A Modeling Study of the Recording Selectivity of Longitudinal Intrafascicular Electrodes

Chemineau ET\textsuperscript{1}, Schnabel V\textsuperscript{1}, Yoshida K \textsuperscript{1}

\textsuperscript{1} Center for Sensory Motor Interaction, Aalborg University, DK-9220, Aalborg Øst, Denmark

Email: eric@smi.auc.dk
Website: www.smi.hst.aau.dk

Abstract

Longitudinal intrafascicular electrodes (LIFEs) are implantable intraneural electrodes that have potential applications in neuroprosthetics and in basic physiology as a chronically implantable stimulating/recording electrode. Recently, LIFEs have been realized using thin-film microfabrication techniques on polymer substrates, and the thin film LIFE was born (tfLIFE). Microfabrication opens up the possibility of creating a nearly infinite number of electrode shapes and geometries, to influence the recording selectivity of the realized electrodes. It allows for the first time the possibility to design an optimally selective electrode. In the present paper, we report on our efforts to create a three-dimensional finite element volume conductor model of the nerve fascicle, electrode and active nerve fiber. This model is used as a tool for predicting the recording characteristics of putative electrode designs for the optimization of potential electrode geometries prior to committing to a microfabrication design. To develop the tool, models were constructed to compare the selectivity of the newly realized tfLIFE and traditional wire LIFE. The models predict that there is a significant improvement in spatial nerve recording selectivity with the tfLIFE compared to the traditional LIFE electrode.

1 Introduction

The Longitudinal Intrafascicular Electrode (LIFE) is a class of recording/stimulating neural electrodes implanted in the peripheral nerve intended for chronic use. Since they are in intimate contact with active nerve fibers within the nerve fascicle, they give a much clearer picture of the activity of the nerve than e.g. traditional cuff electrodes. Typical records from traditional wire based LIFEs show multi-unit activity where it is sometimes possible to resolve single units. Given enough selectivity, they have the potential to ultimately access single channels of information within the peripheral nerve.

Work with traditional LIFEs, however, have shown that although they have significantly higher recording selectivity than extraneural electrodes, significant improvement is required. Microfabrication techniques were applied to realize thin-film LIFEs in an effort to create electrodes with higher recording selectivity [1]. The use of microfabrication opens up the possibility of designing and creating electrodes with higher spatial reproducibility and control. Furthermore, microfabrication on plastic substrates were also considerably more flexible than the traditional LIFEs, and thus a better mechanical match to that of the nerve and presumably more biocompatible.

Given the opportunity of designing multi-electrode structures, tools were needed to optimize potential electrode designs. Mathematical modeling of the electromagnetic fields generated by active nerves and electrodes is needed to quantify these effects and to compare electrode performances. Moreover, it would give a significant insight into an optimal geometrical pattern of the electrode’s active sites on the substrate with respect to their shape, size and placement.

2 Methods

In the present model, a single tfLIFE recording site and a traditional metal LIFE (wire electrode) were simulated to compare their spatial selectivities. The difference between the maximal and the minimal value of the single fiber action potential (SFAP) is a measure for the recorded potentials and is used for characterizing the spatial selectivities of the electrodes.

The mathematical model and computer simulations of recorded potentials from a tfLIFE/LIFE electrode inside a nerve bundle, was based on the concept of lead field combined with the reciprocity theorem, which states that in a passive linear electric circuit the positions of a current source and a voltage-measuring instrument can
be interchanged without affecting the voltage recorded. System linearity and quasi-static conditions were assumed.

The method used for modeling the volume conductor, was the finite element method. The model was simulated in FEMLAB® (Comsol), an interactive finite element solver that has an interface to MATLAB®(MathWorks). Using the reciprocity theorem and the standard model of an active nerve fiber [2], a template for the action current can be combined with the volume conductor model to predict the single fiber action potentials (SFAPs) measured by the electrode’s active site [3].

The first model geometry (figure 1) consisted of a tfLIFE electrode folded around its center line and positioned inside a peripheral nerve. The nerve bundle was modeled by a 20 mm long cylinder, along the z-axis, with a radius of 1.2 mm, the perineurium layer surrounding the fascicle was taken as 50 µm thick and the surrounding medium, representing the nerve tissue outside the nerve bundle, was modeled as a cylinder (radius: 6 mm), to an extent large enough to account for the electric potential boundary conditions (Dirichlet condition set to ground). In this model, conductivities of the fascicle ($\sigma_{xy} = 0.6$ S/m, $\sigma_z = 0.083$ S/m), the perineurium ($\sigma = 0.0034$ S/m) and the surrounding medium ($\sigma = 2$ S/m) were considered.

The folded thin film substrate, modeled as an insulated rectangular structure (total length: 40 mm, width: 160 µm, thickness: 20 µm) was threaded longitudinally inside the nerve bundle so that its length axis coincides with the cylinder axis.

A single recording site consisting of a square electrode ($40 \times 40$ microns), considered to be a perfect conductor, was positioned on the thin film structure in the center of the nerve bundle. The two symmetries of the geometry (figure 1), one in the xy-plane and one in the yz-plane, allows for the volume conductor to be reduced to one fourth. The second model consisted of the traditional LIFE electrode, modeled as a cylindrical structure (diameter: 25 µm, total length: 40 mm, uninsulated part: 0.5 mm in length, perfect conductor) and positioned in the same volume conductor as in the first model, with its cylinder axis coinciding with the nerve bundle to allow for the same symmetry considerations and same model simplifications. The electric field in the volume conductor, which forms as a result of imposing a current between the electrode active site and a distant ground, defined at the boundaries of the model, is computed, and defines the weighting function of the space. A profile of a typical weighting function for a given active fiber is shown in figure 2.

*Figure 1: Simplified model for tfLIFE and LIFE electrodes. Arrow plot shows the current flow in the volume conductor for the reciprocal electrode. Symmetry boundary conditions are used in the xy-plane and the xz-plane.*

*Figure 2: A typical weighting function (A) along the line of action of an active nerve fiber in the volume conductor. (B) is the template action current for a 5 µm myelinated fiber. (C) is the resulting single fiber action potential seen by the electrode.*
The nodal currents are directly calculated from the membrane kinetics at the nodes of Ranvier, and they serve as point current sources in the volume conductor model. The transmembrane current was used as a template for the action currents at all the nodes in the model. In the fiber model the amplitudes of the nodal currents are linear with fiber diameter, whereas the duration of the action potential is independent of fiber diameter. The template was taken from a 10 µm fiber and was scaled accordingly for different fiber diameters. A typical action current is illustrated in figure 2B. The resulting SFAP (figure 2C), as seen by the electrode active site, is a convolution of the weight function with the action current template [3].

3 Results

SFAPs were calculated for 4 different fiber diameters (2.5 µm, 5µm, 10µm and 20µm), for fibers throughout the fascicular space. The difference between the maximal and the minimal value of the recorded single fiber action potentials (peak to peak SFAPs) were calculated to quantify the amplitude of the SFAP recorded by the electrode, and plotted as a function of the position of the active fiber relative to the electrode. The results for 5µm nerve fibers are plotted in figure 3. In the case of the tradition LIFE (figure 3 right), the electrode preferentially responds to closer units, however shows no directional selectivity, whereas, the tLIFE (figure 3 left), responds only to units facing the recording site. The recorded potentials are generally higher for the tLIFE as compared to the LIFE.

4 Discussion and Conclusions

The polyimide layer encapsulating the tLIFE electrode is a good ionic insulator with a relatively low dielectric constant, so that capacitive coupling with the electrode can be neglected.

The results obtained, indicate that the tLIFE electrode has a larger spatial selectivity for myelinated nerve fibers than the uniformly recording LIFE electrode. This can be noted by the distribution of the SFAP amplitudes around the electrode. The effect of the tLIFE’s insulating polyimide substrate is clearly seen, where very little signal has been picked up from back of the tLIFE electrode (up to a factor 10), indicating strong spatial selectivity towards units facing the front of the electrode.

References


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