DIFFERENCE BETWEEN ELECTRICAL AND MAGNETIC NERVE STIMULATION: A CASE FOR THE TRANSVERSE FIELD?

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Abstract - **The cable model for nerve activation is based, among other things, on the assumption of cylindrical symmetry. For the externally applied field in the case of electrical or magnetic stimulation the implication is that the transverse component of the field should be negligible. The present theoretical work shows that for electrical stimulation this assumption is valid in most of the cases, but for magnetic stimulation the assumption is not generally valid, although, with the note that this is strongly dependent on the resistivity of the perineurium of the nerve.**

I. INTRODUCTION

Both for electrical and magnetic stimulation of nerve fibers the activating mechanism is usually described on basis of the cable model [1], [2]. For unmyelinated fibers the cable model leads to the cable equation for the subthreshold transmembrane potential, $V=V(t,x)$

$$\text{(1.)}\quad \tau\frac{\partial V}{\partial t}-\lambda^2\frac{\partial^2 V}{\partial x^2}+V=-\lambda^2\frac{\partial E_x}{\partial x},$$

where τ and λ are the time constant and space constant of the fiber, t is time, x is the space co-ordinate along the fiber, and E_x is the electric field along the fiber, either electrically or magnetically induced.

For myelinated fibers a similar equation holds, where the spatial derivatives are replaced by spatial differences.

Equation (1.) explicitly shows that there should be a non-vanishing gradient of the electric field along the fiber to be able to change the transmembrane potential. Moreover, it is only the gradient of E_x, not other components of the field that may activate the fiber.

Triggered by experimental observations on magnetic stimulation of the median nerve in humans, Ruohonen et al, [3] added the electric field component transverse to the nerve fiber in the right hand side of equation 1. With a small modification (the cosine term) the r.h.s. then reads:

$$\text{(2.)}\quad rhs=-\lambda^2\frac{\partial E_x}{\partial x}+2aE_t\cos(\theta)$$

yielding a good approximation of the transmembrane potential. In (2.) E_t is the transverse field at the fiber, a is the fiber radius, and θ is the azimuthal angle. Note that, implicitly, the transmembrane potential has become a function of θ as well: $V= V(t,x,\theta)$.

The necessity of the addition of the component E_t to the equation is questionable. Other explanations for the experimental results would be obvious: tissue inhomogeneity around the nerve, undulation of nerve fibers within the nerve [4], and physiological and anatomical inhomogeneity of the fiber itself. However, the issue begs for a more profound analysis of the validity of the cable model in the case of strong transverse electric fields.

The key assumption underlying the cable model is rotational symmetry, not only of the fiber structure itself, but also symmetry of the activating field at the fiber membrane. Where this assumption is a fair approximation for most (but not all) cases of electrical stimulation, this is not necessarily true for magnetic stimulation. In the present paper we show that the transverse field cannot always be neglected.

II. METHODOLOGY

The cable model is used for a cylindrical representation of nerve fibers. We, therefore, used a cylindrical model of a fiber situated along the axis of another cylinder representing the nerve fascicle, which in turn was placed off-axis in another cylinder, which represented a limb. Outside the limb a coil was placed, carrying a current I (see fig 1). The nerve fiber itself consists of two concentric cylinders to represent the membrane, which has a thickness of 5 nm. The perineurium, with a thickness of 10 μm, was again created by the use of two concentric cylinders.

The magnetically induced electric field was calculated analytically, by solving Poisson's equation in cylindrical coordinates within the various cylinders with application of the necessary boundary conditions at the cylinder interfaces.

A simpler model was used for electrical stimulation, where the current was induced through a point current source. Here the fiber was immersed in a large homogeneous medium.

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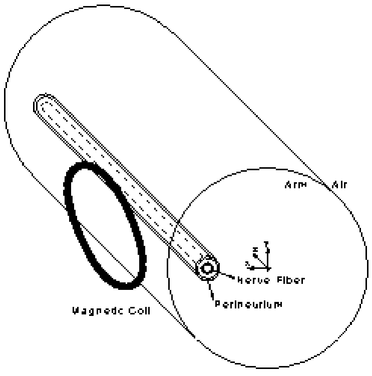

Fig.1 – Cylindrical model of a nerve fiber and nerve trunk in a limb (not to scale), with the relative position of the stimulating coil indicated

Values of the model parameter were: membrane conductance = 6.77 S/m^2, axoplasmatic conductivity = 2.82 S/m, nerve conductivity = 1 S/m, limb conductivity = 2.0 S/m, fiber radius = 3 μm, limb radius = 5.0 cm, nerve position = 1.0 cm under limb surface. Coil diameter = 5.0 cm, with the coil placed in touch with the limb.

The results of the 3D models were compared with the results from the steady state cable equation, either equation (1) or with the r.h.s. replaced by (2.), and in both cases without the time varying term.

For more detailed information on the calculations see [5] and [6].

III. RESULTS

Figure 2 shows the transmembrane current for three different cases of electrical stimulation. Only in fig 2A the situation is rotationally symmetric and does the cable equation (1.) hold. Case B shows a very asymmetric situation due to the fact that the electrode is at 4.5 μm away from the fiber. A situation that might occur in microstimulation. Figure 2C also shows a asymmetric case, but now for an electrode at more than 10 cm away from the fiber.

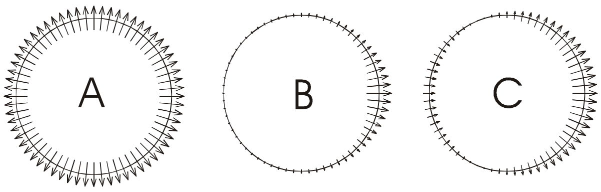

Fig 2 - Arrows indicate membrane current for electrical stimulation. A) the electrode (cathode) is 1 mm away from the fiber, B) electrode very close to the fiber, C) electrode 30 cm from the fiber

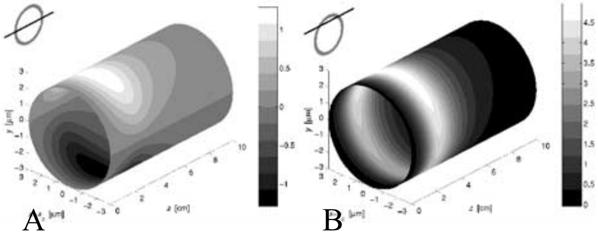

Fig 3 - Transmembrane potential along the positive half of the fiber. The coil position is indicated by the insets

In figure 3 the transmembrane potentials for magnetic stimulation are shown for two cases: A) the coil is positioned symmetrically with respect to the fiber, in which case equation (1.) predicts zero polarization, and B) the coil is positioned in such a way that maximum depolarization exists.

In fig 3A the fiber is strongly depolarized on one side and equally hyperpolarized on the other side. According to equation 1 there should be no polarization at all, because with this symmetrical coil configuration the longitudinal field E_x along the fiber is zero.

In fig. 3B the fiber is depolarized more strongly on one side than on the other. Compared with equation (1.) the maximum difference is about 25% stronger or lesser depolarization. In these cases the transmembrane potential is very well described by eq. 2 (less than 1% difference).

For low values of the conductance of the perineurium the transverse field becomes significantly weaker. For this conductivity being 2.10^{-4} S/m, the transverse field is negligible.

IV. DISCUSSION

This paper focuses on the polarization of nerve fiber membrane in several cases of electrical and magnetic stimulation. The 3D model suggests that the transverse induced electric fields cannot always be neglected, and that therefore, equation (1.) may be insufficient. In contrast, replacing the rhs of eq. (1.) by (2.) always gave an excellent match between the extended cable model and the 3D model.

However, the relative strengths of the two terms in expression (2.) turns out to be strongly dependent on the value of the conductivity of the perineurium. Information on the value of this parameter is scarce [7] in the literature and the availability of more data is highly desirable.

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