Analytical Design of a Cuff Electrode

D. R. McNeal, Ph.D.
A. V. Apkarian, M.S.

Rancho Los Amigos Rehabilitation Engineering Center
Downey, California

INTRODUCTION

The cuff (or wrap-around) electrode is by far the most commonly used implantable electrode for stimulation of peripheral nerve. Its design has been based primarily on considerations of the ease of surgical application and long-term reliability. Little attention has been given to the effect of electrode geometry on factors such as threshold, stimulation efficiency, sensitivity to electrode movement, and electrical isolation of nerves lying outside the electrode. Friedman[1] did present experimental data that indicates that a unipolar design is more efficient than a bipolar design, but outside of that work there is little data that is available for the designer of peripheral nerve electrodes.

A theoretical model for calculating thresholds of myelinated nerve fibers was presented by McNeal[2] for simple point-source electrodes. This model has now been expanded to allow analysis of an idealized cuff electrode which is similar to that used in many clinical applications. The development of this model will be outlined in this paper, threshold data will be presented, and a method for designing an "optimal" electrode is discussed.

THEORETICAL METHOD

The electrode and nerve geometry is illustrated in Figure 1. Shown in the figure is an idealized cuff electrode in an infinite homogeneous medium of resistivity ρ_e. The electrode consists of a thin tubular sheet of insulation with two thin circular rings located on the inside border of the insulation. Planes containing the rings are parallel to each other

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This project has been supported by the Rehabilitation Services Administration of the Department of Health, Education, and Welfare under Grant 23P-55442/9-06.

and intersect the insulation surface at right angles. Both rings are the same distance from the center of the insulating tube. Parameters of interest are the electrode diameter D, the insulation length L, and the interelectrode spacing E. A single myelinated fiber is also shown. It will be assumed in this paper that the fiber runs parallel to the axis of the electrode and is displaced a distance r from the center of the electrode. Nodes of Ranvier are indicated by black dots and are assumed to be equally spaced along the fiber. The parameter a is the distance of the nearest node to the plane of the cathodal ring.

Given the geometry shown in Figure 1, the problem is to calculate the threshold of a 20μ diameter fiber for a 100μs constant-current pulse as a function of the electrode parameters (D, E, L) and the nerve fiber location parameters (r, a).

The problem of calculating threshold is solved in two steps. The first step is to calculate the electrical potential at each of the nodes of Ranvier due to a constant current I passed between the two circular rings. This is accomplished by an iterative numerical technique described in detail by McNeal and Apkarian[3]. Given these external potentials at the nodes, threshold can be computed using the method of Bean[4].

RESULTS

In this paper thresholds will be calculated only for a 20μ diameter myelinated fiber with an internodal spacing of 2 mm. See McNeal[5] for numerical values of axoplasm resistivity, membrane capacitance and resistance, nodal gap width, and other assumptions about the nerve model. All data are presented for an idealized cuff electrode with a diameter of 6 mm, an interelectrode spacing of 7.8 mm, and an insulation length of 12 mm. These dimensions were selected to approximate the cuff electrode used by Waters, et al[6] to treat stroke patients for drop foot. It is assumed that the resistivity of the tissue surrounding the nerve fiber and encapsulating the electrode is 300 Ω-cm. All data are presented for monophasic, constant-current pulses of 100μs duration.

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Thresholds for a 20μ fiber are shown in Figure 2 as a function of the radial displacement r and for two values of axial displacement, a = 0 and 1 mm. Consider first the case a = 0 which implies that one of the nodes of Ranvier lie in the plane of the cathodal ring. As shown in the figure, a fiber lying in the center of the electrode (r = 0) has a threshold of 0.52 ma. This decreases slowly at first and then more rapidly as the fiber position is shifted from the center towards the inside surface of the electrode. Threshold approaches zero as the fiber nears the inside surface because the external potential of the node in the plane of the cathodal ring approaches infinity.

Thresholds for this same fiber placed outside of the electrode are considerably higher. Even when the fiber is placed against the outside surface of the electrode, threshold is 1.76 ma and it increases rapidly as the fiber is moved away from the electrode. For example, threshold is 7.3 ma when the fiber is 2 mm from the insulating surface.

When a = 1 mm, one node lies 1 mm above and one node lies 1 mm below the plane of the cathodal ring. The primary difference between this case and the previous one is that threshold is less variant inside the electrode (0.57 ma at the center to 0.42 ma at the inside surface). Threshold does not approach zero at the inside surface because the external potential at all nodes is finite. Thresholds outside of the electrode are similar to the a = 0 case.

Thresholds for a 20μ fiber for any axial displacement will lie somewhere inside the zones indicated by the cross-hatched regions in Figure 3. Both curves shown in Figure 2, of course, lie inside of these zones as do similar curves for other values of axial displacement.

By definition, the initial site of excitation (ISE) is the node at which an action potential initially occurs following a stimulus pulse. This then initiates a "wave of excitation" which propogates from node to node in both directions from the ISE.

The regions within which the ISE are located are shown in Figure 4. A coordinate system has been selected which is centered at the center of the electrode with the vertical axis running along the electrode axis in the direction of the cathodal ring. The upper half of the insulation and the cathodal ring are indicated in Figure 4. The ISE all fall within the two cross-hatched bands. Each of the bands is 2 mm wide (vertical dimension). Since the internodal spacing of a 20μ fiber is assumed to be 2 mm, only one node can lie within the cross-hatched bands for a given fiber location. This is the node at which excitation will first occur.

In essence, what is shown in Figure 4 is that excitation will initially occur at the node closest to the cathodal ring inside the electrode and at the node which is just beyond the far edge of the insulation when it is placed outside the electrode.

DISCUSSION

Experimental verification of the model used in the calculation of data presented in this paper has not yet been done, but qualitatively, at least, the data look quite good. Threshold data for fibers inside the electrode are within a factor of 2 of threshold data measured during a five-year period from drop foot patients. This is remarkably good considering that values of nerve constants and tissue have been taken largely from the literature of experimental data on frogs and invertebrates. Very little data is available on mammals and none on humans. No attempt has been made to match the calculated data to human data.

The result that there are significant differences in threshold inside and outside the electrode also matches our clinical and experimental experience. To obtain balanced dorsiflexion in our drop foot patients, certain branches of the peroneal nerve were placed outside of the electrode to prevent excitation of these branches. Experimental studies on cats performed in our laboratory have shown that approximately 4-6 times as much current is required to excite a nerve which lies adjacent to but outside of the electrode as compared to a nerve lying inside the electrode. This result matches very well with the data shown in Figure 3.

Given the model described in this paper, it is now possible to investigate questions such as given a 4 mm diameter nerve (bundle, not fiber) lying inside a 6 mm diameter cuff electrode, what proportion of the alpha motoneuron population will be excited at a given stimulus current and where are the excited fibers located inside the bundle? To answer this question, thresholds must be calculated for other fiber sizes within the alpha motoneuron range (12-20μ) and assumptions made about the distribution of fiber diameters and the geometric distribution of alpha motor fibers within the nerve bundle.

Once we are able to calculate the proportion of excited fibers as a function of stimulus current and draw "maps" of the excited populations, the effect on these data of the electrode parameters D, E and L can be investigated and "optimal" electrode dimensions determined for various applications.

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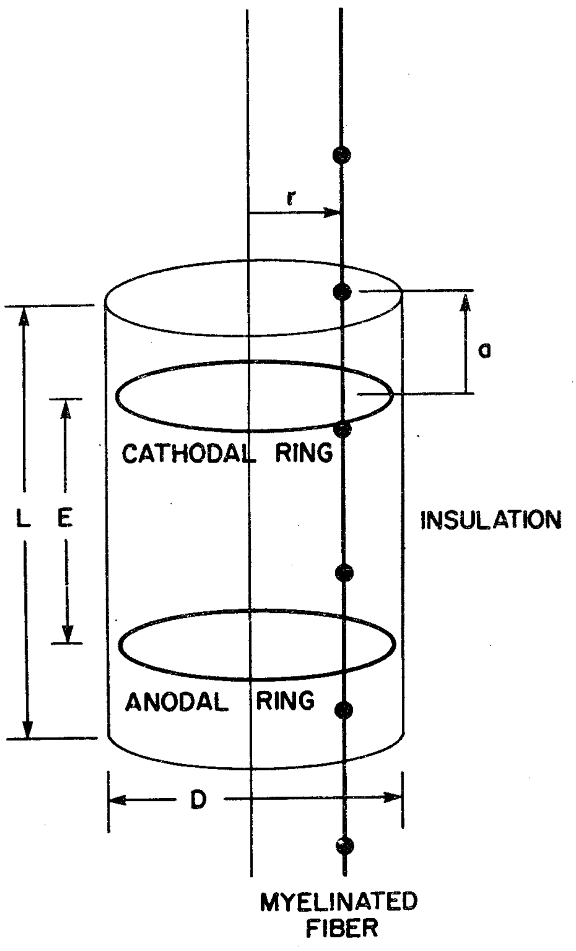

Figure 1. Idealized cuff electrode with two thin circular rings surrounded by a thin tubular sheet of insulation. Electrode geometry is defined by the electrode diameter D, interelectrode spacing E, and insulation length L. A single myelinated fiber is shown displaced a distance r from the axis of the electrode with an axial displacement of a.

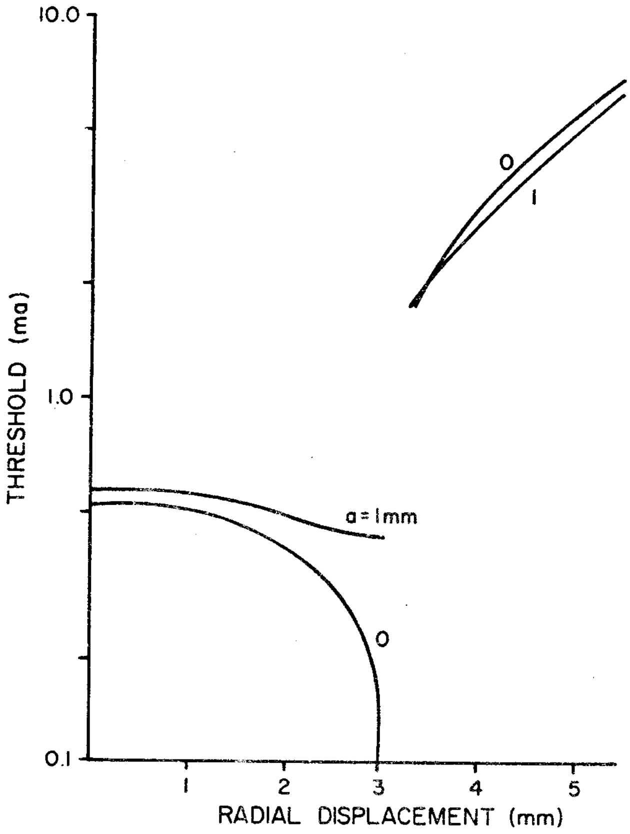

Figure 2. Threshold of a 20μ fiber as a function of radial displacement. Values are shown for a fiber lying inside and outside of a 6 mm diameter cuff electrode with an interelectrode spacing of 7.8 mm and insulation length equal to 12 mm. Axial displacements of 0 and 1 mm are shown.

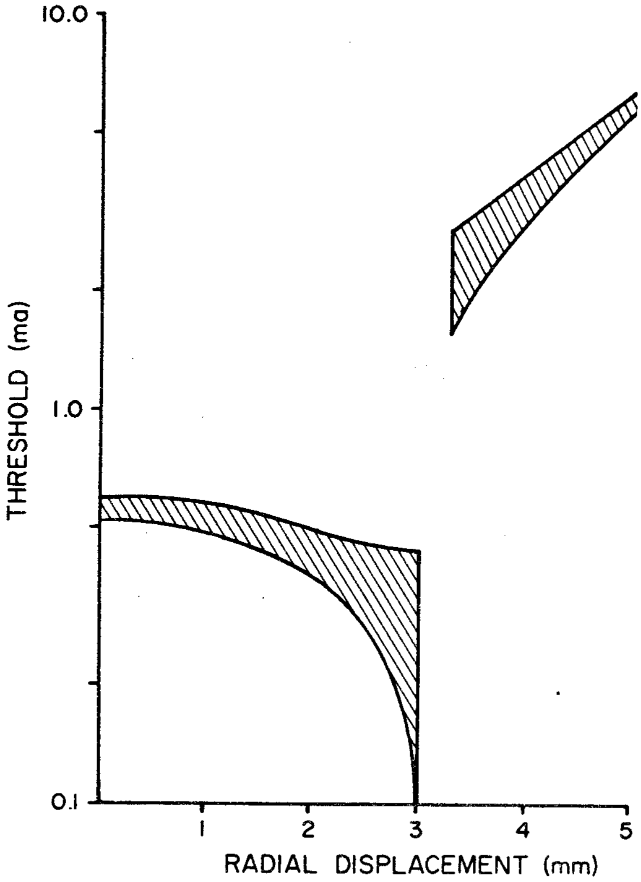

Figure 3. Threshold zones for a 20μ fiber inside and outside of a 6 mm diameter cuff electrode with an interelectrode spacing of 7.8 mm and an insulation length of 12 mm.

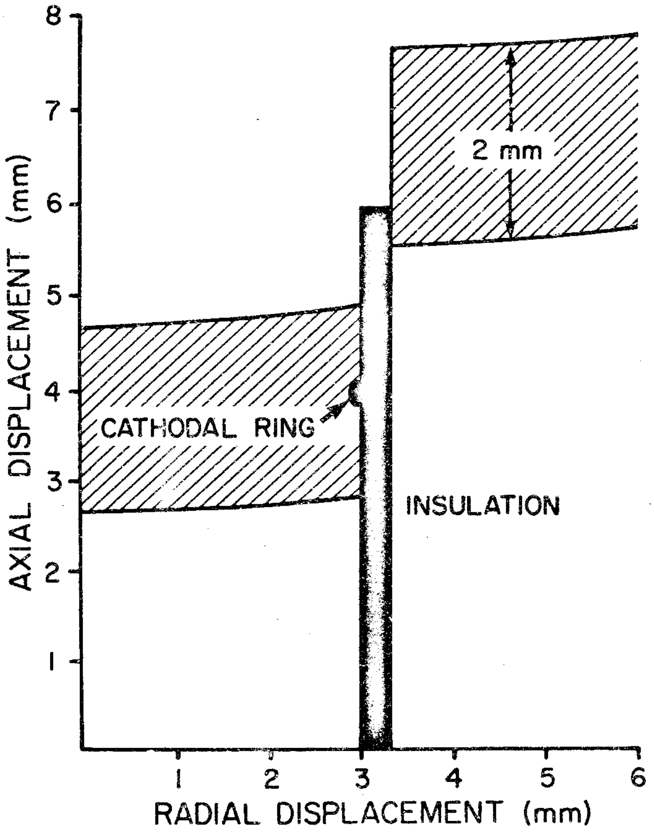

Figure 4. Regions of initial site of excitation for a 20μ fiber inside and outside of a 6 mm diameter cuff electrode with an interelectrode spacing of 7.8 mm and an insulation length of 12 mm. See text for explanation.