Electrical Stimulation of Spiral Ganglion Cells in the Human Cochlea: A 3D Model

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Electrical stimulation of auditory nerve fibers by cochlear implant electrodes has been an approved clinical practice to restore the hearing sensation in profoundly deaf people. Profound deafness is largely attributed to the loss of hair cells and subsequent decay of peripheral processes of auditory nerve fibers in the cochlea. In such pathological condition, spiral ganglion cells (SGN) which are intact with central process of auditory nerve fibers in Rosenthal's canal play a crucial role to generate and propagate the action potentials in response to the applied electric field. In this paper we describe the SGN response to the applied electric field by a bipolar electrode. Unlike the other existing models, we have considered the geometry of SGN and cochlea with essential approximations to discuss the signal propagation through the SGN at basal region of the cochlea via appropriate visualizations. This kind of a detailed 3D model serves as a useful tool to have a deeper understanding about the functionality of cochlear implant electrodes.

***Index Terms*—Computational biophysics, finite element analysis, cochlear implants, computational modeling, numerical simulation**

I. Introduction

AUDITORY TRANSDUCTION from the outer ear to the auditory cortex is a complex electro-mechanical phenomenon in a healthy human ear. In accordance with the frequency mapping quantized by Greenwood function [1], vibrations of basilar membrane induce electrical signals in the corresponding inner hair cells (IHC) which are connected to the peripheral processes (PP) of the auditory nerve (AN). Generally, the profound deafness is a consequence of IHC fall and subsequent PP depletion due to various physical, pathological or genetic reasons [2]. One effective clinical method to restore the hearing sensation partially if not fully of profoundly deaf people is the electrical stimulation of spiral ganglion cells (SGN) which are intact with the central processes (CP) of AN. Although various highly effective cochlear implant (CI) electrodes and efficient stimulation methods are available today, the basic mechanism of applied electric field interactions with SGN is not fully known. Nevertheless, some mathematical models [3], [4] have described the action potential (AP), i.e. the nerve pulse, propagation through auditory nerve fibers but these models either have not explicitly considered the applied field effects on SGN or have used complex ion dynamic equations to describe the AP propagation which in turn hindered the possibility of modelling individual SGN behavior in the cochlea. This advocates the necessity of a detailed mathematical model which contains all essential components yet simple to simulate the realistic scenario.

A. Model geometry

We made some essential simplifications in the geometry of SGN, cochlea and CI electrode to reduce the computational cost. A matrix of SGN at the basal end of the cochlea has been modeled such a way that a sphere of 30 µm diameter with two cylindrical tails of 1.5 µm and 3 µm diameter attached diametrically opposite to it to represent a single spiral ganglion cell intact with the non-myelinated ends of a PP and a CP. Because the focus of present study is to understand the behavior of SGN in the applied electrical field, we have not considered the whole geometry of PP and CP. The electrode is designed with 24 channels to represent a bipolar CI electrode. Arbitrary parametric cochlea geometry [5] about 400 degrees of electrode insertion depth from the round window has been modelled inside a cylindrical structure that represents the temporal bone environment (Fig. 1).

B. Model equations

A biological cell under the influence of applied electrical fields develops a certain amount of non-uniform transmembrane potential (TP) across the cell membrane [6]. A sufficiently high induced TP may trigger action potentials in the cell membrane. Although in SGN stimulation, the initiation site of AP on the cell body is not known so far, we have assumed that the initiation of AP takes place where the induced TP is highest on the cell body. We have used FitzHugh-Nagumo (FHN) equations to model AP propagation through the cell membrane. FHN equations are derived from Hodgkin-Huxley equations by approximating the ion dynamics with a system of fast (u) and slow (w) dimensionless variables [7], [8].

$$du/dt = (\alpha - u)(u - 1)u - w,$$

$$dw/dt = \varepsilon(\beta u - \gamma w - \delta). \qquad (1)$$

Here α, β, γ, δ, ε are the system parameters with customized values set to produce a stable solitary wave that mimics the AP pulse propagation [9]. The FHN equations have been implemented in the commercial software COMSOL MULTIPHYSICS 5.0® which is based on the finite elements method (FEM). To overcome meshing problems with the thin SGN membrane of only 10 nm thickness, it is implemented with the inner boundary condition of the following type available in COMSOL MULTIPHYSICS 5.0® where $\overrightarrow{J_{int}}$, $\overrightarrow{J_{ext}}$, V_{int}, V_{ext} are the interior, exterior current densities and electric potentials of SGN, respectively.

$$n \cdot \overrightarrow{J_{int}} = \frac{\sigma}{d}(V_{int} - V_{ext}),$$

$$n \cdot \overrightarrow{J_{ext}} = \frac{\sigma}{d}(V_{ext} - V_{int}), \qquad (2)$$

Here d is the thickness and σ is the electrical conductivity of the cell membrane. In addition to this, governing equations to model the induced TM on SGN cell bodies due to the applied electrical fields are defined by respective Maxwell's equations [10] in the 'electric currents' physics settings in COMSOL 5.0®. Material properties of all domains have been adapted from [4]. Two consecutive electrodes near to the matrix of SGN at the basal end of the cochlea have been used as a ground and active electrode with 1V input voltage to mimic the bipolar stimulation.

II. Results

Fig.1 shows the potential distribution in the cochlea due to the applied electric field. The induced TP on SGN bodies polarized the cells resulting a favourable condition for AP generation.

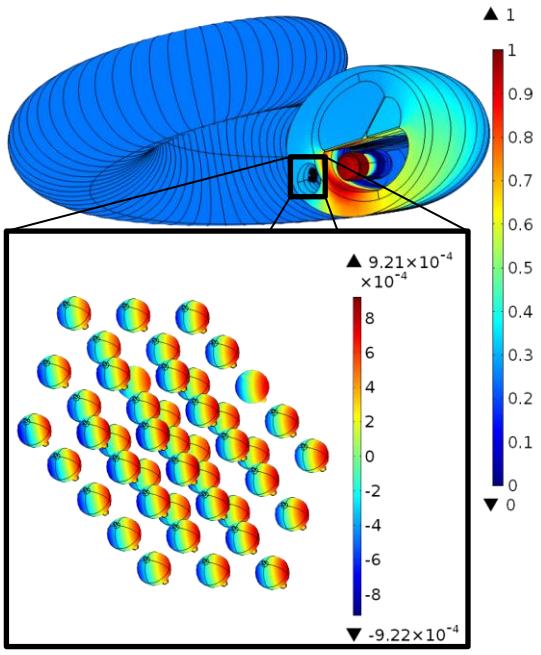

Fig. 1. Potential distribution in the human cochlea model and induced transmembrane potential in SGN matrix (zoomed). All values are in Volts.

AP propagation from its initiation point is shown in Fig. 2. It should be noted that AP has a discrete wave propagation feature for different cells. Fig. 2 (D) is a graphical representation of AP propagation through the cell showing that after 100 µs AP spread over the cell body and after 200 µs AP passes through the CP. The spreading of AP on the cell body may depend on the cell morphometrical properties causing a possible time delay in signal propagation. However, as a first approach we have not imposed any threshold voltage constraints for the initiation of AP at the highest TP points. One big advantage of this model for immediate future studies is its flexibility to investigate the utility of SGN clusters in the cochlea and the possibility of ephaptic coupling which has not been explored properly until now. Furthermore, by varying the ground electrode position in the model, the optimal functionality of the cochlear implant electrode in terms of maximum number of SGN activation can be estimated.

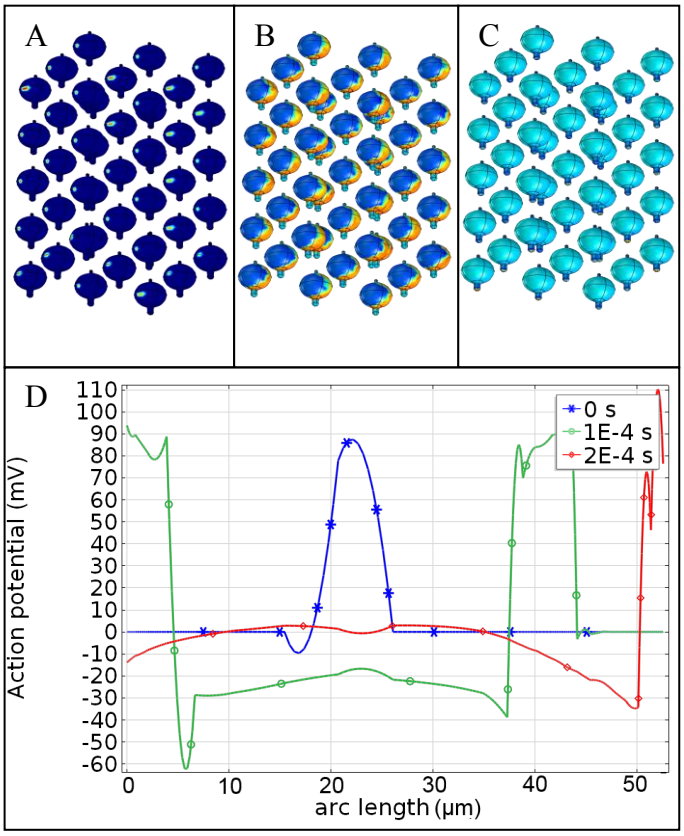

Fig. 2. Snap shots of (A) AP at its initiation sites on SGN (B) AP after 100 µs and (C) AP after 200 µs. (D) AP propagation through a single cell for three time steps.

III. Acknowledgement

This work was supported by the German Science Foundation (DFG) in the scope of the Research Training Group GRK 1505 "Analyse und Simulation elektrischer Wechselwirkungen zwischen Implantaten und Biosystemen" – *welisa*.

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