Hearing Research 322 (2015) 89–98

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research paper

Current focussing in cochlear implants: An analysis of neural recruitment in a computational model

Randy K. Kalkman [a], Jeroen J. Briaire [a, b], Johan H.M. Frijns [a, b, *]

[a] ENT-department, Leiden University Medical Centre, PO Box 9600, 2300 RC Leiden, The Netherlands
[b] Leiden Institute for Brain and Cognition, PO Box 9600, 2300 RC Leiden, The Netherlands

ARTICLE INFO

Article history:
Received 17 May 2014
Received in revised form
5 December 2014
Accepted 9 December 2014
Available online 18 December 2014

ABSTRACT

Several multipolar current focussing strategies are examined in a computational model of the implanted human cochlea. The model includes a realistic spatial distribution of cell bodies of the auditory neurons throughout Rosenthal's canal. Simulations are performed of monopolar, (partial) tripolar and phased array stimulation. Excitation patterns, estimated thresholds, electrical dynamic range, excitation density and neural recruitment curves are determined and compared. The main findings are: (I) Current focussing requires electrical field interaction to induce spatially restricted excitation patterns. For perimodiolar electrodes the distance to the neurons is too small to have sufficient electrical field interaction, which results in neural excitation near non-centre contacts. (II) Current focussing only produces spatially restricted excitation patterns when there is little or no excitation occurring in the peripheral processes, either because of geometrical factors or due to neural degeneration. (III) The model predicts that neural recruitment with electrical stimulation is a three-dimensional process; regions of excitation not only expand in apical and basal directions, but also by penetrating deeper into the spiral ganglion. (IV) At equal loudness certain differences between the spatial excitation patterns of various multipoles cannot be simulated in a model containing linearly aligned neurons of identical morphology. Introducing a form of variability in the neurons, such as the spatial distribution of cell bodies in the spiral ganglion used in this study, is therefore essential in the modelling of spread of excitation.

This article is part of a Special Issue entitled <Lasker Award>.

1. Introduction

Modern cochlear implants (CIs) have multiple electrode contacts along the scala tympani, each potentially capable of electrically stimulating a different sub-population of the surviving auditory neurons in the cochlea. These contacts are usually stimulated in so-called monopolar mode, in which current is injected through a contact in the scala tympani, and returned to a far-field electrode contact. As a result, electrical potential field patterns caused by monopolar stimulation are broad in nature; potentials drop off relatively slowly as one moves away from the stimulating contact. Since electrical potential fields from different sources add up, potential fields induced by different monopoles in the cochlea can greatly influence one another when the contacts are stimulated simultaneously or in rapid succession. This phenomenon, commonly referred to as electrical field interaction, is considered deleterious for speech perception with cochlear implants (Shannon, 1983; White et al., 1984; Wilson et al., 1991; Stickney et al., 2006). On the other hand, these interactions can also be used to reduce the spreading of current, in so-called multipole configurations. In this study the mechanisms underlying current focussing using multipoles will be investigated.

The main goal of current focussing is to increase spatial selectivity, thereby improving spectral resolution and speech intelligibility (Henry et al., 2005; Litvak et al., 2007b; Srinivasan et al., 2013). Multipolar stimulation also allows for reduced far field potentials, which could possibly be used to minimise interactions and allow parallel stimulation of implant channels without negative impact on speech perception. Several different multipolar configurations have been proposed to achieve these goals: bipolar stimulation, (partial) tripoles and phased array stimulation. These have

Abbreviations: CI, cochlear implant; OC, organ of Corti; BM, basilar membrane; SG, spiral ganglion; MP, monopolar; (p)TP, (partial) tripolar; PA, phased array; GSEF, generalised Schwarz-Eikhof-Frijns

* Corresponding author. ENT-department, Leiden University Medical Centre, PO box 9600, 2300 RC Leiden, The Netherlands.
E-mail address: j.h.m.frijns@lumc.nl (J.H.M. Frijns).

http://dx.doi.org/10.1016/j.heares.2014.12.004
0378-5955/

been shown to produce smaller spread of excitation than monopolar stimulation, but at the expense of an increase in the amount of current required to achieve a given loudness (Miller et al., 2003; Snyder et al., 2004; Bierer and Faulkner, 2010; Zhu et al., 2012; Landsberger et al., 2012; Long et al., 2014).

Another method for reducing spread of excitation is to move the electrode array closer to the modiolus, which lowers the threshold of excitation and decreases the dispersion of the injected current towards the neurons. This raises the question of whether it is possible to combine perimodiolar placement of the electrode array with current focussing to improve CI performance. On the other hand, in a perimodiolar position the electrode contacts are very close to the neurons. Consequently, the neurons are in the direct electrical field of the contacts while the benefits of the multipolar stimulation depend on interaction in the far field.

Previous modelling studies that investigated multipolar stimulation in the implanted cochlea have used linearly aligned neurons, with cell bodies of consecutive nerve fibres arranged along a straight line or spiralling curve (Briaire and Frijns, 2000a; Rattay et al., 2001; Hanekom, 2001, 2005; Whiten, 2007; Litvak et al., 2007a; Bonham and Litvak, 2008; Goldwyn et al., 2010; Frijns et al., 2011a; Snel-Bongers et al., 2013; Wu and Luo, 2013). The consequence of modelling the neurons in this manner is that excited neural regions can only expand apically or basally along the cochlea and do not allow for the computation of excitation densities at a specific location.

In reality, the cell bodies in the spiral ganglion (SG) are not aligned in a purely linear fashion, but are distributed throughout a spiralling tunnel in the modiolus called Rosenthal's canal. As a consequence, neural recruitment is not only possible in apical and basal directions, but also by penetrating deeper into the SG. It is therefore conceivable that different stimulation paradigms produce different three-dimensional excitation patterns, even at an equal number of excited neurons.

Another point of interest is the nature of neural degeneration in the human cochlea. A study by Linthicum and Fayad showed that, contrary to most animal models, loss of hair cells and the peripheral processes of cochlear neurons does not necessarily lead to loss of spiral ganglion cells in humans (Linthicum and Fayad, 2009). Since the state of the cochlear neurons currently cannot be determined in living subjects, this makes it unclear to which extent the peripheral processes are present in the cochleae of CI users. This is a potentially important issue, as previous modelling studies have shown that the presence or absence of peripheral processes can have consequences for neural excitation in the cochlea (Rattay et al., 2001; Hanekom, 2001, 2005; Briaire and Frijns, 2006; Whiten, 2007; Snel-Bongers et al., 2013; Kalkman et al., 2014).

The current study will present an updated version of the computational model of the implanted human cochlea developed at Leiden University Medical Centre (Frijns et al., 2000, 2001, 2009a,b, 2011a; Briaire and Frijns, 2000a,b, 2005, 2006; Snel-Bongers et al., 2013; Kalkman et al., 2014). The trajectories of the neurons in the model have been modified to include a more realistic spatial distribution of cell bodies throughout Rosenthal's canal, and have been modelled both with and without peripheral processes. The excitation patterns of monopoles, (partial) tripoles and phased array stimulation will be examined and compared for lateral and medial electrode arrays.

2. Materials and methods

The computational model of the electrically stimulated human cochlea used in this study consists of a volume conduction model, which uses the Boundary Element Method to calculate the potential distribution in a three-dimensional geometry representing an implanted human cochlea (Fig. 1), and an active generalised Schwarz-Eikhof-Frijns (GSEF) nerve fibre model (Frijns et al., 1995), that simulates neural responses in the cochlear geometry. Four different cochlear geometries are included, each modelled with both lateral wall and medial (perimodiolar) electrode arrays, which are model equivalents of the HiFocus1J electrode array. For this study, the model needed to be modified to include spatial distribution of the cell bodies of the auditory nerve fibres and the number of nerve fibres has been increased from 320 to 3200 to retain sufficient resolution along the cochlear duct. These changes are explained in Section 2.1; the morphology of the neurons and all other details of the model are described in Kalkman et al. (2014) and for brevity will not be repeated here.

2.1. Spatial distribution of cell bodies

Fig. 2 illustrates the way the cell body distribution was implemented. The nerve fibre trajectory used in the previous model studies served as a starting point (Fig. 2b); this trajectory is indicated by the orange line in Fig. 2a, and is referred to as the base nerve line L_0. The neuron is defined by 21 vertices. Vertex v_9 corresponds to the position of the cell bodies in our previous modelling studies and is located at the centre of the SG, as is visible in the histological image on which the model geometry is based (insert in Fig. 2a).

For the present study, alternative nerve lines were defined and the locations of the cell bodies were varied in a circle around v_9 with radius R_9, which encompassed the SG on the histological image. These nerve lines are shown in the insert of Fig. 2a as green,

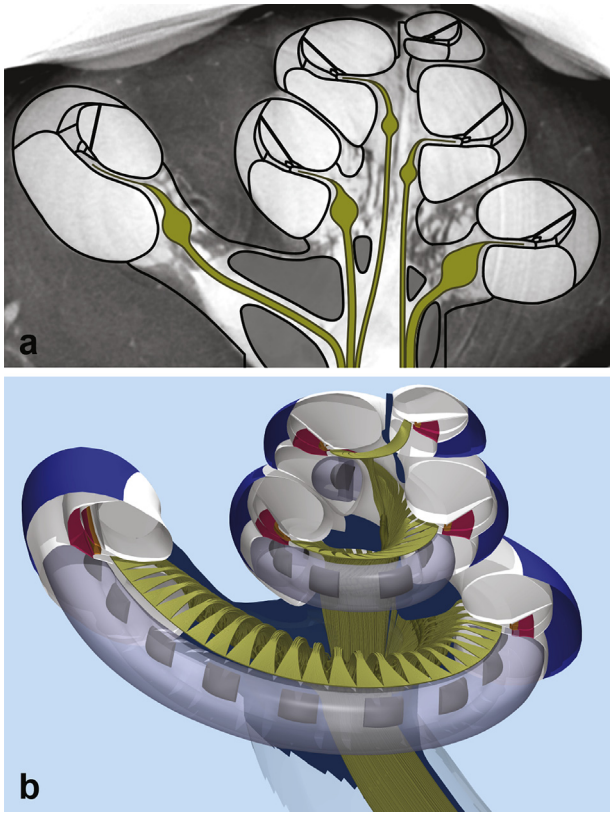

Fig. 1. Visual representations of one of the model's cochlear geometries. Figure a shows a mid-modiolar cross-section from μCT imaging data of a human temporal bone, provided by Advanced Bionics and the University of Antwerp. The lines overlaid on the μCT reconstruction represent the boundaries of the modelled cochlear geometry and the modelled neurons. Figure b is a ray traced image of the three dimensional model cochlea, cut open to reveal the neurons and a laterally inserted electrode array.