SIMULATION OF ACTIVATION AND PROPAGATION DELAY DURING TRIPOLAR NEURAL STIMULATION

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Abstract-- Computer simulations were performed to investigate the influence of stimulus amplitude on cathodal activation delay, propagation delay and blocking during stimulation with a tripolar cuff electrode. Activation and propagation delays were combined in a total delay term which was minimized between the excitation and blocking thresholds.

INTRODUCTION

Cuff electrodes with tripolar contact arrangements can be used to selectively activate small nerve fibers by combining cathodal excitation with anodal block of larger fibers [1],[2]. Action potential (AP) propagation may be delayed near the anode at stimulus levels too low to produce blocking [3]. The temporal relationship of activity from fibers of different sizes produced by tripolar stimulation can be rather complex. Simulations were performed to obtain a better understanding of the influence of stimulus amplitude and fiber size on activation and propagation delay during stimulation with a tripolar cuff electrode. We expect that this will aid in interpreting compound neural signals recorded from stimulated nerves, which can be used as a means of assessing the selectivity of electrical stimulation.

METHODS

A two part computer model was used in our simulations [4]. The potential field within a 3-dimensional volume conductor model of the fascicle, surrounding tissues, and

cuff electrode was computed by solving a discretized Laplace equation by a Red-Black Gauss-Seidel iteration. Electrode contacts were modeled as arrays of linked point current sources and the boundaries of the model were grounded. The transmembrane potentials generated in individual nerve fibers within the fascicle were determined using a McNeal-type model of a myelinated nerve fiber [5].

A monofascicular nerve with a diameter of about 0.7mm, surrounded by a 50 μ m perineurium and 50 μ m layer of epineurium, was modeled (Fig. 1). This is comparable to the largest of the several fascicles typically found in the rabbit peroneal nerve. A total nerve length of 23mm was modeled. The electrode consisted of a cylindrical insulating cuff (1.25mm i.d., 0.25mm thick, 11mm long) with three 1.0mm wide circular contacts spaced 3.0mm apart. The nerve and cuff were surrounded by a layer of saline, and the outermost layer of the model was a lower conductivity boundary layer to simulate a distant ground. The central contact of the electrode served as a cathode, and the outer two contacts as anodes. The current through each anode was half of the current through the cathode, so that the sum of the anodal and cathodal currents was zero. 500 μ s stimulus pulses were used.

RESULTS

During tripolar stimulation, a nerve fiber is typically excited to produce an action potential (AP) in the region under the cathode. The AP then propagates away from the cathode in both directions. Propagation of the AP under

Figure 1: Transverse and longitudinal sections of model. + indicates location of nerve fiber.

Figure 2: Action potential location vs. time. Hatched bar shows stimulus pulse duration; a and c indicate anode and cathode positions.

Figure 3

the anodes may be slowed or blocked entirely depending on the amplitude of the stimulus pulse. Once the AP has travelled beyond the anode, it will conduct along the nerve fiber at a constant velocity. We plotted the position of the AP relative to the cathode as a function of time. The position of the AP was defined as the point where the rising phase of the potential was 50mV.

In Fig. 2, the positions of APs in a 10μm fiber are plotted for several stimulus amplitudes. Near the excitation threshold (0.15mA), the AP travels away from the cathode at roughly a constant conduction velocity. There is an activation delay of 325μs before the AP is produced under the cathode. Near the blocking threshold (0.58mA), the AP appears much earlier and travels quickly near the cathode because multiple nodes are depolarized by the cathodal current. However, propagation is delayed under the anodes. These effects result in the non-linearity of the position-time plot. The arrival time of the AP at a distant point on the nerve will equal the distance travelled divided by the normal conduction velocity, plus a total delay term which includes the activation delay, anodal delay and cathodal acceleration effect. The activation delay (d_a) and total delay (d_t) for the 0.58mA stimulus pulse are indicated in Fig. 2.

Fig. 3 shows d_a , d_p , and the propagation delay ($d_t - d_a$) for a 10μm fiber plotted versus stimulus amplitude. At the excitation and blocking thresholds, d_a increases rapidly. In Fig. 4, the d_t is plotted vs. stimulus current for 5, 10 and 15 μm fibers to illustrate the effect of fiber diameter.

DISCUSSION

Our results indicate that small fibers can be excited while larger fibers are blocked, in agreement with previous simulation and experimental results, and furthermore that activation and propagation delay is dependent on fiber diameter and stimulus amplitude. With the contact spacing we used, increasing the pulse duration beyond 500μs would not have a significant effect because by the end of the pulse the action potentials of all the fibers have travelled beyond the area effected by the anodal current before the end of the pulse. If a shorter pulse was used, anodal effects would presumably be reduced. In this study we have considered only the effect of fiber diameter, but excitation and block-

Figure 4

Figure 3: Activation delay (d_a), total delay (d_t) and propagation delay ($d_t - d_a$) vs. stimulus current, for 10 μm fiber.

Figure 4: Total delay plotted as function of stimulus current for 5 μm, 10 μm and 15 μm fibers.

ing thresholds will be lower for fibers at the edge of the fascicle than at the center, so the influence of fiber position must also be investigated before the compound response of the fiber population in a fascicle to tripolar stimulation can be fully understood.

CONCLUSIONS

The results of our simulations predict that tripolar stimulation is capable of producing selective activation of fibers of different sizes, but with distinct temporal effects. A clear relationship exists between stimulus amplitude, fiber diameter, and activation and propagation delay. We anticipate that this information will aid in the interpretation of tripolar neural stimulation effects. By expressing the relationship in mathematical terms, and also taking into account the influence of fiber position, the pattern of neural activity produced by stimulation with a tripolar cuff electrode could be predicted. The relationship could also be incorporated into algorithms for compound action potential decomposition.

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