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Research paper

Simulating the dual-peak excitation pattern produced by bipolar stimulation of a cochlear implant: Effects on speech intelligibility

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ABSTRACT

Several electrophysiological and psychophysical studies have shown that the spatial excitation pattern produced by bipolar stimulation of a cochlear implant (CI) can have a dual-peak shape. The perceptual effects of this dual-peak shape were investigated using noise-vocoded CI simulations in which synthesis filters were designed to simulate the spread of neural activity produced by various electrode configurations, as predicted by a simple cochlear model. Experiments 1 and 2 tested speech recognition in the presence of a concurrent speech masker for various sets of single-peak and dual-peak synthesis filters and different numbers of channels. Similarly as results obtained in real CIs, both monopolar (MP, single-peak) and bipolar ($BP+1$, dual-peak) simulations showed a plateau of performance above 8 channels. The benefit of increasing the number of channels was also lower for $BP+1$ than for MP. This shows that channel interactions in $BP+1$ become especially deleterious for speech intelligibility when a simulated electrode acts both as an active and as a return electrode for different channels because envelope information from two different analysis bands are being conveyed to the same spectral location. Experiment 3 shows that these channel interactions are even stronger in wide BP configuration ($BP+5$), likely because the interfering speech envelopes are less correlated than in narrow $BP+1$. Although the exact effects of dual- or multi-peak excitation in real CIs remain to be determined, this series of experiments suggest that multipolar stimulation strategies, such as bipolar or tripolar, should be controlled to avoid neural excitation in the vicinity of the return electrodes.

1. Introduction

Most contemporary cochlear implants (CIs) stimulate the auditory nerve by delivering current pulses to individual intra-cochlear electrodes with reference to a far-field ground. This so-called monopolar (MP) configuration produces a broad spread of excitation across the auditory nerve array. Consequently, different electrodes excite overlapping neural populations and limit the number of independent information channels that can be transmitted to CI listeners. Specifically, these interactions are believed to be responsible for the inability of many patients to benefit from more than about eight electrodes (Fishman et al., 1997; Friesen et al., 2001; Fu and Nogaki, 2004).

To overcome this limitation, several multi-electrode configurations have been proposed and tested. Animal studies have shown that the spread of excitation can be reduced using bipolar (BP) or tripolar (TP) stimulation where current pulses are delivered between two or three closely-spaced intra-cochlear electrodes (Kral et al., 1998; Bierer and Middlebrooks, 2002; Snyder et al., 2004, 2008; Bierer et al., 2010). Paradoxically, attempts to use these spatially “focused” configurations in CI users have produced inconsistent results. Using psychophysical forward masking, Kwon and van den Honert (2006) observed no difference between the widths of the patterns produced by MP and BP stimuli in a group of six CI subjects whereas Boex et al. (2003) found a small advantage for BP in the two subjects they tested. Although Nelson et al. (2008) reported forward-masked tuning curves that were narrower for BP than for MP, these tuning curves were measured in different subjects for the two configurations. Given these two groups of subjects

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Abbreviations: AF, Analysis filter; ANOVA, Analysis of Variance; AS, Asymmetric; BP, Bipolar; CI, Cochlear Implant; CTN, Continuous; CTRL, Control; dB, Decibel; Eq., Equation; Exp., Experiment; Fc, Cut-off frequency; Fig., Figure; F0, Fundamental frequency; G, Greenwood's function; HL, Hearing Level; L_{dB}, Intensity spectrum level; MOD, Maximum of depolarization; MP, Monopolar; N, Number of channels; $N_{firings}$, Number of neural firings; RAU, Rationalized arcsine units; SF, Synthesis filter; SPL, Sound Pressure Level; TMR, Target-to-masker ratio; TP, Tripolar; V, Electrical potential

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also had different implant types and electrode designs, it remained unclear whether the difference in tuning was due to the difference in electrode configuration or to some other factors. More recent data comparing forward-masked tuning curves did not find any difference between MP and BP although the same subjects were tested in both configurations (Bingabr et al., 2014). Spatial selectivity of TP stimulation was recently investigated in three studies (Bierer and Faulkner, 2010; Landsberger et al., 2012; Fielden et al., 2013). Modest but significant improvements were reported for TP compared to MP although, here again, substantial inter-subject variability was noticed.

Several studies have also compared speech recognition scores obtained with MP and BP (Lehnhardt et al., 1992; Zwolan et al., 1996; Pfingst et al., 1997; Kileny et al., 1998). These studies did not find any advantage for BP and sometimes even showed better performance for MP. Rather counter-intuitively, Pfingst et al. (1997) reported that speech perception of CI listeners improved when the spacing between the electrodes of each bipolar channel increased from one to six inactive electrodes. More recently, speech processing strategies using the "partial-tripolar" configuration have shown slightly more encouraging results. Partial tripolar is identical to tripolar except that a fraction of the current returns to the extra-cochlear ground electrode. Although Mens and Berenstein (2005) did not find any advantage of using partial tripolar over MP stimulation, Srinivasan et al. (2013) reported an improvement in speech reception threshold of about 3 dB for partial tripolar in a group of five Advanced Bionics subjects.

There may be several reasons for these rather disappointing and inconsistent results. First, as suggested by Kwon and van den Honert (2006), it is possible that MP and focused (BP or TP) stimuli produce similar spreads of excitation when compared at the same loudness. Two electrophysiological studies have underlined the importance of the current levels at which the excitation patterns generated by different configurations are compared. Smith and Delgutte (2007) measured the spread of excitation produced by MP and BP stimuli in the inferior colliculus of the cat. They observed that the patterns produced by both stimuli at levels within a 5-dB range above their respective thresholds had comparable peak amplitudes and spreads of excitation. Similarly, Schoenecker et al. (2012) equated their MP and BP stimuli so that they produced the same peak spike rate in inferior colliculus neurons and found similar tonotopic spreads of excitation for both configurations.

Second, Pfingst et al. (2001) have argued that a broad spread of excitation (i.e. using either BP with a large spacing between electrodes or MP) may provide more robust information to the central auditory system by recruiting a larger population of neurons than BP with closely-spaced electrodes. Consistent with this hypothesis, Middlebrooks (2008) showed that modulation detection thresholds, as measured electrophysiologically at the level of the auditory cortex of guinea pigs, were worse for BP than for MP. He showed that MP stimulation produced synchronous activation over a broader range of neurons than BP, thereby conveying temporally-more precise information to the auditory cortex. This suggests that, even if spatial selectivity is improved in some CI subjects, performance on speech perception tasks may not because of a concomitant decrease in modulation sensitivity.

Third, it has been shown by Kwon and van den Honert (2006) that BP stimulation produces thresholds and forward masking patterns that are more irregular across the electrode array than those produced by MP. This pattern variability may be due to differences in electrode placement or to an irregular distribution of neural survival but also to the fact that focused stimulation requires the stimulation of at least two intra-cochlear electrodes. Several computational modeling studies have shown that this can produce discrete peaks of excitation proximal to each electrode (Frijns et al., 1996; Hanekom, 2001; Litvak et al., 2007; Bonham and Litvak, 2008). For example, in BP stimulation, two main groups of neurons may be excited, close to each stimulated electrode. Such *dual-peak* excitation patterns have also been reported in an electrophysiological animal study (Snyder et al., 2008) and in psychophysical and electrophysiological human CI studies (Lim et al., 1989; Chatterjee et al., 2006; Undurraga et al., 2012). This dual-peak shape may also arise when measuring tuning curves. Kral et al. (1998) reported "tip-splitted" neural tuning curves in about 30% of cats' single auditory nerve fibers subjected to BP stimulation. These tuning curves showed a maximum surrounded by two minima with a threshold difference of about 5 dB between them. Using psychophysical masking, Nelson et al. (2008) and Zhu et al. (2012) also observed tip-splitted tuning curves in some of their human CI subjects stimulated in BP configuration. Similarly, for TP stimulation, if the amount of current returning to the neighboring electrodes is large (e.g. at loud levels), each return electrode may produce excitation in its vicinity, potentially creating a triple-peak excitation pattern and decreasing any putative increase in spatial selectivity (Litvak et al., 2007). One potential problem of transmitting the information extracted from a given spectral channel through multi-peak auditory-nerve excitation arises when considering how electrodes are activated in a speech-coding strategy. If the aim is to maximize the number of spectral channels that are conveyed, each intra-cochlear electrode needs to serve both as the "active" electrode of one channel and as the "return" electrode of another (in bipolar) or several other (in tripolar) channel(s). Therefore, a given electrode may stimulate the same, spatially-restricted, neural population with information extracted from very different frequency bands.

The main goal of the present study was to investigate the effects of such multi-peak excitation patterns on the perception of speech, focusing on the comparison between single- and dual-peak shapes. These effects were tested in normal-hearing subjects listening to noise-vocoded simulations for two main reasons. First, the performance of CI listeners is subject to an inherent variability due to several potential factors including peripheral ones such as the tonotopic distribution of residual nerve fibers or the distance between the electrodes and the fibers (Blamey et al., 2013; Long et al., 2014). These peripheral factors may explain why different electrodes in a given subject show variable degrees of spatial selectivity (Bierer and Faulkner, 2010). These sources of variability are not involved when testing normal-hearing subjects. Furthermore, acoustic simulations provide an accurate control of stimulation parameters that may not be easily manipulated in a real CI. Although a lot of CI simulation studies have investigated the effect of channel interactions on speech (Friesen et al., 2001; Fu and Nogaki, 2004; Bingabr et al., 2008; Strydom and Hanekom, 2011a, 2011b) and pitch perception (Laneau et al., 2006; Crew et al., 2012), to our knowledge, none of them has included multi-peak excitation patterns. Here we present the results of three speech recognition experiments specifically designed to better understand these effects. In Experiments 1 and 2, speech perception is measured for different numbers of channels and different single- and dual-peak simulated excitation patterns. In Experiment 3, we focus on simulating the effect of electrode separation in BP stimulation and try to relate the present findings to previously published CI data (Pfingst et al., 1997, 2001).

2. General methods

2.1. Subjects

17 normal hearing subjects were paid to take part in a series of three vocoded speech recognition experiments. Written informed consent was obtained from all subjects prior to data collection. The