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Influence of Coil Current Configuration in Magnetic Stimulation of a Nerve Fiber in Inhomogeneous and Anisotropic Conducting Media

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Abstract— **In this study, we used a computer simulation to investigate the effects of the coil current waveform and direction on the excitation processes of the nerve axon in inhomogeneous and anisotropic conducting media in magnetic stimulation. We assumed that the nerve axon was located in the media with 2 regions having different conductivities or electrical anisotropy that simulate different tissue types. The distribution of induced electric fields was calculated with the finite element method (FEM). The nerve fiber was modeled after equivalent electrical circuits having active nodes of Ranvier. The direction of the coil current at the intersection of a figure-eight coil was assumed to flow perpendicular to the nerve axon. We observed the excitation threshold when the coil current waveform and direction are changed with varying the electrical properties such as tissue electrical conductivity and anisotropy.**

The simulation results show that the threshold decreases with the increase of conductivity ratio between 2 regions and it also depends on the coil current waveform and direction. Biphasic coil current has lower threshold than monophasic one when the current direction is the same in both waveforms. The results also suggest that the tissue anisotropy strongly affects the excitation threshold. The threshold increases with the increase of tissue anisotropic ratio of longitudinal direction to the transverse one respect to the nerve axon. The results in this study give useful information to explain the experimental results of the magnetic stimulation of human peripheral nervous systems and the theoretical model is applicable to understand the characteristics in magnetic stimulation of both peripheral and central nervous systems.

I. Introduction

MAGNETIC stimulation has been widely used as a non-invasive method to stimulate human peripheral and central nervous systems [1][2]. The nerve excitation model of magnetic stimulation based on cable theory was introduced [3][4], and it is argued that the spatial derivative of induced electric fields parallel to the nerve axon is crucial factor to elicit the nerve action potentials. Several experimental results are consistent with the model prediction [5][6] in magnetic stimulation of human peripheral nerves. On the other hand, some papers showed the inconsistent results with the model study, in which the compound muscle action potentials (CMAPs) are evoked when the coil current direction at the intersection of figure-eight coil flow perpendicular to the nerve fibers [7][8][9]. Ruohonen *et al.*, [10] proposed the model that transverse component of induced electric fields activates the axon membrane potentials. Kobayashi *et al.*, [11] described that the tissue inhomogeneity creates the parallel component of induced electrical fields at the boundary of tissues and then the nerve axon is stimulated, although the coil current flows perpendicular to the nerve axon. Calculation of the distribution of induced electric fields in inhomogeneous volume conductor was developed and it is argued that the boundary of tissues having different conductivity influences the stimulation site in magnetic stimulation by using a computer simulation. [12][13].

However, it is necessary to develop a nerve excitation model that describes the different effect of stimulus parameters, such as coil current waveform or direction, on nerve excitation processes to understand the mechanisms of magnetic stimulation. In this study, we used active membrane model to investigate the excitation processes of the nerve axon which runs in inhomogeneous anisotropic volume conductor. The purpose of this study is to elucidate the effects of stimulus parameters on nerve excitation threshold when the tissue electrical properties are changed by using a computer simulation. The results based on a theoretical model explain the experimental results using commercially available magnetic stimulator and help us to understand the mechanisms in magnetic stimulation of both central and peripheral nervous systems.

II. Model and Methods

A. Location of Coil and Nerve Axon

Fig.1 shows the location of the figure-eight coil and nerve axon. A figure-eight coil with a diameter of 2.0 cm in each wing was placed 0.5 cm above the Air/Tissue interface. The each wing of the coil has 10 turns. The nerve axon was located in an inhomogeneous volume conductor which has two regions of different electrical properties. The tissue was modeled as a medium with 5.0 cm sides in X, Y axes, and 2.5 cm side in Z axis which was composed of 1 mm cubes for calculation of induced electric fields using the finite-element method (FEM). The conducting medium was separated by a plane boundary which was parallel to Y-Z plane. These two regions (Region 1, Region 2) assumed to have different electrical conductivity and anisotropy. A nerve fiber ran

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parallel to the surface of the boundary at a depth of 6 mm. The coil current flowed perpendicular to the nerve axon.

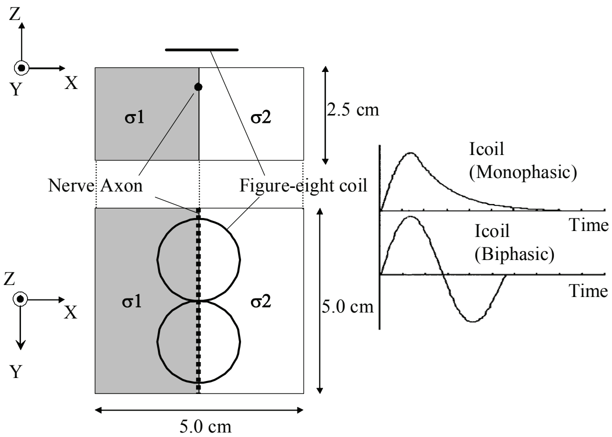

Fig. 1. Location of figure-eight coil, nerve axon, and stimulus coil current waveforms. The nerve axon runs parallel to the Y axis at the boundary of the inhomogeneous volume conductor (5.0 cm * 5.0 cm * 2.5 cm) having tow regions which have different electrical properties. The stimulating coil current waveforms and directions are drawn at right side of this figure. The waveform is monophasic or biphasic. The coil current direction is toward the σ1 region (X(-)), or toward the σ2 region (X(+)).

To investigate the influence of tissue inhomogeneity on excitation threshold, we simulated the nerve excitation processes by varying the ratio of conductivity in tow regions (σ1/σ2). We selected the conductivity ratio of σ1/σ2 = 5.0, 7.5, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, 25.0, where σ2 = 0.05 S/m. Each region was assumed to be isotropic in this case.

We also investigated the effects of tissue electrical anisotropy in region 1. We changed the ratio of longitudinal conductivity (σ1y) to transverse conductivity (σ1x) and simulated the excitation processes of a nerve axon. We selected the anisotropic ratio of σ1y/σ1x=1.0, 2.0, 3.0, 4.0, 5.0, where σ1x/σ2=5.0, σ1z/σ2=5.0, σ2= 0.05 S/m. The changes in nerve excitation threshold were observed when the anisotropic ratio is changed.

B. Stimulus Waveforms and Directions

The current waveforms flowing in the coil (Icoil) are also shown in Fig.1. We simulated the waveforms which are used in commercially available magnetic stimulators that are based on a capacitor charge/discharge system. We assumed that the capacitance, resistance and inductance of the stimulating circuit were 350μF, 20mΩ and 6.5 μH, respectively.

In this system, stimulus intensity is controlled by the capacitor charge voltage. The output coil current waveform is monophasic or biphasic. The initial coil current direction was toward the σ1 region (X(-)), or toward the σ2 region (X(+)).

C. Calculation of Induced Electric Fields and Membrane Potentials of the Nerve Axon

Induced electric fields in the conducting media were calculated using the finite-element method (FEM). We used commercial software for electromagnetic computation based on the FEM, PHOTON-Series by PHOTON Co., Ltd.

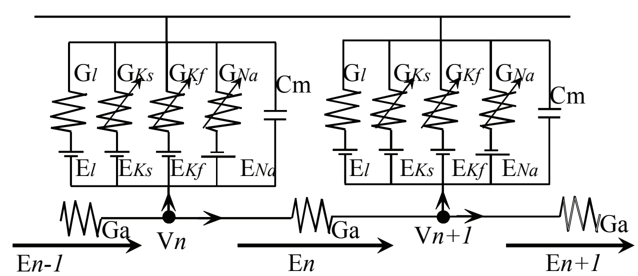

Fig. 2. Equivalent electrical circuits of myelinated nerve axon. Each node contains voltage dependent active sodium channel (G*Na*), fast- and slow-potassium channel (G*Kf*, G*Kl*), passive leak channel (G*l*) and membrane capacitance (C*m*). G*a* is the axial conductance of the axoplasm. The membrane potentials at each node (V*n*) were calculated by using a nerve excitation model in magnetic stimulation. The induced electrical fields parallel to the axon (E*n*) change the membrane potentials in this model.

Fig.2 shows the equivalent electrical circuits of myelinated nerve axon. To simulate the nerve excitation processes, we used the gating kinetics of the human nodes of Ranvier, which were described by Schwarz *et al.*[14]. Each node contains an active sodium channel, fast and slow potassium channels, passive leak channel and membrane capacitance. The nerve excitation model in magnetic stimulation [3] was applied to calculate the membrane potentials elicited by induced electrical fields that are parallel to the nerve axon.

The threshold is determined by the minimum stimulus intensity (minimum capacitor charge voltage of the stimulator) that evokes the membrane action potential.

III. RESULTS

Fig. 3 shows the spatial distribution of the induced electric field along the nerve axon (Ey) by changing the conducting ratio (σ1/σ2). The coil current direction is X-. This result suggests that the electric fields parallel to the nerve axon are induced in inhomogeneous volume conductor and the magnitude of induced electric fields increases with the increase of the conductivity ratio (σ1/σ2).

Fig. 4 shows the change of threshold for nerve excitation when the initial coil current direction and waveform are changed. The threshold decreases with the increase of the conductivity ratio (σ1/σ2) in all coil current configurations. This result also suggests that the threshold is lower when the current direction is toward the region 1 (X(-)) if the current waveform is monophasic. On the other hand, the threshold is lower when the current direction is toward the region 2 (X(+)) if the current waveform is biphasic. The threshold is almost the same when the coil current direction is (X(-)), even though the waveform is changed. These results suggest that the optimal current direction differs among the current waveforms.

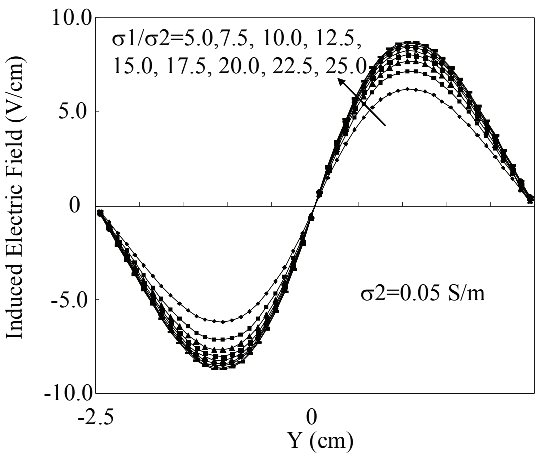

Fig. 3. The distribution of induced electric fields along the nerve axon (Ey) when the conductivity ratio in two regions (σ1/σ2) is changed. The conductivity in region2 (σ2) is 0.05 S/m. The coil current direction is assumed to be toward the σ1 region (X(-)). The rate of change in coil current is 10 A/μs.

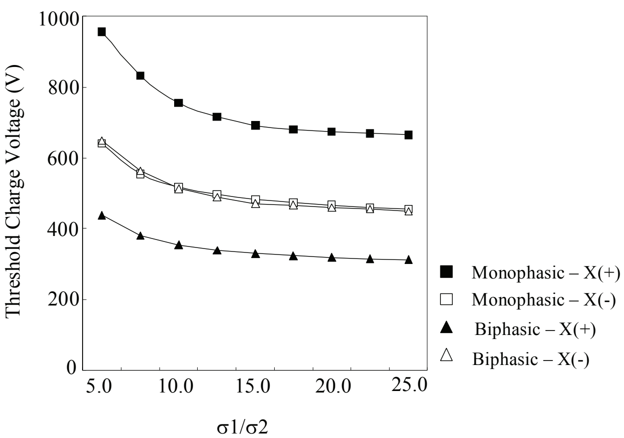

Fig. 4. Change of nerve excitation threshold when the coil current configuration is changed by varying the conductivity ratio (σ1/σ2). The coil current configurations (Waveform- Direction) are "Monophasic – X(+)", "Monophasic – X(-)", "Biphasic – X(+)", and "Biphasic – X(-)". The threshold is expressed as the capacitor charge voltage of the magnetic stimulator based on capacitor charge/discharge system.

Fig.5 shows the spatial distribution of the induced electric field along the nerve axon (Ey) by changing the anisotropic ratio (σ1y/σ1x) in region 1. The coil current direction is toward the region 1 (X(-)). The magnitude of induced electric fields decreases with the increase of anisotropic ratio.

Fig.6 shows the change of threshold for nerve excitation by varying the anisotropic ratio (σ1y/σ1x) and coil current waveform and direction. The result shows that the threshold increases with the increase of anisotropic ratio and biphasic waveform has lower threshold in both directions. The threshold is lower when the current direction is toward the region 1 (X(-)) if the waveform is monophasic. On the other hand, the threshold is lower when the current direction is toward the region 2 (X(+)) if the waveform is biphasic.

It also shows that the difference in threshold between monophasic-X(-) configuration and biphasic-X(-) configuration arises by increasing the anisotropic ratio. In these coil current configurations, the threshold difference is not observed when the tissue is isotropic.

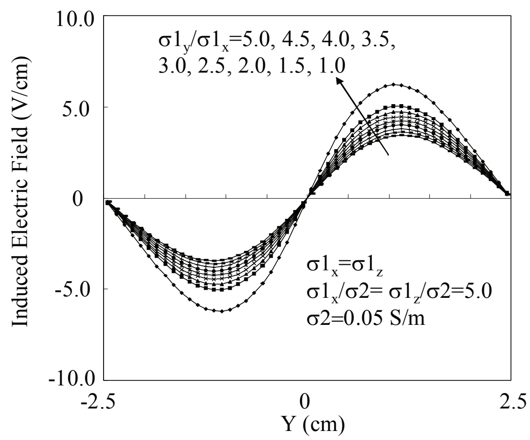

Fig. 5. The distribution of induced electric fields along the axon (Ey) when the anisotropic ratio of longitudinal to transverse direction respect to the nerve axon (σ1y/σ1x) is changed. The conductivity in region2 (σ2) is 0.05 S/m. The coil current direction is assumed to be toward the σ1 region (X(-)). The rate of change in coil current is 10 A/μs.

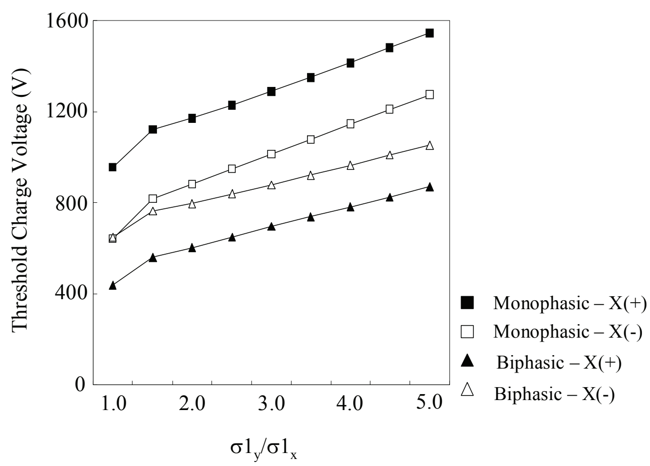

Fig. 6. Change of nerve excitation threshold when the coil current configuration is changed by varying the anisotropic ratio of longitudinal to transverse direction respect to the nerve axon (σ1y/σ1x). The coil current configurations (Waveform- Direction) are "Monophasic – X(+)", "Monophasic – X(-)", "Biphasic – X(+)", and "Biphasic – X(-)". The threshold is expressed as the capacitor charge voltage of the magnetic stimulator based on capacitor charge/discharge system.

IV. DISCUSSION

In this study, we obtained the effects of coil current configuration (current waveform and direction) on nerve excitation threshold when stimulating the nerve axon in inhomogeneous anisotropic conducting media. The simulation results suggest that the optimal direction of coil current is reversed when the coil current is changed between monophasic and biphasic in inhomogeneous isotropic volume conductor. We also investigated the effects of tissue anisotropy on the threshold for nerve excitation. The difference in nerve excitation threshold by changing the coil current waveform and direction were observed when the tissue has different anisotropic ratio of longitudinal to transverse conductivity. The results suggest that the each coil current configuration has different nerve excitation threshold.

Some experimental results showed that CMAPs with large amplitude are evoked when the coil current flows perpendicular to the nerve [7][8][9] which is inconsistent with the prediction using a homogeneous volume conductor model. The simulation results in this study with inhomogeneous anisotropic volume conductor model shows that the nerve can be excited when the coil current flow perpendicular to the nerve axon by using an active membrane model.

Sun *et al*., [9] and Kobayashi *et al*., [11] showed that the amplitude of CMAPs were different by changing the coil current direction in magnetic stimulation of human median nerve. The results in this study also demonstrate that the threshold for nerve excitation differs when the coil current configurations are changed and explain their experimental results theoretically by using a computer simulation.

Our simulation results in this study may help to explain the different characteristics of nerve excitation properties when changing the coil current configurations in inhomogeneous anisotropic volume conductor model and showed that the theoretical model is applicable to understand the mechanisms in magnetic stimulation of both central and peripheral nervous systems.

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