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Perception de la hauteur chez le sujet implanté cochléaire (Extending the range of pitch perception by cochlear implant listeners)

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Pour l'implanté cochléaire, le codage de la hauteur s'effectue suivant deux dimensions orthogonales correspondant au locus d'excitation dans la cochlée (codage spatial) et à la cadence de répétition du signal (codage temporel). Ces deux types d'indices ont toutefois leurs limites. Premièrement, le codage spatial est limité par le fait que les électrodes ne sont en général pas implantées jusqu'au bout (apex) de la cochlée et ne stimulent donc pas les fibres nerveuses codant les fréquences les plus basses. Deuxièmement, le code temporel est en général limité à des cadences inférieures à 300 Hz. Au-delà, la sensation de hauteur ne change peu ou pas. Nous montrons ici qu'il est possible de remédier en partie à ces deux limitations en modifiant la forme du signal électrique délivré par l'implant. Sept implantés cochléaires porteurs de l'implant HiRes90K de Advanced Bionics ont pris part à une série d'expériences. Dans l'expérience 1, ils ont comparé les hauteurs produites par plusieurs signaux électriques présentés en mode bipolaire sur un canal de leur implant. Les stimuli étaient soit symétriques (ayant deux phases de polarité opposée mais de même durée et intensité) soit asymétriques (avec une seconde phase plus longue et de moindre amplitude que la première). La hauteur la plus basse (suivant le codage spatial) fut obtenue pour un signal asymétrique ayant pour anode l'électrode la plus apicale de l'implant. Dans l'expérience 2, ils ont comparé les hauteurs de sons ayant différentes cadences de répétition en utilisant la procédure optimale « mid-point comparison » [1]. Les sujets devaient ordonner plusieurs stimuli ayant des cadences allant de 105 à 1156 Hz. Cette tache fut répétée à différents sites intracochléaires et pour différentes formes de signaux. La fréquence de saturation du code temporel pour le signal asymétrique présenté à l'apex de la cochlée fut supérieure à toutes les autres conditions, avec une moyenne d'à peu près 700 Hz. Des mesures complémentaires de seuils différentiels obtenues avec la méthode du stimulus constant indiquent, cependant, que ce percept est peu saillant.

1 Introduction

Pitch cues can be conveyed to cochlear implant (CI) listeners along two perceptually-independent dimensions corresponding to the locus of excitation along the cochlea (referred to as "place pitch") and to the repetition rate of the electrical waveform ("temporal pitch"). Both of these cues suffer from limitations. First, the range of place pitches is limited by the fact that electrodes are usually not inserted all the way into the apex of the cochlea. Second, most studies of temporal pitch perception reveal an "upper limit" of about 300 to 500 pulses per second (pps), beyond which changes in repetition rate do not produce an increase in pitch [2-3].

Recent physiological data showed that neurons in the inferior colliculus were better at encoding rate when neural information was coming from the apex of the cochlea [4]. If this result applies to human CI listeners, we would expect the upper limit of temporal pitch to be higher for apical than for basal electrodes. However, several studies failed to find any superiority of apical stimulation [3, 5]. Here, we re-examine this issue using different stimuli and methods.

Our stimuli are based on the findings that (1) short pulse durations are more effective (i.e. need less charge) than long pulse durations to elicit the same loudness and that (2) the anodic (positive) phase of an electrical pulse is more effective than the cathodic (negative) phase [6-7].

Figure 1 schematizes some expected spatial excitation patterns in response to different pulse shapes. For symmetric biphasic pulses presented to a monopolar channel ("BI-Mono"), we expect a broad excitation pattern centered (black arrow) on the active electrode (here the most apical). In the case of bipolar stimulation, each intracochlear electrode is stimulated with reference to another nearby intracochlear electrode. This can be viewed as stimulating simultaneously both electrodes with opposite-polarity pulses. When using symmetric pulses ("BI"), the pulse will be anodic relative to the more apical electrode during the first phase and anodic relative to the more basal electrode during the second phase, thereby creating equal amounts of excitation in the vicinity of both electrodes.

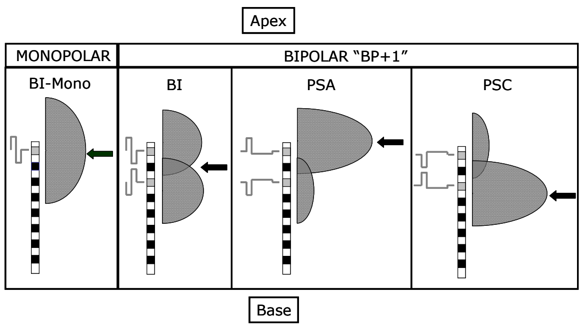

Figure 1: Illustration of four expected spatial excitation patterns (grey zones shown on the right of each panel) in response to different pulse shapes (shown on the left). The arrow indicates the center of gravity of the pattern.

However, by using pseudomonophasic pulses with a short, high-amplitude phase anodic relative to the most apical electrode ("PSA"), we expect nerve fibers proximal to the most apical electrode to be more effectively excited than fibers proximal to the other electrode (because the "effective" anodic short phase is presented on the more apical electrode). The opposite pattern should be obtained if the polarity is reversed ("PSC"). Some recent masking and pitch data collected in a wide "BP+9" bipolar configuration corroborated this hypothesis [8]. The aims of the present study are to extend these results to narrower bipolar configurations (BP+1) and to investigate their impact on the perception of pitch.

Here, we show that such pulses can elicit a lower place pitch percept than symmetric pulses presented in monopolar or in bipolar mode and that they allow the subject to perceive increases in temporal pitch up to higher rates than for other intracochlear stimulation sites and/or pulse shapes.

We also show that the "upper limit" of temporal pitch correlated negatively, across waveform shape and site of stimulation, with the current level needed to reach a comfortable loudness. This and other results suggest that selective stimulation of the cochlear apex may improve temporal pitch perception at high rates via a more effective electrode-neural interface – perhaps resulting from better neural survival – rather than by activating a central pathway dedicated to fine temporal processing.

2 Experiment 1: Place Pitch

2.1 Methods

This experiment was designed to compare the place pitches evoked by the four stimuli illustrated in Fig. 1. Eight users of the CII/HiRes 90k device took part.

Stimuli were trains of 500-ms unmodulated pulse trains presented on a single channel on the most apical channel of the implant in bipolar "BP+1" mode (electrodes 1 and 3) or in monopolar mode (with the case electrode as the return contact). The phase duration was always 97 µs except for pseudomonophasic pulses for which the duration of the second phase was increased by a factor of 4 and its amplitude reduced by the same amount to maintain charge-balancing. We used a very low pulse rate of 12 pulses per second (pps) to avoid any influence of temporal pitch cues on the pitch percept. At this rate, subjects can hear individual pulses and there is, therefore, no temporal pitch component to the percept. Stimuli were presented through the APEX experimental software platform which acts as an interface for the BEDCS software provided by Advanced Bionics [9].

The stimuli were first loudness balanced at a comfortable loudness using a procedure similar to that used by Macherey and Carlyon [10]. Pitch differences were then assessed in a two-interval, two-alternative forced-choice task. In each trial, subjects listened to two different sounds separated by a gap of 500 ms and had to indicate which stimulus had the higher pitch by pressing one of two virtual buttons displayed on a computer screen. Several pitch comparisons were mixed in blocks of 60 or 80 trials. We will show the results of four comparisons (cf. Fig. 1): PSA vs. PSC, PSA vs. BI, PSA vs. BI-Mono and BI vs. BI-Mono. There were at least 60 repetitions for each of these comparisons.

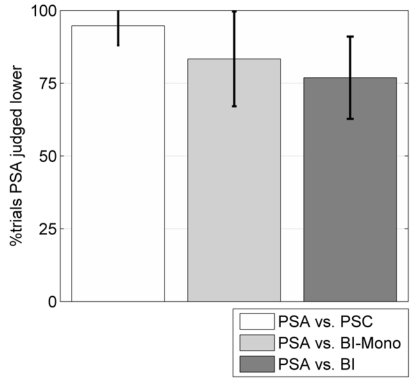

Figure 2 : Results of Experiment 1.

2.2 Results

Fig. 2 shows the percentage of trials on which the PSA stimulus was judged lower in pitch than each of the others. The bars show the mean and 95% confidence intervals and demonstrate that overall, PSA had a significantly lower pitch than PSC, BI and BI- Mono.

This suggests that the center of gravity of the excitation pattern produced by PSA is more apical than that produced by all the other pulse shapes, thereby corroborating the initial hypothesis of this study. The individual results indicate that PSA was lower than all the other stimuli for all subjects except one for whom BI- Mono was the lowest and three for whom BI had the same pitch as PSA.

Finally, although the results of the BI vs. BI-Mono comparison are not shown, there was no consistent pitch difference between these two stimuli (very variable across subjects).

3 Experiment 2: Temporal Pitch

3.1 Methods

In Experiment 2a, the upper limit of temporal pitch was determined for four different stimulus conditions which were PSA at the apex ("PSA-Apex"), PSC at the apex ("PSC-Apex"), PSA in the middle ("PSA-Middle") of the electrode array (electrodes 7 and 9) and BI, also in the middle ("BI-Middle"). The phase durations were the same as those used in Experiment 1 and the total duration of the stimuli was 400 ms. For each condition, there were 7 different pulse rates ranging from 191 to 1146 pps (difference between consecutive rates of 35%). This rather "high" range of rates was chosen because the initially lower range (105 to 859 pps) at which subjects performed the task showed ceiling effects. After loudness-balancing, the stimuli were pitch-ranked using the mid-point comparison procedure, which has been described in detail elsewhere [1, 10]. Briefly, it consists of making pitch comparisons between pairs of sounds. The choice of sounds to be presented on a given trial is driven by the results of previous trials in such a way that the whole set of stimuli can be pitch-ranked in a minimum of comparisons. By repeating the procedure several times, a mean and standard error of the rank is obtained for each stimulus. The four conditions were run in separate blocks presented in alternation and in a randomized order (which differed across subjects). Depending on time available within the session, between 10 and 15 blocks per condition were collected. No feedback was provided. Six CI subjects took part (all had performed Experiment 1).

Although the mid-point comparison allows us to capture the upper limits of temporal pitch in different conditions, it does not give information on the strength of the percept and on how small a difference can the subjects perceive. In Experiment 2b, we measured rate difference limens (DLs) at three different base-line rates (105, 344 and 644 pps) for PSA-Apex. Five subjects took part in this sub-experiment. The procedure was a two-interval forced choice, 2-down, 1-up, adaptive task. The change from increasing to decreasing rate or vice versa was called a turnpoint, and the procedure ended after ten turnpoints. The initial rate difference was 35%, the same difference as that used in Experiment 2a. The step size of the rate change was 8% and switched to about 2% after three turnpoints. The DL value was calculated as the mean of the last six turnpoints. Between 3 and 5 repetitions were collected at each rate. Because we knew that for this range of rates, pitch increased monotonically, feedback was provided.

3.2 Results

Fig. 3a illustrates the results of one subject for three of the four conditions of Experiment 2a (filled squares for PSA-Apex, asterisks for PSC-Apex and open triangles for PSA-Middle). The results for BI-Middle were similar to those obtained with PSA-Middle and are not shown here.

For the six subjects, the rank function of PSA-Apex increased up to very high rates (more than 644 pps) while the other conditions showed more inconsistent results. It is, however, worth noting that for any given subject, it was usually the case that pitch increased up to high rates for one condition other than PSA-Apex, although which condition this was differed across subjects. In other words, good temporal pitch perception at high rates is possible with a range of cochlear sites and waveform shapes, but only occurs consistently for PSA stimuli at the apex.

The upper limits of temporal pitch were obtained by fitting broken-stick functions (comprising one portion increasing linearly as a function of the logarithm of the rate followed by a second, constant portion) to each data set. The upper limit was assumed to be the knee-point between the two portions of the broken-stick fit. Fig. 3b shows the mean and standard errors of these upper limits. A repeated-measures ANOVA performed on the log of the upper limit data revealed a main effect of condition ($F(1.6, 8.0)=7.28$, $p=0.019$). The upper limit for PSA-Apex was significantly higher than that for PSC-Apex ($p=0.029$), PSA-Middle ($p=0.002$) and BI-Middle ($p=0.001$). We also compared the upper limits of PSA-Apex and BI-Middle taking into account the results of an additional subject who did a preliminary experiment using a lower range of rates. A student t-test revealed that the mean upper limit was significantly higher ($p=0.011$) for PSA-Apex (713 pps) than for BI-Middle (374 pps).

Although the higher upper limit of temporal pitch, obtained with the PSA stimuli at the apex, is consistent with better central processing of apical stimulation [5], we wanted to test whether the PSA stimuli could have increased the upper limit of temporal pitch for another reason. Specifically, it has been suggested that that there is a more efficient electrode-neural interface at the apex than at the base of the cochlea, perhaps resulting from better neural survival [11-12]. We therefore investigated whether the current level needed for most comfortable loudness (MCL) correlated, across conditions, with the upper limit of temporal pitch. Fig. 3c shows for each subject and each condition, the log of the upper limit as a function of the MCL in dB re 1 mA. The data were first standardized to remove between-subject differences. Standardized MCL and standardized upper limits were indeed negatively correlated ($r=-0.67$, $df=17$, $p=0.0017$). An additional one-way ANOVA analysis was performed on the upper limits of the four conditions with MCL as a covariate. In this case, the effect of condition was not significant anymore ($p=0.39$). This relation between the upper limit of temporal pitch and the current level needed to reach a particular loudness strongly suggests a peripheral component to the differences in performance observed between the different conditions.

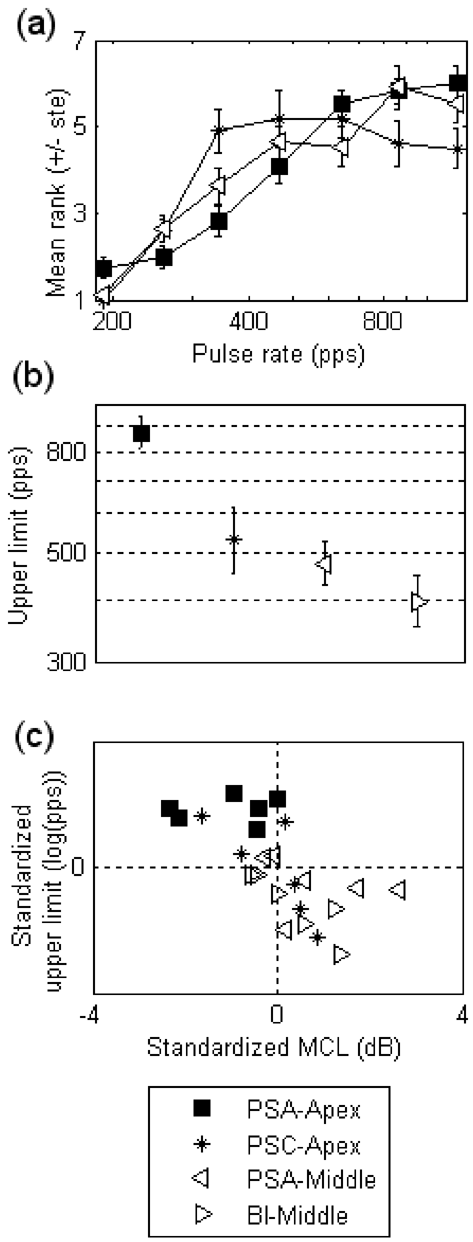

Figure 3: Results of Experiment 2a. (a) Example of results obtained with one subject. (b) Mean upper limits of temporal pitch averaged across subjects. (c) Individual upper limit of temporal pitch plotted as a function of the current level needed to reach a comfortably loud percept.

In Experiment 2b, all subjects performed at ceiling for a 105-pps base-line (their DLs were lower than 5%). However, at 344 and 644 pps, only two subjects could perform the task. Their averaged DLs across repetitions were 24 and 14% for S1 and 18 and 16% for S6, respectively for 344 and 644 pps base-line rates. DLs could not be measured with the other three subjects, suggesting that they were larger than 35%. We further used the method of constant stimuli (without feedback) and measured the percentage of trials where they could detect a 35% rate difference at 344 and 644 pps. At least 60 trials were performed at each rate. At 344 pps, mean percent correct ranged from 69 to 77% whereas it was between 51 and 68% at 644 pps.

This rather poor performance measured at 344 and 644 pps in three of the subjects suggests that, despite a measurable increase in the upper limit of temporal pitch obtained in Experiment 2a, it is likely that the temporal pitch percept is still very weak at such high rates.

4 Conclusion

Extending the range of place pitches towards the apex by using pseudomonophasic pulses may effectively add another (potentially important) channel of information to implant users. It may also be useful to patients with a partial electrode insertion for whom stimulation is restricted to the basal part of the cochlea.

Consistent with the finding of Middlebrooks and Snyder [4], our results suggest that selectively stimulating the apex also leads to a better transmission of phase-locking cues. Interestingly, they found that only a small portion (13 to 14%) of the sampled IC units was able to follow a 600-pps pulse train. Our data showing large DLs (and weak percept) at high rates are consistent with these measures, in that there is probably a very small portion of units conveying the temporal code.

Our results may be interpreted in two different ways. First, it is possible that they partly reflect the existence of a central mechanism able to follow temporal fine structure cues up to high rates only when neural information originates at the apex of the cochlea. Second, it is likely that they also reflect a more peripheral factor. Several observations argue for the peripheral explanation:

(i) Some subjects performed almost as well in the middle of the array.

(ii) There was a negative correlation between the level of stimulation needed to reach a comfortable percept and the upper limit of temporal pitch.

(iii) The upper limit of temporal pitch measured at the base of *normal-hearing* subjects (characteristic frequencies of 9300 Hz) is similar to that found in CI users listening to PSA-Apex pulses [13].

Acknowledgements

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