Efficient Computation of the Neural Activation during Deep Brain Stimulation for Dispersive Electrical Properties of Brain Tissue

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Deep brain stimulation (DBS) is a widely employed neurosurgical method to treat symptoms of neurodegenerative disorders. Computational modeling of DBS can help to gain insight into the mechanisms of its action. Among these models, the estimation of the volume of tissue activated (VTA) comprises a method to predict the extent of beneficial stimulation and unwanted side effects. This method requires the computation of the time-dependent extracellular potential in the proximity of the stimulation electrode, which is, in general, computationally expensive due to the dispersive electrical properties of brain tissue. We present an adaptive scheme based on two interpolation methods, which approximates the transfer function of the extracellular potential distribution in the frequency-domain. The results suggest that the proposed method is able to substantially reduce the computational expense for the computation of the extracellular field distribution and VTA compared to the standard approach.

***Index Terms*—Fast Fourier transforms, Finite element analysis, Implantable biomedical devices, Transfer functions**

I. Introduction

Deep brain stimulation (DBS) is a neurosurgical method to treat symptoms of neurodegenerative disorders. Despite DBS being a widely employed method in many clinical fields, the mechanisms of action of DBS remain uncertain. For the investigation of its therapeutic effects as well as unwanted side effects, the extent of neural activation during DBS constitutes an important quantity. The computational method of the "volume of tissue activated" (VTA) is one common method to estimate this extent [1]. The VTA depends on the time-dependent extracellular field distribution during DBS and, therefore, is influenced by the dispersive electrical properties of biological tissue. [2].

In this study, we present a computational efficient method to determine the time-dependent extracellular field distribution and VTA for the dispersive electrical properties of brain tissue by using an adaptive scheme to approximate the transfer function of the extracellular potential in a finite element model of the human brain. With this method, the effect of varying electrical properties of the encapsulation tissue layer on the extracellular field distribution and the VTA is investigated.

II. Methods

A. Computational Model of Deep Brain Stimulation

The computational model to estimate the volume of tissue activated for DBS is based on preliminary work presented in [3]. It comprises a finite element model of the human brain segmented into the tissue compartments gray matter, white matter, and cerebrospinal fluid coupled to multi-compartment axon models distributed in the proximity of the electrode (Fig. 2) [4]. The thickness of the encapsulation layer, which is formed by body reactions to the implant, was set to $0.2\,\mathrm{mm}$ [2]. Cathodal current-controlled square-wave stimulation pulses with a frequency of $130\,\mathrm{Hz}$ and a pulse duration of $60\,\mu\mathrm{s}$ as used in clinical practice [3] were applied to the second electrode contact of the DBS electrode, while the bottom of the brain model was set to ground. The resulting extracellular potential in the proximity of the electrode was applied to the 221 segments of each axon model to compute the required stimulation amplitude to elicit an action potential in each axon. The computation of the extracellular field distribution and the volume of tissue activated was performed by using COMSOL MULTIPHYSICS® (http://www.comsol.com) and NEURON (http://www.neuron.yale.edu/).

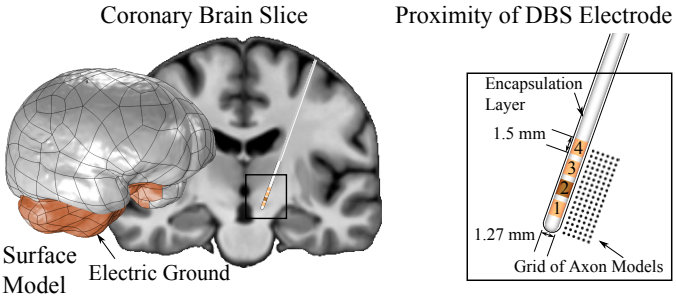

Fig. 2. Finite element model for DBS based on magnetic resonance images of the human brain and coupled to axon models distributed in the proximity of the electrode.

B. Efficient Computation of the Volume of Tissue Activated

The extracellular potential is computed using the Fourier finite element method (FFEM) [1], for which the Laplace equation with complex material properties (conductivity and relative permittivity of each compartment) is solved in the frequency-domain. Due to the heterogeneity of the computational domain and its dispersive electrical properties (taken from [5]), the solution has to be computed for the whole frequency spectrum of the DBS signal, which comprises non-negligible energy in a range from Hz-MHz. To compute the transfer function of the extracellular field distribution in the frequency-domain, we propose an adaptive scheme based on the approximation of the transfer function by third order poly-

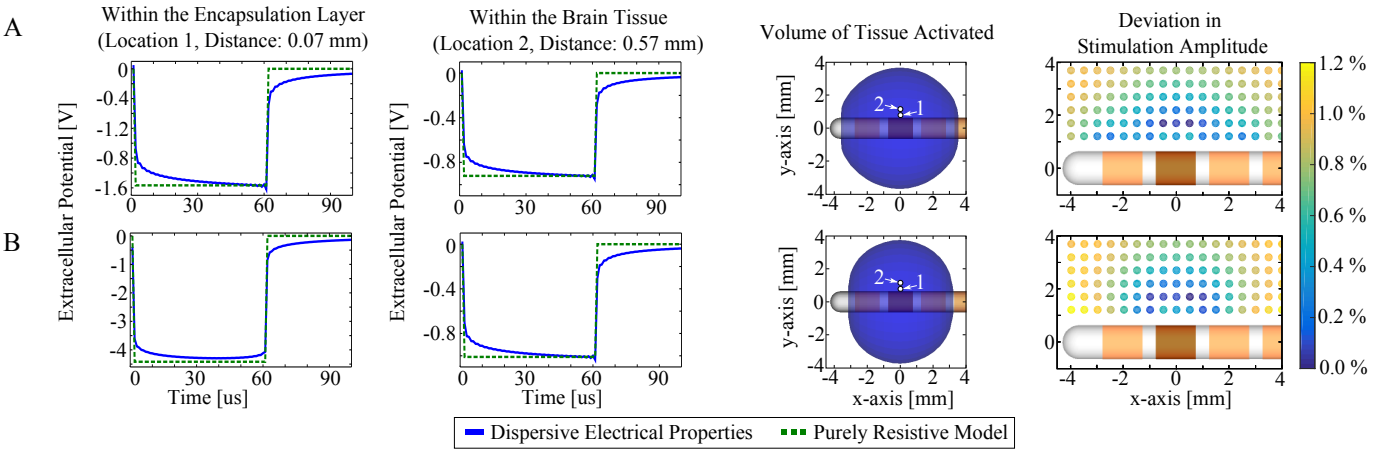

Fig. 1. Extracellular potential, volume of tissue activated for a stimulation amplitude of 1.5 mA, and deviation in the stimulation amplitude to elicit an action potential in each axon computed for the dispersive electrical properties of brain tissue and its purely resistive electrical properties approximated at a frequency of 2 kHz. Encapsulation layer conductivity is set to (A) half of and (B) 5 % the value of gray matter and its relative permittivity to (A) the value of gray matter and (B) to zero, to model a purely resistive encapsulation layer.

nomials and spline interpolation of the solution for samples distributed logarithmically in the frequency range between 130 Hz and 1 MHz. After the computation of the solution for the lower, mean, and upper value of the sample set, the next sample is chosen at the frequency, at which the deviation of the interpolated solutions is maximal with respect to the infinity norm. This procedure was continued until the deviation was below a value of $1 \cdot 10^{-3}$. The resulting extracellular potential and the VTA computed with this method was compared with that computed for the electrical properties of brain tissue modeled as purely resistive tissue properties estimated for a frequency of 2 kHz. The electrical properties at this frequency have been found to allow for a good approximation of the dispersive electrical properties for the computation of the extracellular potential in finite element models of DBS in a previous study [6].

III. Results

To investigate the influence of varying electrical properties of the encapsulation layer on the extracellular field distribution and the VTA, its electrical properties were set to values representing a capacitive as well as a purely resistive encapsulation layer to resemble different post-operative states. Based on [2], the encapsulation layer conductivity was set to half the value of gray matter and 5 % of the value of gray matter and its relative permittivity to the value of gray matter and to zero, respectively. The adaptive scheme to compute the model solution with respect to the dispersive electrical properties of brain tissue required 29 and 24 frequency samples, respectively, to provide the desired accuracy of $1 \cdot 10^{-3}$ in the interpolated transfer functions. The varying electrical properties of the encapsulation layer influenced at most the waveform of the extracellular potential within the encapsulation layer, while that within the brain tissue showed only slight deviations in amplitude (Fig. 1). The approximation of the extracellular field distribution and of the VTA with a purely resistive model showed a good agreement with the dispersive model for the applied DBS stimulus.

IV. Discussion

The proposed adaptive scheme to compute the extracellular potential distribution with respect to the dispersive electrical properties of brain tissue requires substantially less model realizations compared to the common Fourier finite element method (FFEM) [1], which would require several thousand model realizations. The approximation of the electrical properties of brain tissue by purely resistive parameters showed a good agreement in the predicted VTAs. However, if the electrical properties of the considered brain tissue compartments are varied or voltage-controlled instead of current-controlled stimulation is applied, the deviation between both solutions might be larger. In addition, the proposed scheme allows for an efficient computation of the best approximating frequency of the dispersive electrical properties of living tissue to provide a purely resistive model approximation. Therefore, it could also be used in other bio-electrical applications of numerical dosimetry, which take into account the dispersive electrical behaviour of living tissue over a large frequency range.

This work was supported by the German Science Foundation (DFG) in the GRK 1505.

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