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Selective Fascicular Recording of the Hypoglossal Nerve Using a Multi-Contact Nerve Cuff Electrode

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Abstract—**The use of nerve cuff electrodes as part of a closed loop functional electrical stimulation (FES) system has been demonstrated as a reliable alternative to artificial sensors (e.g., strain gauge). To circumvent the need for multiple electrodes to record neural activity from different fascicles within a nerve, the flat interface nerve electrode (FINE) is presented as a potential approach to discern spatially disparate sources using a single implantable device.**

The recording selectivity of the FINE was investigated using both experimental and computational methods. This involved analyzing recorded action potentials from six acute beagle experiments and a finite element model, which was constructed from a nerve image obtained from one experiment.

The performance of the electrode was assessed by a selectivity index that quantified the recording selectivity at the fascicle level. The computed overall selectivity of the FINE was SI_FINE = 44.5 ± 11.2 and SI_FINE = 52.2 for the experimental (n=7) and computational (n=1) data, respectively.

The results of this study indicate the feasibility of using the FINE as a means of selectively recording neural signals from a multifasciculated nerve.

Keywords—**selectivity index, flat interface nerve electrode, hypoglossal nerve, action potential; neural recording**

I. Introduction

An important design criterion for functional electrical stimulation (FES) systems is the incorporation of a closed loop control mechanism that can further enhance the therapeutic effects of activating neurologically impaired muscles. While the feasibility of using artificial sensors (e.g. strain gauge) to measure variables such as joint angle or force has been demonstrated in spinal cord injury (SCI) patients, issues concerning safety and reliability (e.g., biocompatibility) have limited its application in FES systems [1, 2].

Nerve cuff electrodes present an alternative approach to achieving a closed loop system: recording the peripheral nerve activity of natural sensors (e.g., cutaneous pressure receptors) innate to that particular biological system. The reported long-term reliability and safety of these nerve electrodes are further validated by studies demonstrating the successful implementation of this technology into FES systems [3-7].

The use of a single electrode for each nerve branch, however, suggests that multiple electrodes would be required for multi-fasciculated nerves, e.g., sciatic nerve. To this end, the flat-interface-nerve-electrode (FINE) offers a unique multi-contact design that reshapes the nerve into a more flattened cross-section. While this reshaping has been shown to improve recording selectivity, the finite element model (FEM) used to demonstrate this point was limited to a geometrically ideal representation of the nerve anatomy [8].

The objective of this study was to investigate the feasibility of selectively recording neural activity from a multi-fasciculated nerve using the FINE. The elicited signals were obtained from six acute animal experiments and a realistic finite element model, which was derived from an actual image of a nerve. The performance of the electrode was quantitatively expressed as a selectivity index.

II. Methodology

The recording selectivity of the FINE was investigated using both experimental and computational methods. In either case, the electrical activity recorded from the thirteen tripoles (i.e., center cathode and adjacent anodes) of the FINE was used to quantify selectivity.

1) *Acute Experiments*: Six adult beagles (9-12 kg) were anesthetized with an initial I.V. injection of Pentothal (1ml/kg) and subsequent ventilation of 1-3% halothane with 100% oxygen. Access to the hypoglossal (XII) nerve and its distal branches was achieved through a submandibular incision and blunt dissection of the overlying fascia and muscle tissue [Fig. 1]. The recording FINE was implanted just proximal to the branching point of the XII nerve, while the stimulating cuff electrodes were placed on the branches.

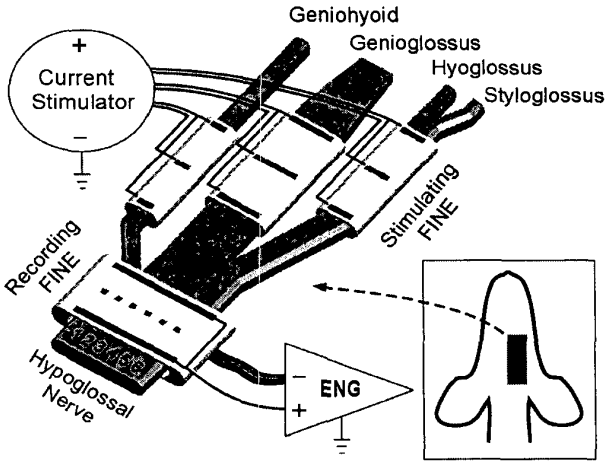

Fig 1. Schematic diagram of hypoglossal nerve with recording FINE and stimulating cuff electrodes implanted proximal and distal to the branching point, respectively. The site of surgical incision is given in the inset.

As current pulses (I = 0.5 to 2 mA; pulse width = 50 μs; frequency = 2 Hz; number of pulses = 16) were delivered to each branch electrode, the corresponding antidromic compound action potentials (CAP) were recorded using the 13-tripole FINE. The elicited signals were filtered (bandpass: 10 Hz – 10 kHz; notch: 60Hz) and amplified (gain: 5000 – 100,000) with an AC-coupled differential amplifier (Grass P511, Astromed Inc) and subsequently archived (sampling rate = 40 KHz) on a PC.

Following each experiment, the XII nerve was excised and stored in 10% formalin solution. These were later sectioned, stained (methylene blue) and fixed in paraffin.

2) *Finite Element Model (FEM)*: A cross-section of the nerve (exp. #4) corresponding to the middle of the FINE was traced, digitized and imported into a finite element software package (Maxwell 3D, Ansoft Corp.), where it was extruded (L = 60 mm) into a 3-dimensional model [Fig. 2(a)-(c)]. A cuff electrode (length = 1 cm; width = 6.5 cm; window height = 0.4 mm) was placed around the nerve and completely surrounded by a large saline bath. The model components are presented in table I [8, 9].

Single fiber action potentials (SFAP) were simulated by solving a series of finite element models, where a single node of Ranvier (radius = 3μm; length = 4 μm) was located at successfully distal locations (ΔL = 1 mm; 10μm axon) along the fascicle. The node was defined as a voltage source (V = 0.1 volts), while the outer boundary of the saline bath represented the electrical ground. For each solved model, the membrane current of the node of Ranvier and the corresponding voltage profile on the inner surface of the FINE were saved as individual data files.

Assuming electrical linearity, a simple code written in Matlab® (Mathworks Inc.) combined these voltage profiles with the time-dependent nodal membrane current values, which was obtained from a Neuron model using Sweeney

TABLE I
FINITE ELEMENT MODEL COMPONENTS

Material	Conductivity (S/m)
Endoneurium	Radial = 0.0826; Long = 0.5714
Perineurium	0.0021
Epineurium	0.0826
Cuff Electrode	1×10^{-7}
Saline	2

membrane dynamics [10], to simulate the recorded SFAP. This was repeated for five axons distributed within each fascicle of the nerve [see medial branch in Fig 3(a)].

3) *Selectivity Index (SI)*: For each active fascicle *m*, the peak-to-peak voltages of the recorded CAP or SFAP from *n* tripoles were used to define a matrix ($V_{m,n}$), where the maximum number of fascicles and tripoles were M and N, respectively. As described in more detail by Perez-Orive *et al* [8]., $V_{m,n}$ was normalized across all tripoles and fascicles to yield $W_{m,n}$, which was used to compute the Euclidian distance ($d_{m1,m2}$) between two fascicles (*m1 and m2*):

$$d_{m1,m2} = \frac{100}{\sqrt{2}} \cdot \sqrt{(w_{m1,1} - w_{m2,1})^2 + (w_{m1,2} - w_{m2,2})^2 + \cdots (w_{m1,N} - w_{m2,N})^2}. \quad (1)$$

Accordingly, the selectivity for fascicle *m1* is defined as the average distance between this fascicle and the remaining fascicles, while the selectivity index (0 < SI < 100) is defined as the average selectivity for all fascicles:

$$SI = \frac{1}{M} \sum_{m2=1}^{M} \left(\frac{1}{M-1} \sum_{m1=1, m1 \neq m2}^{M} d_{m1,m2} \right). \quad (2)$$

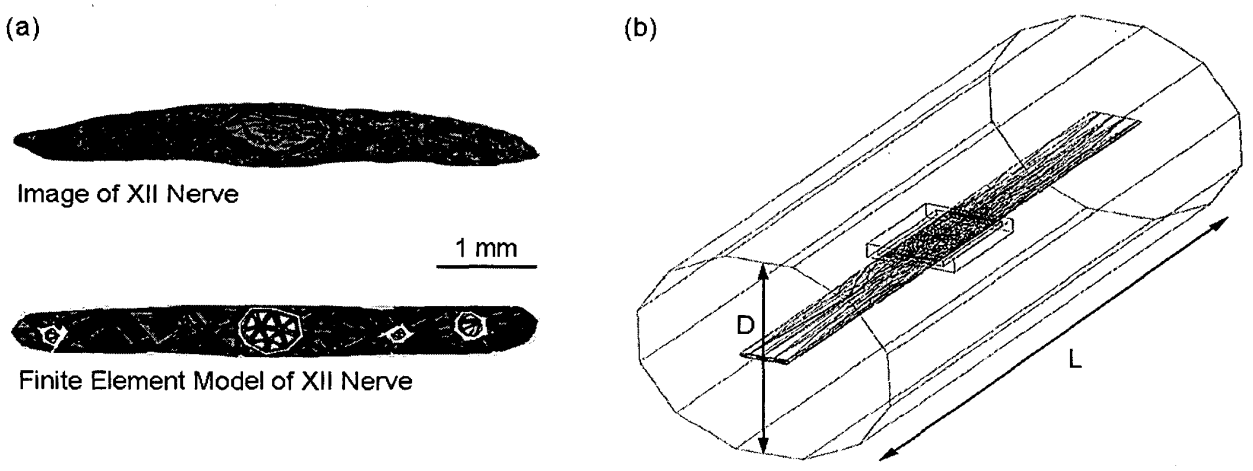

Fig 2. (a) Cross-sectional image of an actual XII nerve, taken from the middle of the FINE, and that of a constructed FEM based on the actual image. (b) FEM of the XII nerve that includes the FINE and the surrounding saline bath of diameter (D = 24mm) and length (L = 60 mm).

The SI was computed for all possible recording combinations (i.e., number of tripoles = 2 to 13) using the thirteen tripoles of the FINE. This analysis yielded an average and a maximum SI for the number of tripoles used in each case. These were termed Mean SI and MAX SI, respectively. The overall recording selectivity was defined as SI_FINE and was computed using all 13 tripoles.

III. Results

The SI was computed using three active fascicles of the canine XII nerve, as the branches innervating the functionally synergistic HG and SG muscles were stimulated as a single fascicle. The FEM also used three active fascicles. The SFAP, in this case, was generated from single axons located in the middle of each fascicle.

A. Neural Recording

A CAP elicited by stimulating the medial XII nerve branch is shown in Fig 3(b), where the signal was recorded from tripole #4 [Fig 3(a)]. This signal is typical for an experimentally recorded CAP using this cuff electrode (L = 1 cm). A SFAP of a simulated nerve fiber is shown in Fig 3(c). In this case, the source is a single axon located in the middle of the same branch [Fig 3(a)]. The amplitude, duration and waveform of the simulated signal is similar to reported single unit recordings [11].

B. Fascicular Recording Selectivity of the FINE

The selectivity was computed for all experiments and the single FEM simulation. For each number of tripoles used to compute SI (n = 2 to 13), all possible combinations for that number of tripoles used to compute the average SI. This is shown in Fig. 4, as the MEAN SI for both Experiment 4 and the corresponding FEM is plotted (bar graph) with

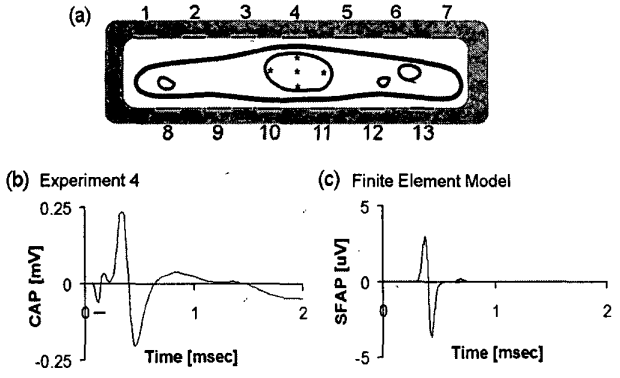

Fig. 3 (a) Traced image of an actual XII nerve section with the tripoles labeled 1 to 13. The five simulated axons of the FEM are indicated as an asterisk in the medial branch. (b) Recorded compound action potential (CAP) with stimulus artifact at t = 0.3 msec. (c) Recorded single fiber action potential (SFAP) from the FEM. Note the different units used for the amplitude.

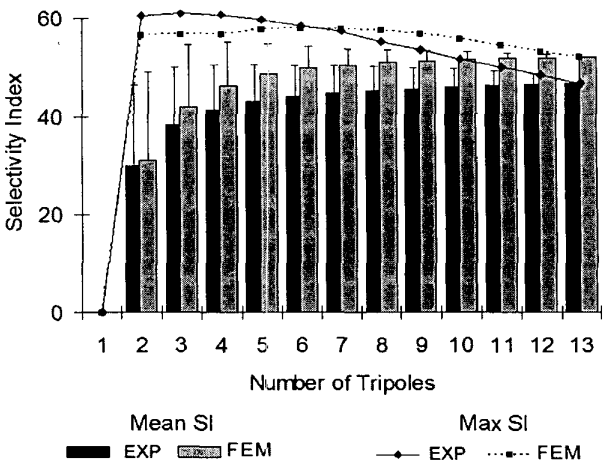

Fig. 4 Plot of computed SI for both experiment 4 and the finite element model (FEM). The MEAN SI and MAX SI are plotted with respect to the number of tripoles used to compute selectivity.

respect to the number of tripoles used for computation. The maximum selectivity (MAX SI) for each case (i.e., number of tripoles) is also plotted (line graph) in Fig. 4.

The MEAN SI increases with the number of tripoles, while the MAX SI (EXP 60.6; FEM = 56.6) plot peaks when the number of tripoles approximately equals the number of fascicles (N = 3). This general trend and the computed selectivity values are consistent between the experimental and FEM data sets. The overall selectivity (SI_FINE) and MAX SI for all data sets are given in table II.

Multiple action potentials within a fascicle [Fig 3(a)] were also simulated and the SI_FINE was computed for the following two cases: (1) a single active fiber randomly chosen from the five axons located in each fascicle (number of possibilities = 3 fascicles x 5 fibers = 125) and (2) all five fibers simultaneously active in each fascicle. The results are presented in Table III.

TABLE II
COMPUTED SELECTIVITY INDEX

Experiment	SI_FINE (13 tripoles)	MAX SI (3 tripoles)
1	29.9	39.1
2	36.3	43.2
3	35.9	51.3
4	46.8	61.0
5a*	46.8	64.9
5b*	61.9	80.6
6	53.6	74.4
FEM	52.2	56.6

* Both XII nerves were used

TABLE III
COMPARISION OF SELECTIVITY INDEX FOR FEM

	Random Single active Fiber (n=125)	Five Active Fibers	Single fiber (ref. Table II)
SI_FINE	52.5 ± 0.5	52.4	52.2

IV. Discussion

The performance of a multi-contact nerve electrode was evaluated using data obtained from acute beagle experiments (n = 7) and compared to results generated from a finite element model (FEM) depicting a multi-fasciculated, non-homogeneous and anisotropic nerve. This was quantified by a selectivity index (SI), which can be simply thought of as the average difference among the recorded action potentials from the electrode tripoles. Consequently, the SI increases (e.g., theoretical maximum = 100) as the difference in recorded signals among the tripoles becomes larger.

The overall selectivity (SI_FINE) of the experimental data [table II] exhibits a high degree of selectivity (mean ± standard deviation = 44.5 ± 11.2), which suggests that the FINE can distinguish signals with an average difference of about 44%. While these values are comparable to those previously reported [8], there is also significant variation in the computed selectivity, which is indicative of the complex branching pattern of the hypoglossal nerve near the site of electrode implant [8, 12].

The selectivity (i.e., MEAN SI and MAX SI) for experiment 4 and the corresponding FEM shows good agreement between the two data sets [Fig. 4]. There are minor discrepancies between these computed SI values that can be attributed to approximations made in implementing the FEM. The most obvious is the use of a single axon to compare fascicular selectivity.

The effect of this approximation was investigated by simulating five evenly distributed nerve fibers within each fascicle and computing the SI_FINE for (1) randomly active single fibers and (2) all five active fibers. While the results [Table III] suggest that the radial position and number of active fibers within the fascicle do not significantly affect the overall selectivity, there are other factors to consider: (1) type of fiber (i.e., axon diameter); (2) longitudinal position of the nodes of Ranvier and (3) fascicular variations (i.e., different nerve cross-sectional images). Incorporating these into the current FEM should further verify the validity of our model and provide additional evidence supporting the feasibility of using the FINE as part of a closed loop FES system.

V. Conclusion

The computed selectivity using the experimental data suggests that the FINE can identify significant differences among the recorded tripolar signals of the electrode, i.e., SI_FINE = 44.5 ± 11.2. The computed selectivity of the FEM data confirms this conclusion (SI_FINE = 52.2). Further validation of the FEM is, however, is warranted to account for various factors that may affect these conclusions.

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