ANODAL BLOCK OF MYELINATED NERVE FIBERS: A MODELING STUDY

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ABSTRACT

Electrical stimulation of myelinated nerve fibers was analyzed, using point sources in a simple (homogeneous) volume conductor model and a dynamic model of mammalian nerve fiber properties. The stimulus conditions resulting in anodal block of a propagating action potential were calculated as a function of electrode position. Results were compared with those from an analytical approach, using a passive fiber model under steady–state conditions. In comparison to the range of stimulus amplitudes suitable for cathodal nerve fiber recruitment, anodal block appears to be restricted to a small range and – at small electrode distance – to depend on the position relative to nodes of Ranvier.

INTRODUCTION

Selective stimulation of nerve fibers in peripheral nerves is one of the options in functional electrical stimulation (FES) of the motor system in patients having upper motoneuron lesions. This may be accomplished by activation and/or blocking of nerve fibers having specific characteristics. Although several theoretical studies on nerve fiber recruitment exist [1,2], little is known about nerve block. In this modeling study electrical stimulation of myelinated nerve fibers was investigated, with emphasis on anodal block.

METHODS

According to the model of myelinated nerve fiber stimulation, introduced by McNeal [1] (Fig.1), the change of nodal membrane potential ($V_{m,n} = V_{a,n} - V_{e,n}$) was described by:

$$\frac{dV_{m,n}}{dt} = \frac{1}{R_a.C_m}\left[\{V_{e,n-1} - 2V_{e,n} + V_{e,n+1}\} + \{V_{m,n-1} - 2V_{m,n} + V_{m,n+1}\}\right] - \frac{V_{m,n}}{R_m.C_m} \quad (1)$$

Field potentials Ve in an infinite, homogeneous, isotropic medium (conductivity σ),generated by a point source (current I), were calculated at the nodes of the fiber model:

$$V_e(x,y,z) = I \,/\, 4\pi\sigma\,(x^2+y^2+z^2)^{\frac{1}{2}} \quad (2)$$

(source at $x = y = z = 0$)

From (1) it follows that the nodal membrane potential V_m is related to the second order difference of the nodal field potential V_e: the **activating– or driving function**.

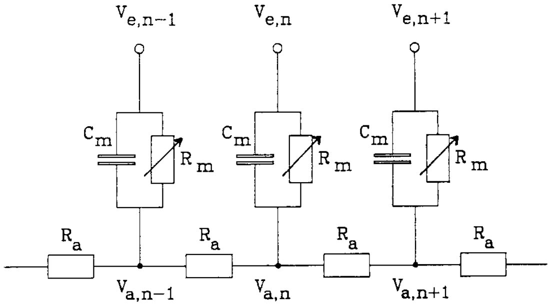

Figure 1. *McNeal model of myelinated nerve fiber stimulation* ***Ra**: internodal intracellular resistance,* ***Rm**: (variable) nodal membrane resistance,* ***Cm**: nodal membrane capacity,* ***Va**: nodal intracellular potential,* ***Ve**: nodal field potential.*

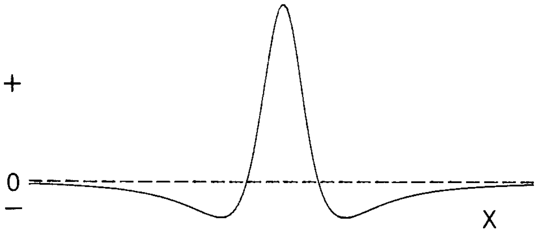

Figure 2. *Cathodal (continuous) activating function (mV) in a homogeneous medium. X–axis: position at nerve fiber; x–position of electrode corresponds with maximum (y).*

The continuous activating function along a straight fiber has a peak (100%) at the position closest to the electrode and two smaller peaks (20%) of opposite sign at both sides (Fig.2). At cathodal stimulation the maximum is positive, resulting in local membrane depolarization, while at the negative "side–lobes" hyperpolarization will occur. At anodal stimulation the opposite effects will be found.
The variable nodal membrane current I_m (= V_m/R_m) was calculated with the equations of the non–linear, voltage dependent nodal conductivity of rabbit myelinated nerve fiber (Chiu et al.[3]), summarized as:

$$I_m = \pi.d.l\,[\,\bar{g}_{Na}.h.m^2.(V_m - E_{Na}) + g_L.(V_m - E_L)] \quad (3)$$

d is the axon diameter, l the nodal gap width and h and m the Na–activating and inactivating function, resp. Repolarization is only due to the (constant) leakage conductance g_L.

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By this dynamic model anodal and cathodal stimulation was simulated at varying electrode position. We also used a simple, steady–state fiber model to calculate the stimulus range for obtaining anodal block at various parameter values.

RESULTS

Usually, the dynamic model was a 10 μm myelinated fiber, consisting of 61 nodes at intervals of 1 mm. At **cathodal stimulation** a fiber could be excited and the action potential propagated in two directions, but at a stimulus of at least 5.3x rheobase propagation was blocked. At **anodal stimulation** the fiber was hyperpolarized close to the electrode, but at a stimulus of at least 5.2x cathodal rheobase excitation and propagation occurred at both sides. **Block** of a propagating action potential was only possible at a minimum pulsewidth of almost the action potential duration. Anodal block threshold was 1.8x cathodal rheobase of the fiber, but propagation could not be blocked by stimuli larger than 3.2x anodal block threshold. These ratios were found when the electrode was at 1 mm from the fiber at nodal position and varied somewhat at varying distance.

The relation between stimulus range for anodal block and anodal position relative to nodes of Ranvier was investigated by both simulations and a steady–state model of the nerve fiber. In Fig.3 upper and lower threshold for block of a propagating action potential are shown at various distances between anode and fiber. At 0.5 mm it appeared that block is not possible at all internodal positions (Fig.3A). At increasing distance variation of thresholds with internodal position decreases and thresholds get constant within 5% at 2 mm (Fig.3B). At larger distance the ratio upper/lower anodal block threshold was almost constant (≈2.2) at varying fiber diameter. Results from the steady–state model showed that stimulus range for anodal block varies with action potential amplitude. The stimulus range for cathodal excitation also has some variation at varying internodal electrode position (Fig.4).

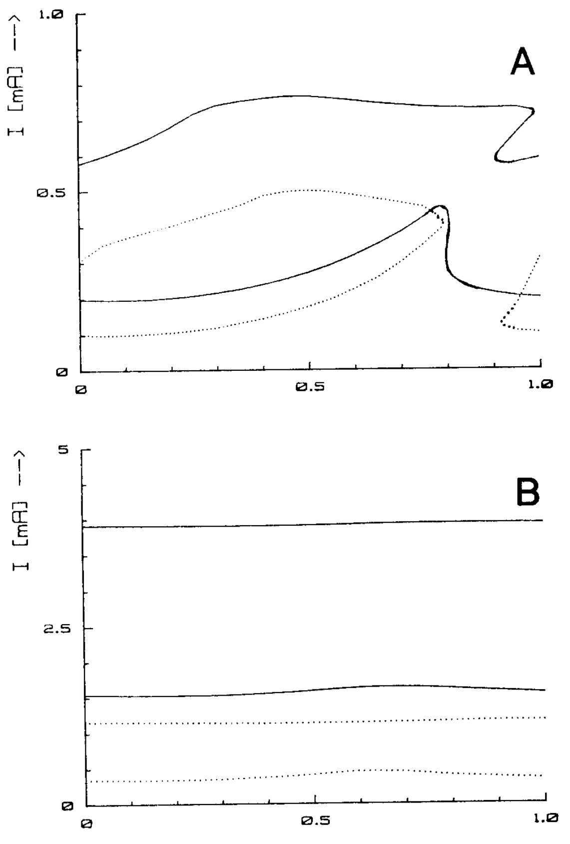

Fig.3. *Stimulus range for anodal block at varying internodal electrode position; 1 ms pulse. Nodes at positions 0 and 1; excitation at node 0, propagating from left to right; $\rho = 3.0\,\Omega$m. A. anode at 0.50 mm (...) and 0.75 mm (—) from fiber (10μm); B. anode at 1.0 mm (...) and 2.0 mm (—).*

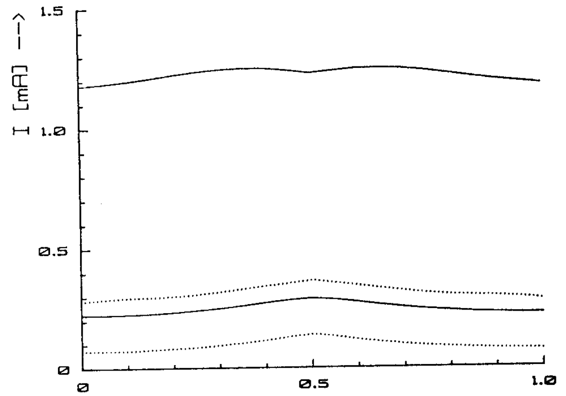

Fig.4. *Stimulus range for cathodal excitation at varying internodal electrode position; 1 ms pulse; cathode at 0.5 mm (...) and 1.0 mm (—) from 10μm fiber.*

CONCLUSION

Results from modeling predict that the range of stimulus amplitudes suitable for excitation or block depends on both the peak value of the activating function and amplitude of its side–lobes (Fig.2), and their positions relative to nodes of Ranvier. At an electrode distance less than 2x internodal distance of the fiber, the stimulus range for anodal block varies largely at varying internodal position.

REFERENCES

[1] D.R. McNeal, "Analysis of a model for excitation of myelinated nerve", IEEE Trans. Biomed. Engin. Vol. 23, pp. 329–337, 1976.

[2] F. Rattay, "Analysis of models for external stimulation of axons", IEEE Trans. Biomed. Engin, Vol. 33, pp. 974–977, 1986.

[3] S.Y. Chiu, J.M. Ritchie, R.B. Rogart, D. Stagg, "A quantitative description of membrane currents in rabbit myelinated nerve", J. Physiol. Vol.292, pp. 149–166, 1979.

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