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Fascicle-selective multi-contact cuff electrode

Olivier Rossel Fabien Soulier Jonathan Coulombe Serge Bernard Guy Cathébras*

Abstract— **Neural recording is one of the main issues to be addressed in order to allow closed-loop functional electrical stimulation systems. Because each fascicle in nerves carry specific information, new sensors providing high spatial selectivity are required for chronic implantable devices. This work aims at evaluating the feasibility of a new device using a highly spatial-selective multi-contact cuff electrode. The proposed electrode configuration is evaluated based on simulations using a model of a nerve comprising multiple fascicles. Study of the electrode selectivity is done and compared with a state-of-the-art electrode designed for the same purpose and shows that activity of two fascicles separated by as little as $1\,\mathrm{mm}$ can be distinguished. Implementation challenges and perspectives for such electrodes are also discussed.**

I. Introduction

In the context of functional electrical stimulation, feedback from the functional response to electrical stimulation is required in order to achieve closed-loop control. Muscle force and contraction speed are important information for muscular stimulation that are available on the afferent paths (*e.g.* the sciatic nerve for lower limbs) from neuromuscular spindles or Golgi tendon organs. However, ENG signals are the result of the superposition of the activity of several fascicles, while only one or few fascicles carry useful information.

Whereas sieve [1] and intrafascicular [2] electrodes can measure neural activity from single fibers, they are highly invasive and/or hardly suitable for chronic implantation. Conversely, cuff electrodes are relatively non-invasive for the nerve, but measure global activity, *i.e.* the sum of individual Action Potentials (APs) from different axons within a set of active fascicles. In this context, the feasibility of micro-machined matrix cuff electrodes [3] opens a way to increase the selectivity of cuff electrodes by allowing flexibility on the electrode design. Ideally, one could distinguish the activity of all fascicles present in a nerve. To reach this goal, the first step is to have several poles with a distribution matching the locations of fascicles. This can be achieved by using a flat shaped cuff electrode, such as the FINE electrode proposed in [4], reshaping the nerve, hence increasing its exposed surface and making each fascicles closer to the electrode poles. Nevertheless, standard multipolar electrodes measure, to some extent, the activity of many fascicle, even if each pole is placed nearby a unique fascicle. Some authors intend to use source separation algorithms to discriminate the activity in a fascicle from another [5], but this may prove to be difficult when multiple fascicles are active simultaneously.

All authors are with Laboratoire d'Informatique de Robotique et de Microélectronique de Montpellier, 161 rue Ada, 34392 Montpellier, France
Université Montpellier II — CNRS — INRIA — INSERM
*Firstname.Lastname@lirmm.fr

In a previous paper [6], we studied single fiber extracellular APs, and showed that the periodicity and position of Nodes of Ranvier (NORs) can be observed on the surface of a nerve for nearby axons. The proposed filtering was computed as a tripolar recording on small poles placed in the longitudinal axis of the nerve. It was also shown that the signal resulting from the small tripoles decreases rapidly as a function of distance, leading to high selectivity although its amplitude was only about the micro-volt [6]. It can be expected that a plurality of such tripoles distributed around a nerve could record the complete ENG activity.

Many questions remain to be answered before an actual device can be implemented based on the proposed concept, and relate mostly to the properties of the compound signal resulting from multiple fibers being activated simultaneously in close proximity, *i.e.* within a fascicle. First, we need to confirm that the effects of NoRs observable at the surface of a nerve for single fibers are still present in these conditions. Second, we need to know what the properties (amplitude, relation with distance) of this filtered compound signal are. Finally, how does the selectivity of an electrode based on the proposed concept compares to what can be found in the literature? This paper intends to answer these questions quantitatively.

Section II presents the single-fibre model used for simulations on which this work is based (also presented in [6]), the small tripole definition. It also investigate - using analytical analysis and simulations - the extracellular AP properties for submillimetric distances, highlighting the influence of NoRs. Analysis of compound signals resulting from multiple-fiber activity follows in section III. Study of the proposed electrode selectivity is done and compared with a state-of-the-art electrode in section IV. The main observations stemming from this study are then discussed in section V before concluding in section VI.

II. Single-Fiber Study

A. Analytical Model

We use the axon model presented in Fig. 1 to compute the extracellular AP. Let $v(M)$ be the monopolar potential at point M, y the distance between the point M and the axon, and l_{my} the myelin length, *i.e.* the distance between two NoR. It is shown in [7] that $v(M)$ is the sum of the contribution of each active NoR. In an homogenous isotropic medium, these contribution are computed from the membrane currents i_n affected by r_n, the distance between

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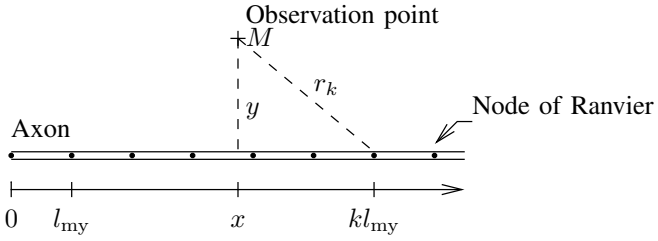

Fig. 1. Axon model with equally spaced nodes of Ranvier.

TABLE I
AXONS PARAMETERS USED FOR SIMULATIONS AS PRESENTED IN [8] (IN μm)

Fiber diam.	NoR diam.	l_{my}	Fiber diam.	NoR diam.	l_{my}
5.7	1.9	500	12.8	4.2	1350
7.3	2.4	750	14	4.7	1400
8.7	2.8	1000	15	5.0	1450
10	3.3	1150	16	5.5	1500
11	3.7	1250			

M and the n^{th} NoR, using

$$v(M) = \frac{1}{4\pi\sigma} \sum_n \frac{i_n}{r_n} \text{ with } r_n = \sqrt{y^2 + (x - nl_{\mathrm{my}})^2}. \quad (1)$$

The n^{th} NoR influence is denoted by the term $(x - nl_{\mathrm{my}})^2$ in (1). Thus, at distances larger than l_{my} the term y is predominant and this influence disappears. On the other hand, at small distances, when $x = nl_{\mathrm{my}}$ (in front of a NoR), the potential exhibits a local extremum. The small tripole is defined to be sensitive to this phenomenon.

B. AP Simulation at Submillmetric Distances

The NEURON software[1] is used with the axon model described in [9] to compute currents at each NoR, and potentials are obtained from (1). As an illustration, two axonal extracellular APs are represented Fig. 2.

For the shorter distance ($y = 200\,\mu$m), the curve clearly exhibits pseudo-periodical variations due to the discontinuities along the myelin shield. The pseudo-periodicity of this signal is directly due to the distance between NoRs (l_{my}). The signal pseudo-frequency range can be determined and is comprised between $1/l_{\mathrm{my}}(\max)$ and $1/l_{\mathrm{my}}(\min)$.

Looking at the second signal ($y = 500\,\mu$m) these variations are less present but the global shape of the AP remains similar. The classical ENG measurements are based on the amplitude difference due to the AP length (about 1 cm related to the AP duration and the velocity propagation) and are only sensitive to this global shape.

C. Small Tripole Definition

The preprocessing used in classical ENG systems to reject parasitic signal such as muscular activity is based on a tripolar measure resulting in a Laplacian filter. In our case, Laplacian filtering is also used thanks to contacts placed along the longitudinal axis of the nerve, but the novelty resides in the tripole dimensions adjusted to be sensitive to the submillimetric phenomenons.

[1] http://www.neuron.yale.edu

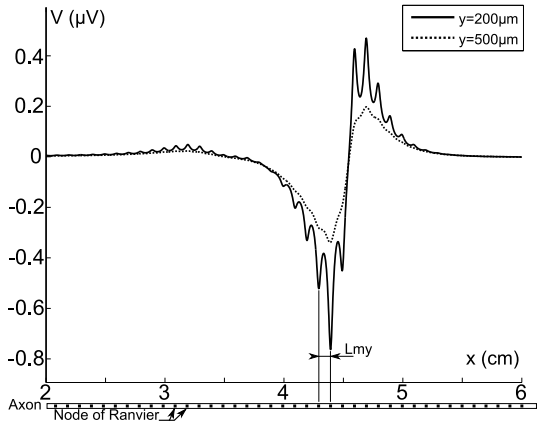

Fig. 2. Behavior of the monopolar extracellular AP along a single axon ($8.7\,\mu$m diameter and 1 mm of myelin length) at two submillimetric distances: $y = 200\,\mu$m (solid line) and $y = 500\,\mu$m (dashed line).

We demonstrated in [6] that the inter-pole distance (d_e) must be equal to $375\,\mu$m in order to fit the band-pass of the filter with most of the spatial frequency of the sub-millimetric variations (between$1/l_{\mathrm{my}}(\max)$ and $1/l_{\mathrm{my}}(\min)$) according to tab. I). Thus, a new design of multipolar cuff electrode is proposed, using small tripoles distributed all over the cuff Fig. 4.

III. MULTI-FIBER STUDY

The compound ENG signal can be described as the supeposition of extracellular potentials generated by several axons.

A. Simulation Method

Fascicles within a nerve are represented by numerous fibers in close proximity (one from the others), and extracellular APs are estimated using (1) with randomized parameters. Namely:

- fascicles with random elliptic shapes are positioned in the nerve;
- sizes of the fibers are randomly chosen from tab. I.
- fibers are located randomly in the fascicles (without overlap, fill factor between 25 % and 75 %);
- the position of the fibers along the longitudinal axis is randomized;
- APs are triggered by synaptic current at one end of the fibers within a 0.1 ms window;
- the number of active fibers within a fascicle is randomly set between 50 and 250.

B. Compound Signal Properties

Typical raw extracellular APs of two fascicles at different distances from recording small tripoles are presented in Fig. 3, part A. At short distances ($y = 200\,\mu$m), high spatial frequencies exist in the compound AP, whereas at longer distances ($y = 500\,\mu$m), these variations are significantly attenuated, and the global shape of the AP is flattened. This observation is coherent with that of single fibers, validating

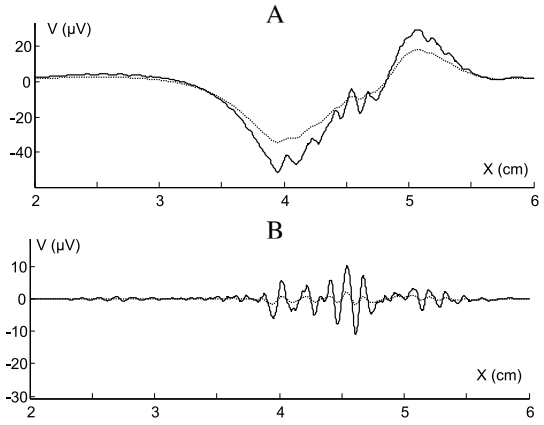

Fig. 3. Example of a monopolar extracellular AP along a fascicle (A), and the output for a myriad of small tripoles placed along the axon (B) for the AP in A. Two sub-millimetric distances are used: $y = 200\,\mu\mathrm{m}$ (solid line) and $y = 500\,\mu\mathrm{m}$ (dashed line).

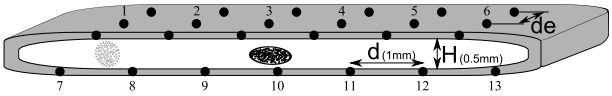

Fig. 4. Electrodes A and B have the same shape but differ on the longitudinal inter-pole distance (d_e). Two fascicles are represented, with corresponding signals in the Fig. 5.

the concept of observing effects of NORs for multi-fiber APs. The peak-to-peak amplitude of these two signals, on the other hand, are very similar, and relate to the maximum amplitude that can be measured using a classical tripolar electrode with spacing between the poles of several millimeters. Thus, classical electrodes would measure similar signals for these two distances.

Part B of Fig. 3 shows the spatial filtering of the compound AP (small tripole outputs), and conveys the spatial high-frequency component. The maximum value of this signal (around $10\,\mu\mathrm{V}$) represents the amplitude that can be measured with the proposed new electrode. Since the high-spatial frequency component of the AP decreases dramatically according to the distance, the measured signal is also strongly attenuated with the distance. This explains why the proposed small tripole has a sensitivity radius beneath the millimeter. It is worth noticing that the compound signal amplitude is not proportional to the number of active axons and remains in the same magnitude range as for a single-fiber APs.

IV. Selectivity Results

A. Comparison of simulated ENG

Two types of electrodes are simulated and quantitatively compared. The reference electrode A has an inter-pole distance adjusted to the spatial low-frequency portion of the AP and represents a state-of-the-art multi-polar selective cuff electrode [4] (inter-pole distance in the longitudinal axis : $0.5\,\mathrm{cm}$ and pole diameter : $500\,\mu\mathrm{m}$). The proposed electrode B has the same shape but differs in the spacing between its poles along the longitudinal direction, as introduced in section II-C. Fig. 5 presents the filtered signals from electrodes A and B for two fascicles (Fig. 4) at different locations around the cross-section of a nerve.

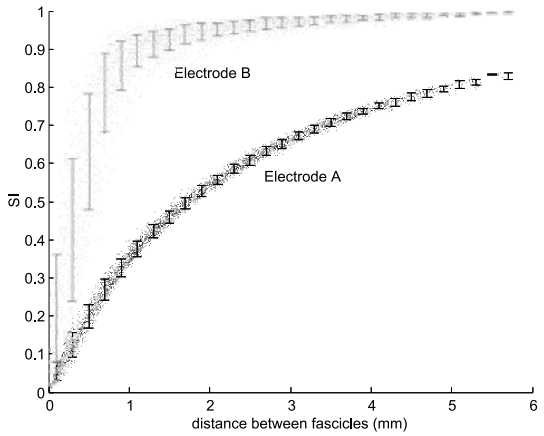

Fig. 6. Selectivity index computed for random combinations of simulated fascicles, plotted as a function of the distance between each couple of fascicles.

It should be noted that, for reference electrode A, the activity of a fascicle is measured on every tripole. In contrast, for the proposed electrode B, only the closest tripole exhibits this activity. As a result, in this example, if both fascicles were active simultaneously:

- using electrode A, the measured AP would be of the same order of magnitude on each pole;
- using electrode B, very few small tripoles would see the activity, hence allowing easy source discrimination.

This property is quantified and discussed in more details in section IV-B.

However, the amplitude of the measured AP is higher (about one order of magnitude) for the reference electrode A than for the proposed electrode B (about $50\,\mu\mathrm{V}$ vs. $5\,\mu\mathrm{V}$), and might cause issues for practical implementation, as discussed in section V.

B. Selectivity Index

The Selectivity Index (SI) quantifies the ability to record and distinguish between different active fascicles in such a manner that $\mathrm{SI} = 0$ corresponds to a case where an active fascicle yields identical signals at every recording site, while $\mathrm{SI} = 1$ occurs when one recorded signal is different from every other [4]. This SI has to be presented according to the inter fiber spacing.

One hundred simulations with different fascicle configurations were done according to the method described in sec. III-A, and the SI was calculated for each pair of fascicles for electrodes A and B. From Fig. 6, the proposed electrode B appears to be much more selective than the reference electrode A.

Let's consider for example two fascicles distant of $1\,\mathrm{mm}$ from each other. In this case, the SI for electrode B (≈ 0.9) is more than double that of electrode A (< 0.4). electrode B achieves a similar performance ($\mathrm{SI} = 0.4$) for fascicles distant of about $0.5\,\mathrm{mm}$, which is less than the typical size of a fascicle. Finally, for well separated fascicles, the SI of electrode A remains below 0.8, while that of electrode B nearly reaches $\mathrm{SI} = 1$.

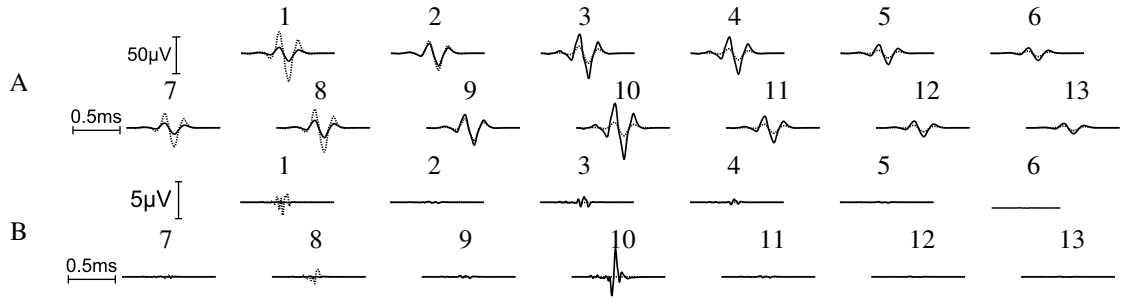

Fig. 5. Filtered AP from two multi-polar cuff electrodes around a flattened nerve. Electrode A is based on [4] and electrode B is the one proposed in this work. The simulated recordings are plotted following the tripole locations and numbered according to the Fig. 4. APs represented in solid and dashed lines correspond to the activity of right and left fascicles, respectively (Fig. 4). Each fascicle contains 200 actives axons activated within a $100\,\mu$s window.

V. Discussion

A. Validity of the Results

Two facts provide us with a high level of confidence regarding the validity of the simple model used in this work:

1) our study and conclusions relate to the fact that the periodicity and position of NoRs can be observed at the surface of nerves, a statement also supported by [10] based on a model taking into account inhomogeneities and anisotropy of the nerves;
2) despite using a different simulation method than [4] (analytical vs finite elements), our simulations yield very similar results when estimating the SI of the reference electrode;

B. Fascicle Selectivity

It is shown that a virtual tripole is only sensitive to its closest fibers, statistically part of a same fascicle. Also, from the location of poles, we can expect that each tripole is sensitive to a different fascicle, hence little or no post-processing should be required for determining the source of a recorded signal. In fact, our SI measurements show that our proposed electrode is more effective at separating fascicles distant by only $1\,\mathrm{mm}$ than any pair of fascicle using state-of-the-art electrodes from the literature [4].

C. Implementation Challenges

The multi-fiber simulations also showed that the observable signal from a small tripole is very weakly influenced by the number of active fibers in a fascicle.

Considering that the input signal-to-noise ratio (SNR) is fundamentally limited by the noise at the electrode-electrolyte interface and that poles need to be relatively small due to their proximity (about $100\,\mu\mathrm{m}$ diameter), we can expect a weak SNR for the recorded signals. According to the amplitudes given by this study, microelectrodes having an impedance lower than $1\,\mathrm{k}\Omega$ might be needed to achieve a suitable SNR. This, as well as sufficiently low-noise and high gain electronics, represents a real technological challenge.

VI. Conclusion

In this paper we have expanded the investigation of the electrode proposed in [6], based on the spatial properties of a single axon AP, by evaluating its properties for entire fascicles. These are simulated by combining many randomized axon signals. The results show that high-frequency submillimetric components can be extracted from the compound AP. Evaluation of the selectivity of the proposed electrode showed that the proposed design is significantly more selective than comparable devices from the literature. The study also shows that the expected measurable signal amplitude is weak, and raises technological issues that need to be addressed before actual implementation of the design can be tested and used in practical applications. However, a first experimental proof of concept is planned thanks to an *artificial* axon allowing the nodal currents to be increased for several orders of magnitude to get rid of the SNR limitation.

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