14	47	6	HiRes 90K/HiFocus
C19	62	12	CII/HiFocus

2.3. Procedure

The psychophysical experiment was controlled by Bionic Ear Data Collection System (BEDCS) which is a custom software package developed at Advanced Bionics. For each subject, electrode impedances were measured for sixteen electrodes by capturing the electrode voltage at the beginning of the first phase of the 32 μs per phase pulse. The access impedance was then estimated by dividing the measured voltage by the applied current, which was kept at 32 μA (Tykocinski et al., 2005). The impedance values were used to determine the upper limit of the current (Imax) that could be applied to each individual electrode using the formula:

$$\mathrm{Imax} = (8\mathrm{V} - 0.7\mathrm{V})/(R + 0.01{*}\mathrm{PW}) \quad (1)$$

In the above equation Imax is the maximum current (in mA), 8 V (Volts) is the maximum voltage of the CII/HR90K device, and 0.7 V is the maximum polarization voltage that can be developed on a platinum contact surface driven by a current source (Hibbert et al., 2001). R is the electrode access impedance (in kOhms), PW is the phase duration (in μs). The additive term on the impedance is used to account for the charge buildup on the internal blocking capacitor which has a value of 0.1 uF. The compliance limitations of the device are particularly important when considering that larger currents are needed to achieve comfortable loudness levels with PE stimulation.

A 10-point loudness scale was used to determine MCL levels for each cochlear implant user. 0: Off; 1: Just noticeable; 2: Very soft; 3: Soft; 4: Comfortable but too soft; 5: Comfortable but soft; 6: Most comfortable; 7: Loud but comfortable; 8: Loud; 9: Upper loudness limit; 10: Too loud. The MP masker was balanced in loudness to the

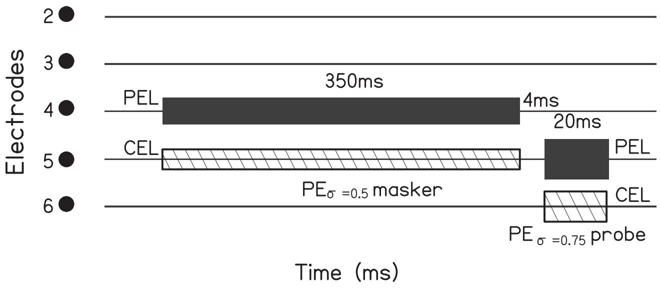

Fig. 2. PEL = primary electrode and CEL = compensating electrode. PE = phantom electrode. This figure (not to scale) shows the schematic representation of a forward masking paradigm with a phantom masker (PEL = 4, CEL = 5) and a phantom probe (PEL = 5, CEL = 6).

low-pitch $PE_{\sigma = 0.5}$ masker. Initially, most comfortable loudness (MCL) level or level 6 was measured for the low-pitch $PE_{\sigma = 0.5}$ stimulation on electrode 4. In this procedure, the subject heard the MP and the low-pitch PE masker alternately while adjusting the current level of the MP stimulus. Then the loudness level of the MP masker was fixed at the most comfortable loudness level and the current level of the high-pitch $PE_{\sigma = 0.5}$ masker was balanced to the MP masker. An average of two ascending and two descending tracks were used to define the loudness levels for the MP and high-pitch PE maskers.

Unmasked and masked thresholds were measured for a $PE_{\sigma = 0.75}$ probe from electrodes 1 to 10. A two-interval forced-choice procedure with a three-down one-up rule was used to measure the unmasked and the masked thresholds. Initially the probe level was varied in steps of 32 μA. After three reversals the probe levels was varied in steps of 8 μA. A threshold was calculated by averaging six reversals with a step size of 8 μA. For each electrode, unmasked or masked threshold was defined as the average of three runs.

3. Results

Table 2 shows the current levels (μA) producing most comfortable loudness levels for MP, low-pitch, and high-pitch PE maskers. Relative to MP stimulation, larger current levels were needed to generate comfortable loudness levels for PE stimulation. Fig. 3 shows the unmasked thresholds measured for a $PE_{\sigma = 0.75}$ probe (black solid line) and the masked thresholds measured for MP (red squares with solid line), low-pitch $PE_{\sigma = 0.5}$ (green circles with dotted line), and high-pitch $PE_{\sigma = 0.5}$ (blue triangles with dashed line) from probe primary electrodes 1 to 10. The abscissa shows the probe primary electrodes from 1 to 10 (1 = most apical electrode) and the ordinate shows the current (dB re: 1 μa). The error bars represent the standard error of the mean. For most conditions masked thresholds obtained for the PE probe in the presence of MP and the two PE maskers were elevated as compared to the unmasked thresholds. The difference between the unmasked and the masked thresholds is attributed to the spread of electrical excitation produced by the masker stimulus. In some conditions, the unmasked and the masked thresholds were similar for MP and the two PE maskers which is likely due to minimal spread of excitation from the masker stimulus in the vicinity of the corresponding probe electrode. The unmasked thresholds were subtracted from the masked thresholds to obtain masking patterns. The masking patterns obtained for MP and PE maskers cannot be compared directly due to overall level differences. For this reason the masking patterns were normalized by dividing the amplitude of the masking pattern at each electrode by the peak in the masking pattern. Fig. 4 shows the normalized masking patterns for MP (red squares with solid line), low-pitch PE (green circles with dotted line), and high-pitch PE (blue circles with dashed line) stimulation as a function of the probe primary electrode.

Table 2
Shows the current levels (μA) needed to produce most comfortable loudness (MCL) sensation, for low-pitch phantom (LP-PE), monopolar (MP), and high-pitch phantom (HP-PE) electrode stimulation in eight cochlear implant users.

Subject	MCL		
	LP-PE	MP	HP-PE
S1	133	72	142
S2	152	104	158
S3	208	128	210
C1	216	123	259
C3	104	56	113
C7	200	126	207
C14	248	138	295
C19	168	105	238
Average	178.62	106.50	202.75

To quantify the differences in the spread of excitation for MP and PE stimulation the normalized masking patterns were analyzed in terms of their area. Fig. 5 (left panel) shows the changes in area for the normalized LP-PE (box with green vertical hash marks) and HP-PE (box with blue diagonal hash marks) masking patterns relative to area calculated for the normalized MP (red dashed line) masking patterns. Overall a decrease in area was obtained for PE masking patterns which is consistent with the idea that PE stimulation can produce narrower spread of excitation relative to MP stimulation. A repeated measures ANOVA showed significant difference ($F_{2,14} = 7.046$, $p = 0.008$) between the area measured for LP-PE, MP, and HP-PE masking patterns. A post-hoc paired *t*-test revealed significant differences between the area measured for LP-PE and MP ($t_7 = 3.1954$, $p = 0.0151$), MP and HP-PE ($t_7 = 2.3182$, $p = 0.0054$), and a non-significant difference between the area measured for LP-PE and HP-PE ($t_7 = 2.1219$, $p = 0.0715$) masking patterns. As dictated by Rom's Bonferroni modification (Rom, 1990), we considered the post-hoc *t*-test to be significant when $p \leq 0.0169$.

To further characterize the differences in the spread of excitation between MP and PE stimulation, the normalized masking patterns were compared for the apical and basal regions of the forward masked spread of excitation curves separately. For MP, low-pitch, and high-pitch PE masking patterns the apical area was defined as the sum of the normalized masked thresholds on electrodes from 1 to the peak electrode of the MP masking pattern. The basal area was computed as the sum of the normalized masked thresholds on electrodes from the peak electrode of the MP masking pattern to electrode 10. Table 3 shows the apical and basal area for the normalized MP, low-pitch, and high-pitch PE masking patterns for the eight cochlear implant subjects. Fig. 5, middle and right panel show the changes in the apical and basal area for normalized LP-PE and HP-PE masking patterns relative to that calculated for normalized MP masking patterns. A repeated measures ANOVA showed significant differences across the apical ($F_{2,14} = 14.552$, $p < 0.0001$) and basal ($F_{2,14} = 24.595$, $p < 0.0001$) areas measured for normalized LP-PE, MP, and HP-PE masking patterns. Paired post-hoc *t*-tests showed significant differences between the apical area measured for LP-PE and HP-PE ($t_7 = 3.6244$, $p = 0.0085$), MP and HP-PE ($t_7 = 4.9135$, $p = 0.0018$), and a non-significant difference between the area measured for LP-PE and MP ($t_7 = 0.1254$, $p = 0.904$) masking patterns. A paired *t*-test revealed significant differences between the basal area measured for LP-PE and MP ($t_7 = 4.4876$, $p = 0.0029$), LP-PE and HP-PE ($t_7 = 5.5907$, $p = 0.0008$), and MP and HP-PE ($t_7 = 2.7801$, $p = 0.0269$) normalized masking patterns. As dictated by Rom's Bonferroni modification (Rom, 1990), we considered the post-hoc *t*-test to be significant when $p \leq 0.025$ for the apical area and when $p \leq 0.05$ for the basal area. These results are discussed in detail in the discussion section.

To quantify the differences in the centroid of electrical stimulation associated with MP and PE stimulation, the normalized masking patters were analyzed for their center-of-gravity which determines the location of the geometric center of excitation. Fig. 6 shows the changes in center-of-gravity calculated for normalized LP-PE (green box) and HP-PE (red box) masking patterns relative to normalized MP (red dashed line) masking patterns. The changes in center of gravity for PE stimulation show a more apical spread of excitation for low-pitch PE stimulation and a more basal spread for high-pitch PE stimulation as compared to MP stimulation. A repeated measure ANOVA showed significant differences ($F_{2,14} = 28.791$, $p = 0.0005$) between the center-of-gravity calculated for the three masking patterns. A paired *t*-test revealed

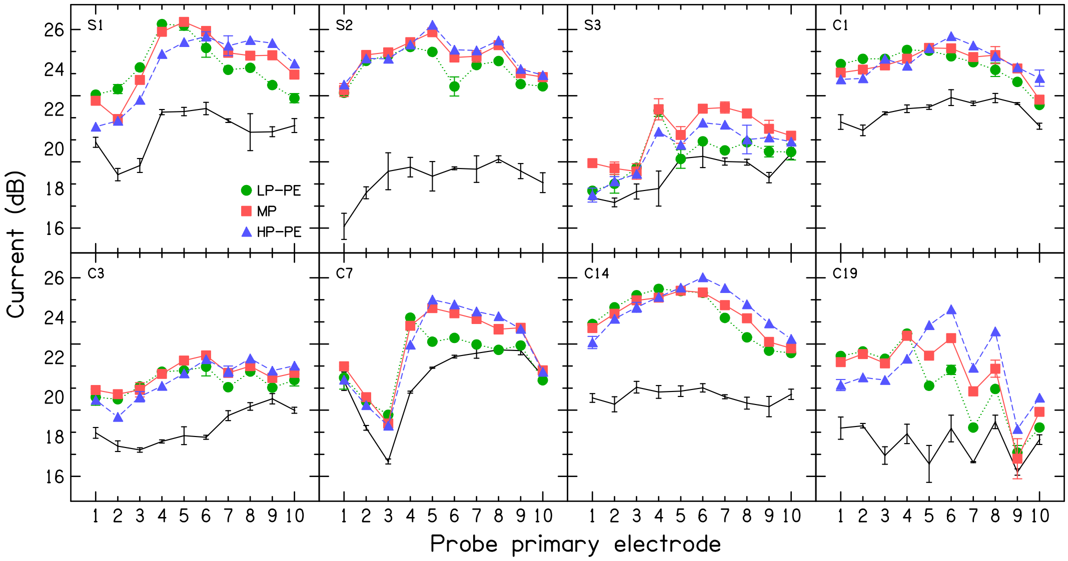

Fig. 3. This figure shows the unmasked thresholds (black solid line) and the masked thresholds for low-pitch phantom (LP-PE, green circles with dotted line), monopolar (MP, red squares with solid line), and high-pitch phantom (HP-PE, blue triangles with dashed line) in eight cochlear implant listeners. The error bars represent the standard error of the mean.

a statistically significant difference between the center of gravity measured for the LP-PE and MP ($t_7 = 4.3316$, $p = 0.0034$), LP-PE and HP-PE ($t_7 = 5.7297$, $p = 0.0007$), and MP and HP-PE ($t_7 = 5.8008$, $p = 0.0006$) masking patterns. As dictated by Rom's Bonferroni modification (Rom, 1990), we considered the post-hoc *t*-test to be significant when $p \leq 0.05$. These results are consistent with the direction of pitch shift reported by the cochlear implant users while comparing the pitches associated with MP, low-pitch, and high-pitch PE stimulation (Wilson, 1993; Saoji and Litvak, 2010) and are further discussed in the following section.

4. Discussion

In the present study, masking patterns were obtained to characterize the spread of excitation associated with MP, low-pitch PE, and high-pitch PE stimulation. The MP masking patterns showed a peak near the masker location and a decrease in masking as the spatial separation increased between the masker and probe. However, the MP masking patterns obtained for only two subjects C3 and C7 shows a peak on electrode 4 or the masker electrode. For other subjects the masking patterns revealed off-electrode tuning with a peak on electrode 5 or 6. Such off-electrode tuning has been reported previously (Hughes and Stille, 2009) and may be attributed to off-electrode listening (Dingemanse et al., 2006), asymmetric current flow in the cochlea where a greater portion of the current flows towards the base (Girzon, 1987), dead regions that may be attributed to inhomogeneous survival of peripheral and central auditory processes in implant users, and/or larger separation between the modiolus and the electrode due to the proximity of the electrode array to the lateral wall of the cochlea. Additionally,

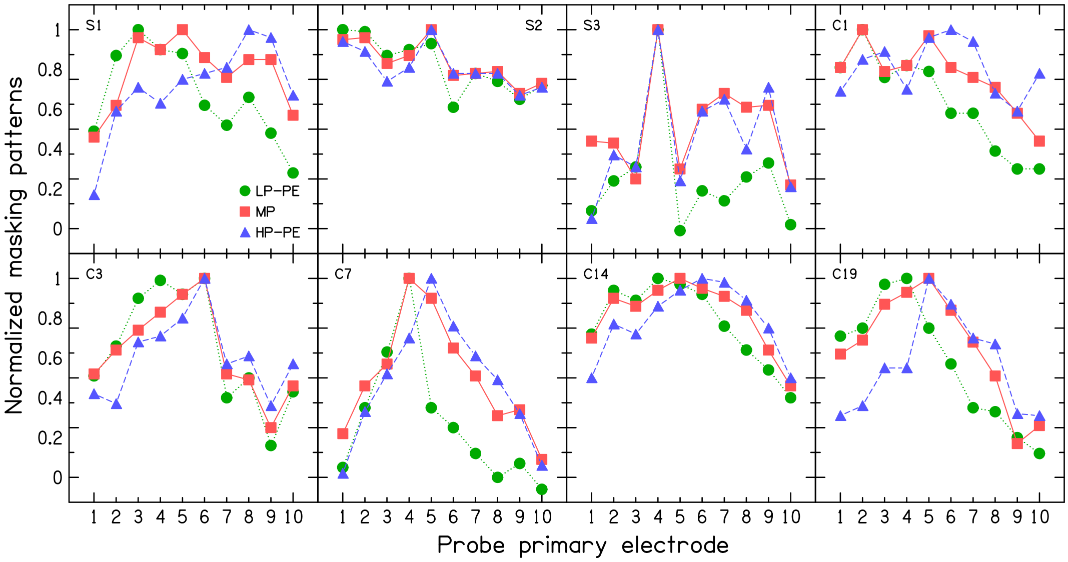

Fig. 4. This figure shows the normalized masking patterns for low-pitch phantom (LP-PE, green circles with dotted line), monopolar (MP, red squares with solid line), and high-pitch phantom (HP-PE, blue triangles with dashed line) stimulation in eight cochlear implant listeners.

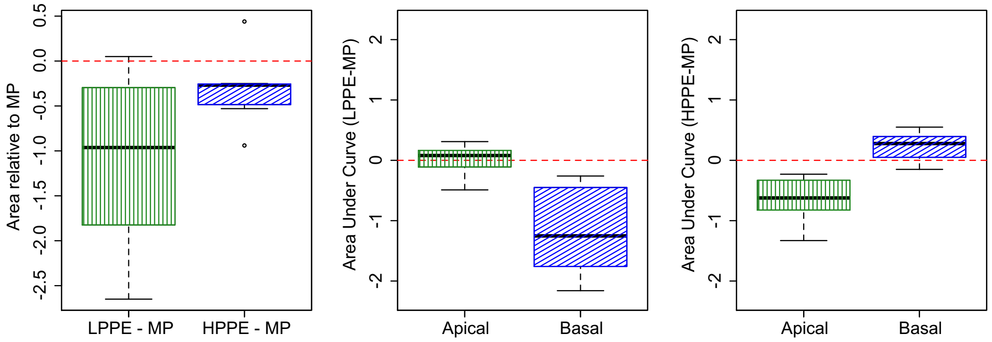

Fig. 5. In this figure, the left panel shows changes in area for low-pitch PE (LP-PE, box with green vertical hash marks), and high-pitch PE (HP-PE, box with blue diagonal hash marks) normalized masking patterns relative to MP (red dashed line) masking patterns. The middle and right panels show changes in apical and basal area for low-pitch PE (LPPE) and high-pitch PE (HPPE) relative to MP masking patterns. In each plot, the top and the bottom of the box represents 25th and 75th percentile and the horizontal line in the box shows the 50th percentile. Whiskers represent the minimum and maximum values in the distribution excluding outliers. Outliers are calculated to be more than 1.5 times the interquartile range and are represented with circles.

in the present study, a low-pitch $PE_{\sigma\,=\,0.75}$ probe was used to measure masked thresholds which results in a centroid of electrical stimulation that is apical to the location of the probe electrode. For example, $PE_{\sigma\,=\,0.75}$ probe on electrodes 5 (primary electrode) & 6 (compensating electrode) will result in a pitch sensation closer to that produced by electrode 4. For a monopolar masker on electrode 4 one is likely to achieve maximum masking when the PE probe is presented on electrode 5 which may explain some of the basally shifted off-electrode tuning obtained in this study.

It is important to note that the overall shape of the masking patterns reported here may be influenced by the partial-bipolar probe used in this study. Saoji et al. (2010) reported a reversal in the direction of pitch change for higher σ values. Therefore in some patients it is likely that the side lobe produced by the compensating electrode could be used to detect the partial bipolar probe with σ of 0.75. As a result one would expect slightly lower thresholds for the electrodes that are basally located to the peak electrode in the masking patterns. However, the same low-pitch $PE_{\sigma\,=\,0.75}$ was used to measure masked thresholds for the three modes of electrical stimulation and therefore is unlikely to affect the interpretation of the results obtained in this study.

In the present study, larger current levels were needed to achieve comfortable loudness sensation for PE stimulation relative to MP stimulation. These results are consistent with the reports that large current levels are needed to achieve comfortable loudness sensation for multipolar stimulation such as bipolar, tripolar and quadrupolar stimulation (Chatterjee et al., 2006; Litvak et al., 2007; Landsberger et al., 2012). The areas under the normalized masking curves obtained for LP and HP-PE stimulation were lower than that measured for MP stimulation which indicates that PE stimulation is able to produce narrower spread of electrical excitation as compared to the widely used MP stimulation in cochlear implants. These results are in contrast to the psychophysical forward masking patterns measured for MP and BP stimulation that have not shown a consistently narrow spread of excitation for BP relative to MP stimulation (Cohen et al., 2001; Chatterjee et al., 2006; Kwon and van den Honert, 2006b). One hypothesis is that large current levels are needed to achieve comfortable loudness sensation for bipolar stimulation that can exceed the compliance limit of the implant system and bipolar + n configurations have been shown to produce broader electrical excitation with a double peak electrical excitation pattern (Chatterjee et al., 2006). These results are consistent with the report that the cochlear implant speech perception is similar for MP and bipolar stimulation (Pfingst et al., 1997). Relative to bipolar simulation, lesser current is needed to achieve comfortable loudness sensation with $PE_{\sigma\,=\,0.5}$ (Saoji and Litvak, 2010) which results in a smaller compensation current for PE stimulation and consequently narrower electrical excitation as compared to MP stimulation. Therefore, the electrical field or the side lobe is much smaller than the large side lobe generated by the component electrodes used for bipolar stimulation (Chatterjee

Table 3
Shows the individual and average apical and basal area computed for the normalized masking patterns obtained for monopolar (MP), low pitch phantom (LP-PE), and high-pitch phantom (HP-PE) stimulation for eight cochlear implant subjects.

Subjects	LP-PE		MP		HP-PE	
	Apical	Basal	Apical	Basal	Apical	Basal
S1	4.14	3.41	3.93	4.86	2.97	5.16
S2	4.69	4.46	4.61	4.80	4.38	4.77
S3	1.67	1.97	2.16	4.13	1.77	3.98
C1	1.80	5.52	1.81	6.89	1.54	7.44
C3	4.93	2.46	4.62	2.72	3.97	3.11
C7	2.04	1.73	2.25	3.80	1.56	3.93
C14	4.52	4.24	4.40	4.80	3.80	5.06
C19	4.18	2.32	4.10	3.46	2.77	3.86
Average	3.50	3.26	3.48	4.43	2.84	4.66

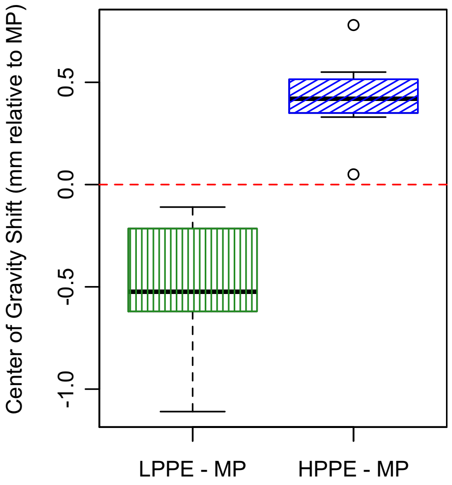

Fig. 6. This figure shows changes in center-of-gravity for low-pitch (LPPE, green box with vertical hash marks) and high-pitch (HPPE, blue box with diagonal hash marks) PE stimulation relative to the center-of-gravity calculated for the MP (red dashed line) masking patterns. The circles represent the outliers that exceed 1.5 times the interquartile range (for details see Fig. 5 caption).

et al., 2006). Further research is needed to determine if a multi-electrode PE speech coding strategy with presumably lesser overlapping bands of electrical excitation as compared to MP stimulation will result in improved speech perception and music appreciation by implant users.

The center-of-gravity calculations show a more apically located centroid of electrical stimulation for low-pitch PE stimulation and more basally located centroid of electrical stimulation for high-pitch PE stimulation which are consistent with the direction of pitch shift reported by the cochlear implant users (Wilson, 1993; Saoji and Litvak, 2010; Macherey et al. 2011; Macherey and Carlyon, 2012). Some of the changes in the center-of-gravity can be attributed to the narrower spread of electrical excitation associated with PE stimulation. To further understand the changes in spread of excitation for PE stimulation relative to MP stimulation, the normalized masking patterns were analyzed in terms of their apical and basal area. This analysis shows a significantly lesser excitation at the basal end for low-pitch PE stimulation and a significantly lesser excitation at the apical end for high-pitch PE stimulation. This is consistent with the notion that the compensating electrodes in the low-pitch and high-pitch PE stimulation limits the spread of current towards the basal and the apical end of the cochlea, respectively.

The changes in the apical and basal area for HP-PE stimulation relative to MP stimulation suggests that the compensating electrode limited the apical spread of excitation and simultaneously pushed the current more basally for HP-PE stimulation. These results are consistent with the spread of excitation shown for HP-PE stimulation relative to MP stimulation in Fig. 1, panel C. For LP-PE stimulation only the basal area was significantly different from that measured for MP stimulation which is similar to the spread of excitation patterns plotted in Fig. 1, panel A. However, it should be noted that masking patterns obtained for individual implant users such as C1, C3, and S19 suggests that the LP-PE stimulation was able to push the spread of excitation more apically than produced by MP stimulation. Relative to MP stimulation, the center-of-gravity analysis shows a larger shift in the centroid of electrical stimulation for HP-PE as compared that produced by LP-PE stimulation. The larger shift in the centroid of electrical stimulation for high-pitch PE stimulation as compared to low-pitch PE stimulation may be attributed to the asymmetry of the current flow in the cochlea, whereby there is a tendency for a greater portion of the current flows towards the basal end of the cochlea (Girzon, 1987). It should be noted that in some implant users low-pitch and high-pitch PE stimulation may have produced a change in the peak of electrical excitation by less than 1 electrode which cannot be measured by the limited resolution or a step size of 1 electrode that is used to measure psychophysical forward masking patterns in cochlear implants.

The results of the present study show that in some cochlear implant users it is possible to push the current more apically or basally than that achieved by MP stimulation of the most apical and most basal electrode in implant users. Therefore PE stimulation can provide a non-invasive method of extending the range of lower and higher pitches generated by the stimulation of the most apical and most basal electrode in cochlear implants. Also, PE stimulation is able to reduce spread of excitation relative to MP stimulation and produce more focused electrical stimulation. Another application of PE stimulation is to compensate for the loss of stimulation from a disabled apical (electrode 1) or basal (electrode 16) electrode if there are functional problems with either of these electrodes.

5. Conclusions

In the present study, psychophysical forward masking was used to obtain masking patterns for MP, low-pitch, and high-pitch PE stimulation. The masking patterns show differences in the spread of excitation between MP and PE stimulation that are consistent with the direction of pitch shift produced by PE stimulation. Masking patterns revealed (1) narrower spread of electrical excitation for PE stimulation as compared to MP stimulation which can be attributed to the compensating electrode (2) a change in the centroid of electrical stimulation which is consistent with the direction of pitch shift produced by PE stimulation. Further research is needed to determine if PE stimulation can be used to extend the range of pitches in cochlear implant recipients that allows better encoding of the speech spectrum. Also, PE stimulation may be used to limit the spread of electrical excitation associated with multi-electrode stimulation which could potentially lead to increased spectral resolution and consequently improved speech perception in implant recipients.

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