Deep Brain Stimulation Models Incorporating Electrode-Tissue Interfaces

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Abstract — Deep Brain Stimulation (DBS) is an effective treatment of Parkinson's disease and essential tremor. It involves electrical stimulation of the deep brain area through an implantable electrode. In previous studies, the DBS electrode-tissue interface was modeled by non-faradaic charge transfer. The electrode was represented by a double layer capacitance only, when faradaic reaction was not considered.

In this paper, a novel electrode-tissue interface, which incorporates faradaic reaction, was incorporated into a finite element (FE) model of DBS. A FE model of DBS was used to compute the stimulation region or the Volume of Tissue Activated (VTA). Finally, an equivalent circuit model of the electrode/tissue interface was created to validate the finite element modeling result.

***Index Terms*—finite element method, biological system modeling, electrical stimulation, brain stimulation.**

I. Introduction

DBS is a clinically effective treatment for movement disorders, including Parkinson's disease and essential tremor and other neurological disorders [1]. Chronic high-frequency electrical stimulation of subcortical structures can provide 50% improvement in clinical ratings of motor symptoms [2]. This system is divided into three compartments: the implanted pulse generator (IPG), the lead with four platinum iridium electrodes, and the extension. In previous studies, we used different stimulating strategy to compute the VTA of the DBS model by non-faradaic charge transfer [3]. Faradaic charge transfer has not been incorporated in any previous DBS model. The objective of this study is to examine the influence of the faradaic reaction [4] on electrical stimulation in the DBS electrode/tissue interface, and to analyze the change in VTA at different input waveform and frequency. We will discuss the influence of faradaic reaction, which is generated at the electrode/electrolyte interface (also known as electrode tissue interface in the DBS), in DBS VTA [5] computation. Faradaic reactions are divided into reversible and irreversible reactions. Irreversible reactions will be considered in this paper, and represented by an equivalent circuit.

II. Method

A. Finite Element Method of DBS system and faradaic reactions

An axisymmetric FEM model of DBS was created with bulk homogeneous medium which represented brain tissues (Fig. 1). The DBS model with approximately 300,000 nodes and electrode contact dimensions are 1.5mm in height and 1.27mm in diameter. These dimensions were based on the Medtronic 3387/3389 DBS

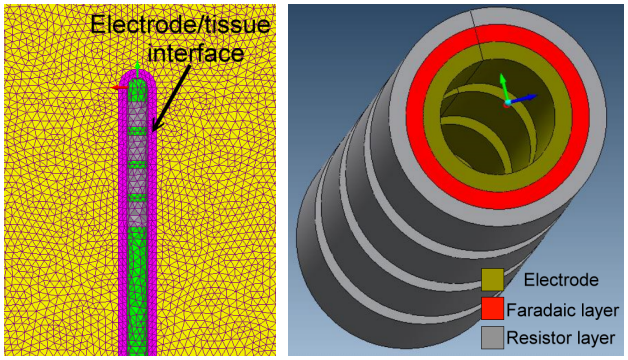

Fig.1 (left side) shows a finite-element model with about 300,000 finite element nodes. The green part shows a lead electrode; the purple part shows an electrode/tissue interface with a width of 0.5mm and conductivity of 0.1S/m, and the yellow part show the surrounding tissue (gray matter) with an isotropic conductivity of 0.2S/m [6]-[7].
Fig.2 (right side) shows the detail of inner layer of electrode. This equivalent circuit includes electrode, faradaic layer, and resistor layer [8].

electrode contact dimensions [10]. The DBS electrode carrier was modeled as an electrical insulator and the DBS electrode contact was used as a voltage source. To incorporate the faradaic reaction in the DBS model, each electrode is divided to three layers, including an electrode layer, a faradaic layer, and a resistor layer (Fig. 2) [8].

B. Neural model and VTA

A DBS model is coupled with a neural model, which is a 7x11 array with 5.7μm diameter myelinated axon model and each axon has 21 nodes of Ranvier with 0.5mm intermodal spacing [7]. After the electrical potential distribution of the DBS model was computed by solving Poisson's equation, it can be used to compute the current distribution in the tissues around the DBS electrodes. First, we convert the potential distribution generated within the tissue to current distribution by (1):

$$I_{int}(n) = G_i(-)[V_{(n-1)} - V_{(n)}] + G_i(+)[V_{(n+1)} - V_{(n)}] \quad (1)$$

where $G_i(-)$ represents the inter-segmental conductance between the n and n-1 compartments and $G_i(+)$ represents the inter-segmental conductance between the n and n+1 compartments of the neuron in the finite element model. The VTA computation is based on current distribution (1) and the neuron threshold, which decides whether an axon is excited after an electrical stimulation. Faradaic reaction will be incorporated in the DBS model.

Finally, an electrical equivalent circuit model of a DBS electrode with faradaic reaction incorporated was created to validate the finite element model of DBS electrode with faradaic reaction incorporated [10].

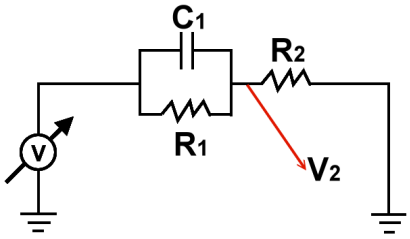

Fig. 3 An electrical equivalent circuit model of the finite element model (Fig. 2). This circuit model includes one capacitance and two resistors. C_1 and R_1 represent the faradaic layer and R_2 represent the resistor layer in Fig. 2.

C. An electrical equivalent circuit model for electrode tissue interface

With faradaic electrodes, charge can cross the electrode tissue interface and produce chemical changes in the vicinity of the electrode [11].

The finite element model of DBS electrode (Fig. 2) can be represented by an electrical equivalent circuit model as shown in Fig. 3. PSPICE was used to analyze the circuit model in Fig. 3.

The parallel connected R_1 and C_1 represent the faradaic layer of the DBS model, and the series connection of the R_2 represents the resistor layer of the DBS model in the Fig. 2.

All of parameters of each component of the circuit model are based on previous published parameters [9].

III. Result and Discussion

Fig. 4a shows the input voltage for the electrical equivalent circuit model (Fig. 3), and from Fig. 4b ~ 4d show the output voltage V_2 from Fig. 3. While the R_1 and R_2 in each figure are kept the same, the capacitance C_1 has three different values since a precise capacitance value is not available: The value of R_1 is 400Ω, R_2 is 250Ω, and C_1 are 1.66μF, 3.3μF, and 6.6μF.

Each figure (Fig. 4b ~ 4d) shows three results, including a reference [9], time domain finite element model, and PSPICE results. PSPICE is used to construct an electrical circuit model of Fig. 3. To order to validate the finite element model (Fig. 2), we apply the same input (Fig. 4a) to both the time domain finite element model (Fig. 2) and the equivalent circuit model (Fig. 3) and the results are shown in Fig. 4b ~ 4d.

Except for the minor discrepancy between the FEM and circuit results with the reference result in Fig. 4b, the FEM and circuit modeling results are consistently matching each other in Fig. 4b ~ 4d.

A finite element model of DBS incorporating an electrode tissue interface with faradaic reaction was presented and validated by an equivalent circuit model and reference result [9]. The VTA computation based on the same FEM and result will be presented in the full version of paper.

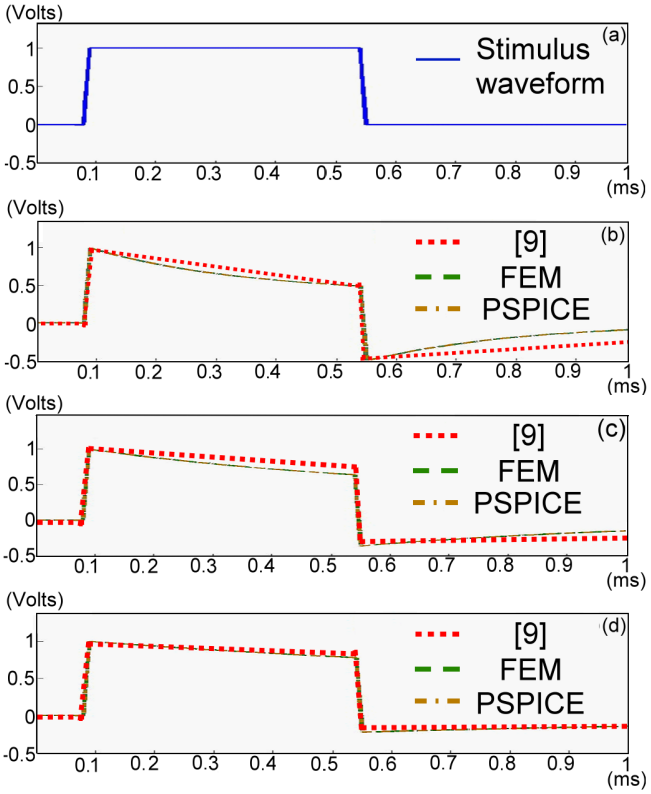

Fig. 4 (a) shows the input waveform. (b) to (d) show the output voltage V_2 with capacitance C_1 value of 1.66μF, 3.3μF, and 6.6μF, respectively.

IV. References

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