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Research paper

Loudness and pitch perception using Dynamically Compensated Virtual Channels

Waldo Nogueira [a, *], Leonid M. Litvak [b], David M. Landsberger [c], Andreas Büchner [a]

[a] Medical University Hannover, Cluster of Excellence “Hearing4all”, Hannover, Germany
[b] Advanced Bionics LLC, Valencia, CA, USA
[c] New York University School of Medicine, New York, NY, USA

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ABSTRACT

Reducing power consumption is important for the development of smaller cochlear implant (CI) speech processors. Simultaneous electrode stimulation may improve power efficiency by minimizing the required current applied to a given electrode. Simultaneous in-phase stimulation on adjacent electrodes (i.e. virtual channels) can be used to elicit pitch percepts intermediate to the ones provided by each of the physical electrodes in isolation. Virtual channels are typically implemented in monopolar stimulation mode, producing broad excitation patterns. Focused stimulation may reduce the excitation patterns, but is inefficient in terms of power consumption. To create a more power efficient virtual channel, we developed the Dynamically Compensated Virtual Channel (DC-VC) using four adjacent electrodes. The two central electrodes are current steered using the coefficient α ($0 < \alpha < 1$) whereas the two flanking electrodes are used to focus/unfocus the stimulation with the coefficient σ ($-1 < \sigma < 1$). With increasing values of σ, power can be saved at the potential expense of generating broader electric fields. Additionally, reshaping the electric fields might also alter place pitch coding.

The goal of the present study is to investigate the tradeoff between place pitch encoding and power savings using simultaneous electrode stimulation in the DC-VC configuration. A computational model and psychophysical experiments in CI users have been used for that purpose.

Results from 10 adult Advanced Bionics CI users have been collected. Results show that the required current to produce comfortable levels is significantly reduced with increasing σ as predicted by the computational model. Moreover, no significant differences in the estimated number of discriminable steps were detected for the different values of σ. From these results, we conclude that DC-VCs can reduce power consumption without decreasing the number of discriminable place pitch steps.

1. Introduction

Cochlear implants (CIs) are implantable medical devices that are used to restore the sense of hearing for people with profound hearing loss or deafness. Over the past few decades, the CI sound processor has been extensively developed to improve speech intelligibility outcomes (Wilson et al., 1991; Loizou, 1998; Wouters et al., 2015). With current technology, CI users tend to have good speech recognition in quiet but have difficulty in understanding speech in more difficult listening environments. Additionally, the size of the CI sound processor has been greatly reduced. Nevertheless, both performance with the CI and size of the sound processor still need to be improved. Because the batteries limit miniaturization of the sound processor, it is crucial to design strategies and implants that more efficiently use power while maintaining or improving performance.

Current CI systems require the user to wear an external device with batteries, microphone, sound processor, and transmitting coil to power and control the internal device. Both the internal and external components are powered by the batteries in the speech processor. Low power consumption is required to miniaturize the CI batteries and to provide smaller CI sound processors (Mertens et al., 2015) or to achieve the long-term goal of a fully implantable system (Briggs et al., 2008). For this reason, new developments in CIs often try to reduce power consumption without compromising speech intelligibility and quality. One possibility to achieve

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* Corresponding author.
E-mail address: nogueiravazquez.waldo@mh-hannover.de (W. Nogueira).

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Abbreviations

3D	Three Dimensional
AFC	Alternative Forced Choice
ANOVA	Analysis of Variance
CI	Cochlear Implant
CIS	Continuous Interleaved Sampling
DC-VC	Dynamically Compensated Virtual Channel
ELC	Equal Loudness Contour
FEM	Finite Element Method
MPVC	Monopolar Virtual Channel
QPVC	Quadrupolar Virtual Channel
TP	Tripolar
VC	Virtual Channel

low power consumption consists of minimizing the supply voltage of the implant (Zeng et al., 2008). The supply voltage, which depends on the maximum current delivered to the electrode contacts and their corresponding impedances, needs to be higher than the maximum voltage required to achieve comfortable loudness. For this reason, stimulation modes requiring low currents and low impedances are desired.

One limitation of CIs is the limited spectral information that they deliver. Although only 4 spectral channels are required to understand speech in quiet (Shannon et al., 1995), speech perception in more difficult listening conditions requires more spectral channels (Shannon et al., 2004). Spectral information is probably limited by the channel interactions created when different electrodes stimulate overlapping populations of neurons (e. g. Fu and Nogaki, 2005). Reducing the spread of excitation from a stimulated electrode could narrow the population of activated neurons and can potentially reduce channel interactions across electrodes. Speech intelligibility in noise may be improved by reducing electric and neural interactions across electrodes which in theory should improve spectral resolution (e.g. Henry et al., 2000; Litvak et al., 2007).

Multiple electrode stimulation can also be used to elicit several pitches intermediate to the pitches provided by the physical electrodes (e.g. Firszt et al., 2007; Landsberger and Galvin, 2011) using monopolar virtual channels (MPVCs). In a MPVC, the current field is steered between the physical electrodes according to a parameter α, which ranges from 0 to 1 and represents the proportion of current delivered to the more basal physical electrode (see Fig. 1). For example, if $\alpha = 0$, all of the current is delivered to the apical electrode; if $\alpha = 1$, all of the current is delivered to the basal electrode; if $\alpha = 0.5$, 50% of the total current is delivered to each of the physical electrodes. Electrical models of the human cochlea and psychoacoustic experiments have shown that VCs delivered through simultaneous stimulation are generally able to produce a single, gradually shifting intermediate pitch (Frijns et al., 2009; Luo et al., 2010, 2012). Evoked compound action potential (ECAP) measures (Busby et al., 2008; Hughes et al., 2013) and modeling (Litvak et al., 2007) suggest that the current spread from a MPVC is similar to that of MP stimulation on a single electrode. VCs have been implemented in Advanced Bionics' Fidelity 120 speech processing strategy, with no clear advantage in speech perception (Buechner et al., 2008) or spectral resolution (Berenstein et al., 2008) over the standard 16-channel continuous interleaved sampling (CIS) strategy. These results may be explained by the fact that channel interactions due to current spread may limit the spectral resolution with VCs to a similar degree as with physical electrodes.

Improvements in spectral resolution performance can be obtained using current focusing to reduce channel interaction. One current focusing implementation is tripolar stimulation (TP; e.g., Litvak et al., 2007; Berenstein et al., 2008; Bierer and Faulkner, 2010; Landsberger et al., 2012). With TP stimulation, an active electrode is stimulated and the two flanking (ground) electrodes are stimulated in opposite polarity phase relative to the active electrode, with each receiving half the current of the active electrode (see Fig. 1). Physiological (e.g. Bierer and Middlebrooks, 2002), computational (e.g. Spelman et al., 1995; Briaire and Frijns, 2010; Litvak et al., 2007), and psychophysical (Bierer and Faulkner, 2010; Landsberger et al., 2012; Fielden et al., 2013; Padilla and Landsberger, 2014) studies have shown that TP stimulation reduces current spread compared to MP stimulation. Current focusing can be implemented in combination with virtual channels. One example of a current focused virtual channel is the quadrupolar virtual channel (QPVC, Landsberger and Srinivasan 2009; Srinivasan et al., 2012). QPVCs are created by simultaneously stimulating four adjacent electrodes (see Fig. 1). The middle two electrodes are used for current steering, similarly to MPVCs. The remaining two flanking electrodes are used as grounds or partial-grounds to focus the stimulation, reducing current spread, similarly to TP stimulation. However, as previously mentioned, maintaining a fixed loudness with focused stimulation requires much greater current than with MP stimulation. Even with large phase durations (which ultimately limit the stimulation rate), it is difficult to achieve maximally acceptable loudness (Landsberger and Srinivasan, 2009).

It is worth noting that the benefits of current focusing are still unclear. Two studies (Landsberger and Srinivasan, 2009; Srinivasan et al., 2012) have shown that adding current focusing to a virtual

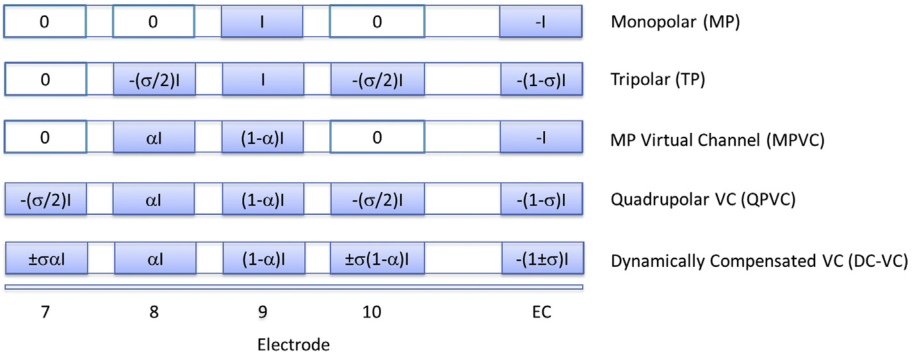

Fig. 1. Illustration of different stimulation modes. The sign indicates the polarity and the absolute value indicates the magnitude of the current provided on the corresponding electrode. The x-axis describes the electrode position (EC = extra-cochlear electrode). Note that the sign of σ in Landsberger and Srinivasan (2009) is inverted.