A NUMERICAL ANALYSIS OF THE ELECTRIC FIELD GENERATED BY A NERVE CUFF ELECTRODE

Rekha R. Chintalacharuvu, David A. Ksienski, and J. Thomas Mortimer*

Department of Electrical Engineering and Applied Physics,
** Department of Biomedical Engineering*
Case Western Reserve University, Cleveland, Ohio

ABSTRACT

We have developed a three dimensional finite element model of an unifascicular nerve and studied the effects of electrode configurations and the effects of tissue conductivities in and around the nerve trunk on the potential distribution due to a cuff electrode. From the potential distribution we can estimate the region of the nerve trunk where fibers of specific diameter are excited. Our results indicate that selective activation of the nerve fibers was affected by the anisotropy of the nerve trunk and the perineurium. Tripolar configuration with a smaller spacing between the anodes and the cathode, was more effective in confining the current to the superficial regions of the nerve trunk relative to a monopolar configuration and selectivity of excitation was further improved by steering the current with an anode located across the cathode.

INTRODUCTION

In spinal cord injured patients independent control of motor neurons innervating different muscles or muscle groups with different functions can be achieved with a nerve cuff electrode [6, 11]. The capability of a nerve cuff electrode to stimulate specific motor neurons depends on the geometry of the specific electrode configuration, the electrical conductivities of the tissues in and around the nerve trunk. The composition of the tissues surrounding the nerve trunk changes due to growth of connective tissue in the space between the nerve and the cuff in a chronic implant. The connective tissue is organized into a tight cell layer close to the cuff and a loose cell layer close to the nerve [1]. A three dimensional finite element model of an unifascicular nerve was developed to provide insight into improving the design of cuff electrodes.

METHODS

The electrical potential distribution due to a nerve cuff electrode was obtained by solving the Poisson's equation within a three-dimensional domain using the finite element method coded in Fortran [13,7]. The model comprises a unifascicular, 3mm diameter anisotropic nerve with $\sigma_{longitudinal}$= 1.0S/m and $\sigma_{transverse}$= 0.1S/m surrounded by a 30μm perineurium with σ = 0.0021S/m, two layers of connective tissue; a 150μm loose connective tissue layer with σ = 2.0S/m and a 50μm tight connective tissue layer with σ = 0.06S/m such that the effective σ = 0.22S/m, a 50μm saline (0.9% NaCl) with σ = 2.0S/m to represent the fluid trapped between the connective tissue and the cuff, the electrodes (surface area of 1.57mm^2) imbedded on the inner surface of the cuff and a 1mm insulating cuff surrounded by a 20mm saline layer [3,12,2].

A core conductor model of a myelinated axon with the cable parameters based on the properties of a mammalian myelinated nerve was used to analyze the effects of the electric field applied to the nerve trunk by a cuff electrode [5,10]. A modified activating function was used to predict the nerve fiber excitation [8]. The threshold activating function was calculated as 0.0267V with a 100μs pulse [4]. Finite element solutions were obtained with a stimulus of -1mA at the cathode. The threshold current to excite a 10μm diameter nerve fiber at point A (I_{thr}), was calculated by scaling 1mA with the ratio of 0.0267V to the activating function at point A. Equi-activating function contours with values 0.0267V and 0.0134V were plotted for 20μm and 10μm diameter nerve fibers using I_{thr}. Contour with a value of 0.0134V indicates that twice I_{thr} is required to excite the region bounded by that contour. These contour plots were used to analyze the effect of anisotropy of the nerve, perineurium and connective tissue and selective activation of the nerve using different electrode configurations.

RESULTS

In contrast to an isotropic nerve with the conductivity of saline, the equi-activating function lines were convex for anisotropic nerve (Fig. 1a & b). The presence of perineurium confined most of the current to the peripheral regions of the nerve trunk (Fig. 1c). The absence of dotted lines in Fig. 1c indicates that all the 20μm diameter nerve fibers in the nerve trunk were activated in the presence of perineurium. The shape of activating function lines and the region of excitation for an anisotropic nerve surrounded by perineurium with and without connective tissue were similar (Fig. 1d).

We investigated the ability of four different electrode configurations reported by Sweeney et al. to selectively excite superficial regions of the nerve trunk in the presence of perineurium and connective tissue [11]. The significant change in the shape of the equi-activating function lines and the presence of the dotted lines with the addition of a 0.146mA steering current to a monopolar configuration indicate that the steering current improved the selectivity of excitation (Fig. 1e). The tripolar configuration with the two anodes located ±3mm (edge to edge) longitudinally from the cathode confined the current to the superficial regions of the nerve trunk and improved the selectivity of excitation. The effect of the steering current for the tripolar electrode configuration was similar to that of the monopolar configuration with steering (data not shown). The equi-activating function contour with a value of 0.0134V was shifted towards the central regions of the nerve trunk and the dotted lines were not observed when the distance between the two anodes and the cathode was increased from ±3mm to ±6mm (Fig. 1f & data not shown). These results indicate that the tripolar configuration with the anodes located ±3mm from the cathode was more efficient than when the anodes were located at ±6mm from the cathode, in confining the current to the superficial regions of the nerve trunk.

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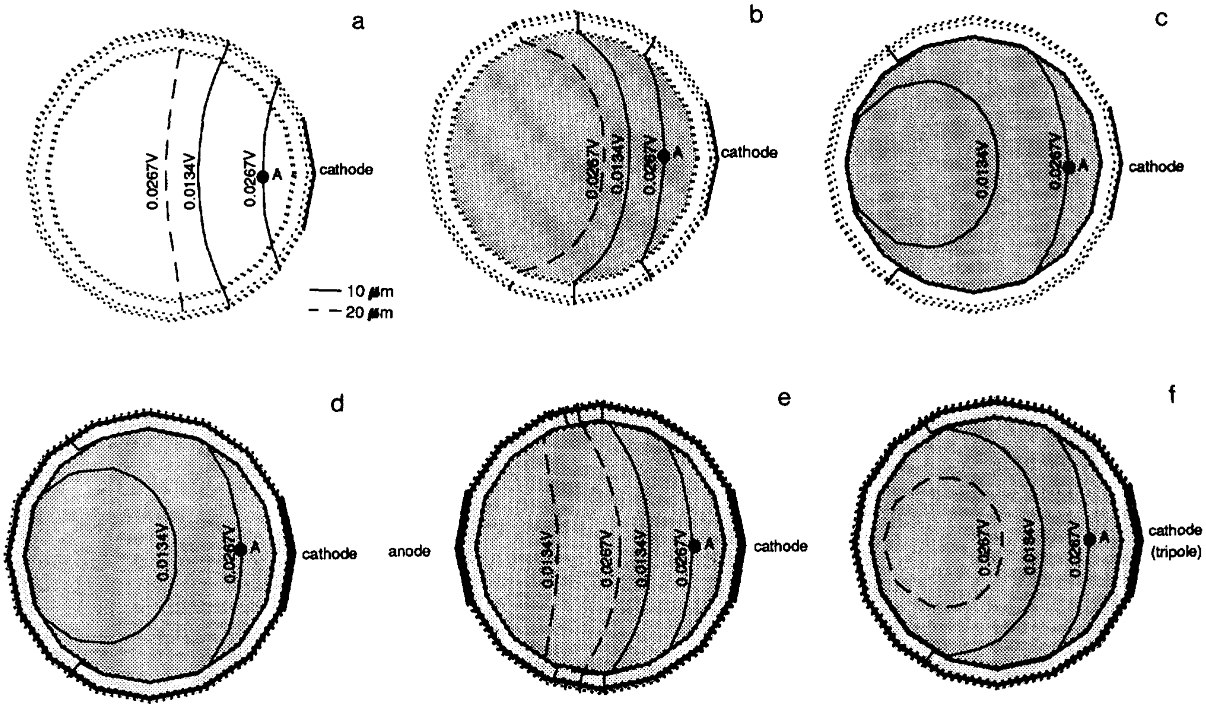

Figure 1: Equi-activating function lines showing excitation regions in the nerve trunk; a) isotropic nerve, b) anisotropic nerve, c) anisotropic nerve with perineruium, d) anisotropic nerve with perineurium and connective tissue, e) monopolar configuration with a steering electrode and f) tripolar configuration with the two anodes located ±3mm longitudinally from the cathode.

CONCLUSIONS

Our three dimensional finite element model indicates that 1) the anisotropy and the perineurium act as barriers to the current flow between the electrode and the nerve fiber and the presence of the perineurium results in a loss of selective activation of nerve fibers proximal to the cathode, 2) the connective tissue has no effect in scattering the electric field generated by the cuff electrode (for the conductivities chosen in this example), 3) the steering current improved the selectivity of excitation due to both monopolar and tripolar configuration and 4) a smaller spacing between the anodes and the cathode in a tripolar configuration was efficient in confining the current to the superficial regions of the nerve trunk. Quantitatively accurate results can be predicted with the model incorporating accurate values of the dimensions and conductivities of the tissue in and around the nerve trunk which are not well established. The model is flexible enough to test multiple electrode configurations including large array of electrodes and geometries and can be adapted to include multifascicular nerve trunks.

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ADDRESS
Rekha R. Chintalacharuvu
Applied Neural Control Laboratory
3480 Charles B. Bolton Building
Case Western Reserve University
Cleveland, OH 44106

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