Selective Activation of Four Fascicles Using a Four Contact Nerve-Cuff Electrode with Anodic Steering Current

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Abstract. Any one of the four motor nerves in the cat sciatic nerve could be activated selectively and independently, from threshold to saturation, using a self-sizing spiral cuff electrode containing four radially placed monopolar contacts. The results of these experiments support the hypothesis that selective and independent activation of any of four motor fascicles in the cat sciatic nerve is possible using a four contact self-sizing spiral cuff electrode. Furthermore, in a more general case, these results support the concept of a “tunable” electrode that is capable of “steering” the excitation from an undesirable location to a preferred location.

Keywords: cuff electrode, selective stimulation, steering current, self-sizing

1. Introduction

The restoration of sensorimotor functions to those who lost limbs due to disease, traumatic injury, and amputation is a very important and interesting field of research. Several types of peripheral nerve interface have been developed for this purpose including nerve cuffs, penetrating electrodes of various types, and regeneration sieves [1]. Nerve cuffs may be regarded as the most mature technology as they have reached clinical use in diverse applications including phrenic nerve stimulation for diaphragmatic pacing [2], peroneal nerve stimulation for foot drop [3], sacral root stimulation for bladder control in paraplegia [4], and vagus nerve stimulation for epilepsy [5]. There are promising experimental results using cuffs for whole nerve recording to provide feedback to functional electrical stimulation (FES) systems [6], [7]. Nerve cuffs are particularly well suited to these applications because they do not demand highly detailed spatial selectivity of stimulation or recording within the nerve. Selectivity is the ability of the interface (cuff electrode) to activate distinct population of neural fibers with similar properties, for example, fibers innervating a specific muscle or inducing a specific type of sensation without activating other nearby, nontarget populations. Stimulation selectivity is traditionally assessed by placing the neural interface around or inside the peripheral nerve and delivering electrical stimulation while measuring one or more parameters giving insight into which axons of the nerve are being activated. Spatial selectivity tends to be limited because the electrical contacts are at the periphery of the nerve, remote from many of the fibers inside. Selectivity can be improved with multipolar cuffs [8]-[10], in which each contact stimulates its adjacent fascicle. Communicating with deeper fascicles is particularly problematic. A specific design proposed by Tyler and Durand [11], the flat interface nerve electrode (FINE), slowly reshapes the nerve into a flat configuration by applying a small, noncylindrical pressure. Flattening the nerve may allow better access of

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the electrical currents to the axons within the nerve, improving the selectivity. But the safety of this approach
not proof yet, because reshaping of the nerve may cause nerve damage.

Intranuclear electrodes have the potential to be more selective than extraneural electrodes since their
stimulating contacts are located in close proximity to the motor axons. Most intraneural electrodes are also
intrafascicular, meaning that they penetrate into the bundles of axons, or fascicles, within the nerve.
Intrafascicular electrodes consist of fine wires or polymers that are inserted into the individual fascicles. The
longitudinal intrafascicular electrode (LIFE) consists of fine wires that are inserted into and sutured to the
fascicular endoneurium [12]. This electrode is effective at selective stimulation and recording but has
unstable long term properties. A polymer version of this electrode was developed, called the polyLIFE [13].
The polyLIFE has a better long term interface but still has unknown chronic recording Properties.

Another type of intrafascicular electrode consists of penetrating probes. Several types of penetrating
microelectrode arrays have been developed. The Utah slanted electrode array (USEA) places electrodes of
different length in a 3D array to span the entire cross section of the nerve [14]. Acute testing has shown
selective fascicle stimulation and limited intrafascicular selectivity [15].

Because of simplicity and noninvasive character rather than other approaches, cuff electrode is the most
interested to selective stimulation. A strategy to increase the selectively of nerve cuff electrodes is to use
multi-contact stimulation to decrease the spread of current and activate only fascicles close to the stimulation
contact [12]-[16]. All fascicles attempted could be selectively recruited using multi-contact stimulation [12].
Multi-contact stimulation uses subthreshold currents through contacts other than the primary one to shape the
electric field. Simultaneous anodic stimulation on the opposite contact shapes the electric fields causing the
current to remain closer to the cathode. When multicontact cuff electrodes are placed around a peripheral
nerve, contacts may not necessarily be aligned with a target fascicle. A remedy could be either to add more
contacts to the electrode assembly a means to tune the electrode. With multiple contacts available, virtual
excitation sites can be created by superimposing the electric fields generated by simultaneous application of
currents to two or more contacts in the electrode assembly. Field steering is a technique to creating virtual
excitation sites that are different from the physical location of an actual simulating contact. The main aim of
this work is to describe the potentials and limits of the use of a cuff electrode to selective recruitment of
target nerve. This experiment was carried out with spiral cuff electrode containing four radial contacts,
implanted on sciatic nerve of Rat. It can be shown that by random chance, about two thirds of the time one of
the four contacts was positioned to excite selectively and controllably one of the four motor fascicles in the
sciatic nerve. In this case where a single contact could not activate a target fascicle, field steering is an
effective means of creating a virtual excitation site confined to a target fascicle.

2. Materials and Methods

2.1. Simulations

Given the opportunity of designing multielectrode structures, tools were needed to optimize potential
electrode designs. Mathematical modeling of the electromagnetic fields generated by active nerves and
electrodes is needed to quantify these effects and to compare electrode performances. Moreover, it would
give a significant insight into an optimal geometrical pattern of the electrode’s active sites on the substrate
with respect to their shape, size and placement.

The method used for modeling the volume conductor, was the finite element method. The model was
simulated in Comsol, an interactive finite element solver that has an interface to MATLAB®(MathWorks).
A three-dimensional, anisotropic, inhomogeneous volume conductor of a rat’s sciatic nerve was modeled
with Comsol v.3.5, using the conductive media DC to solve Maxwell’s equations. A linear solver with a
relative error of 1.0E-6 was used in all models. A cross section of a rat sciatic nerve was constructed,
containing four fascicles of different sizes. For the cuff electrode the nerve had a diameter of 1 mm. The
diameter of different fascicles was 0.2mm (fascicle A), 0.25mm (fascicle B), 0.375mm (fascicle C) and
0.3mm (fascicle D). no fascicles were compressed using circular cuff. The thickness of perineurium was
equal to 3 % of the diameter of the fascicle [17]. Lengths and conductivities are given in table 1. The size of
the volume conductor was 2 × 2 mm in diameter and encased the cuff together with the sciatic nerve. A
volume conductor that had a volume that was twice as large was also tested, with insignificant difference in the results. The contacts were made of platinum and the insulating electrode was made of silicone. At the model boundary the Dirichlet boundary condition ($V=0$) was applied.

### 2.2. Cuff electrode and nerve model

The Circular cuff electrode (fig. 1) was designed to eliminate pressure on the fascicles. AAMI recommend that the cuff should exceed the nerve diameter by at least 20 percent ($\text{CNR}=1.5$) [18]. The circular cuff was constructed with a rectangular (tripolar) contact, $1 \times 1$ mm, placed near the top of the largest fascicle to compare with four equally placed rectangular contacts placed $0^\circ$, $90^\circ$, $180^\circ$, $270^\circ$ degrees apart from each other that used as cathodes (or also as anodes), and 2 anode ring electrodes at the outer part. The sciatic nerve cross section was taken for the right hind limb just proximal to the branching point into the tibial and common peroneal divisions [19]. Table 1 shows the parameters used for cuff electrode and nerve. One of the main specifications of cuff electrode is selectivity of the electrode. Selectivity is defined as ability of electrode in activation of target fascicle without activation of other fascicles. In this work we investigated the selectivity of cuff electrode using steering anode effect.

Table 1: Values of materials conductivity and parameters used in the modeling

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity(s/m)</th>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saline</td>
<td>2</td>
<td>Nerve lenght</td>
<td>30mm</td>
</tr>
<tr>
<td>Epineurium</td>
<td>$8.26 \times 10^{-2}$</td>
<td>Cuff lenght</td>
<td>15mm</td>
</tr>
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<td>Perineurium</td>
<td>$2.1 \times 10^{-3}$</td>
<td>Diameter of nerve</td>
<td>1mm</td>
</tr>
<tr>
<td>Endoneurium</td>
<td>$x,y: 8.26 \times 10^{-2} \ z: 0.571$</td>
<td>Surface area of cathodes</td>
<td>$8.8236 \times 10^{-7}$ m²</td>
</tr>
<tr>
<td>Cuff (Silicon)</td>
<td>$1 \times 10^{-12}$</td>
<td>Surface area of ring anodes</td>
<td>$1.1788 \times 10^{-5}$ m²</td>
</tr>
<tr>
<td>Contacts(Platinum)</td>
<td>$8.9 \times 10^{6}$</td>
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Fig. 1: Model of nerve trunk and cuff electrode.

### 3. Results

Table 2 shows that the minimum currents needed to stimulate fascicles are different and fascicle C has maximum amount of current among three other fascicles. Therefore, if we want to stimulate all of the fascicles with one current value, we should select the current of fascicle C that is $19.3 \text{A/m}^2$ ($17\mu\text{A}$). Table 2 also shows that each fascicle has a maximum amount of stimulation current in which if the current exceeds that value, other fascicles may be stimulated in addition to the target one. Selected stimulation current
density (19.3A/m²) is lower than the maximum current of Fascicle A and B. so, there is no problem in these fascicles, except for fascicle D, at which this current is more than the maximum current of this fascicle. If this current be applied to contact D, fascicle A will also be recruited in addition to fascicle D (Fig. 2).

Table 2: Minimum and maximum current density to activate only target fascicles

<table>
<thead>
<tr>
<th>Fascicle (A)</th>
<th>Fascicle (B)</th>
<th>Fascicle (C)</th>
<th>Fascicle (D)</th>
</tr>
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<tbody>
<tr>
<td>ring</td>
<td>dot</td>
<td>ring</td>
<td>dot</td>
</tr>
<tr>
<td>Minimum</td>
<td>18.4</td>
<td>16</td>
<td>18.8</td>
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<tr>
<td>current</td>
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<tr>
<td>density</td>
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<td>needed to</td>
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</tr>
<tr>
<td>stimulate (A/m²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>19.9</td>
<td>17.2</td>
<td>19.4</td>
</tr>
<tr>
<td>current</td>
<td></td>
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<tr>
<td>density</td>
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<td>stimulate</td>
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<tr>
<td>only target</td>
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</tr>
<tr>
<td>fascicle</td>
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<td>(A/m²)</td>
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</tbody>
</table>

Fig. 2: Electric potential of fascicles with stimulating pulses applied to fascicle D in ring configuration

To solve this problem, steering anodic current could be used. Applying an anodic current to contact A, spatial distribution of the electric field around the fascicle A will be positive and this will prevent recruitment of fascicle A. Simulations show that 1 A/m² anodic current (0.8 uA) could be used as steering current to fascicle A. Figure 3 illustrates electric potential of all of the fascicles with applying steering anodic current to contact A.

Fig. 3: Electric potential of fascicles with stimulating pulses applied to fascicle D and steering anodic pulses applied to fascicle A in ring configuration
4. Discussion

We interpret these results to support our hypothesis that any one fascicle of a four-fascicle nerve can be fully and selectively activated using a four contact nerve-cuff electrode. Anodic steering current was found to be a viable method to shift the excitatory field away from one fascicle to allow activation of an adjacent fascicle. Cathodic steering current was found to be a viable method to activate a fascicle located between two different contacts. Based on the results from this simulation, a four contact cuff electrode could be used to produce the same torque output as any one of the four fascicles in the sciatic nerve. The results of this experiment support the hypothesis that with a multicontact, self-sizing, spiral cuff electrode, it is possible to activate selectively, from threshold to maximum activation, any specific motor fascicle contained within a nerve trunk. Further, these results suggest a new concept for neural prostheses, —tunable‖ electrodes; electrodes that can create virtual excitation sites when coupled to stimulators that can effect simultaneous positive and negative stimulation at several contact sites.

5. References


