An optimized layout for multipolar neural recording electrode

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Abstract

The propagation of action potentials along the axons can be recorded via the electrical activity of the nerve (electro-neurogramm). This paper focuses on the use of cuff electrodes being very usual for chronic measurement. The main issues with this kind of electrode are parasitic noise and poor selectivity of the recorded signal.

Then, we propose an optimized layout for multipolar recording electrode. The main idea is to find the best value for the inter-pole distance and the most relevant processing in order to both improve selectivity in the nerve and to reject external parasitic signals. In this study, we put emphasis on simulation of action potential as a method to help the electrode specification. The amplitude of the expected signal is evaluated in both spatial and frequency domains, with respect to axons variability. Then, the selectivity of the proposed design is compared to state-of-art electrode layout. The proposed design, with the associated pre-processing shows a real improvement of the electrode selectivity. The drawback is a decrease of the sensitivity that nevertheless remains compatible with integrated micro-circuit amplifiers.

Keywords – electro-neurogramm, electrode array, selectivity, simulation.

1. Introduction

In the context of functional electrical stimulation it is of high interest to have an objective measure of the effect of stimulation and to get a sensitive feedback from afferent neural signal. Many studies aim to detect or record this information from inside the nerve but they have to overcome several difficulties. In chronic implants, measure of the nerve activity has to be little invasive making the use of a cuff electrode very suitable.

Unfortunately, the electro-neurogramm (ENG) appears to be of very low level and even often below the micro-volt. Moreover, bioelectrical activity makes the *in-vivo* environment very noisy, the worst noise being the signal generated by muscle activity (electro-myogram, or EMG). This parasitic signal will inevitably hide the ENG signal. Analog pre-processing must therefore be carried out in order to reject EMG-type noise.

The majority of ENG recording systems are based on tripolar [1,2], multipolar [3] or flat [4] cuff electrodes. The electrodes consist of three or more conductor contact (poles) distributed around the nerve. Based on the flat shape, we propose a new multipolar electrode with a selectivity optimized according to the nerve physiology and topology.

The first sections of this paper detail the axon model used for simulation and give some characteristics of the expected signal. Then, the electrode layout is optimally adapted to the appropriate spatial filtering. Eventually, a comparative selectivity study will be presented, with some remarks and perspectives.

2. Methods

2.1. Axon model

The ENG signal can be described as the superimposition of extracellular potentials generated by several axons activated at the same moment. Our objective is to detect activity from a set of these axons. We can assume that if the electrode characteristics are optimized to detect one axon activity then they can be extrapolated to be the best solution for a set of axons. We thus start by simulating an individual axon thanks to the *Neuron* simulation software [5].

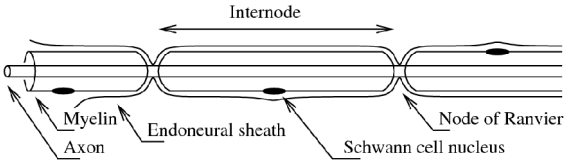

Figure 1: Structure of a myelinated nerve fiber (adapted from [6]).

For the simulation, we consider the myelinated axon illustrated figure 1 where l_{my} is the distance between two successive nodes of Ranvier (internode) and d is the fiber diameter. According to the study by McIntyre *et al.* [7], l_{my} can vary from 0.5 to 1.5 mm, with d varying from 5.7 to 16 μm. We used these characteristics to build several *Neuron* models composed of 150 myelinated sections.

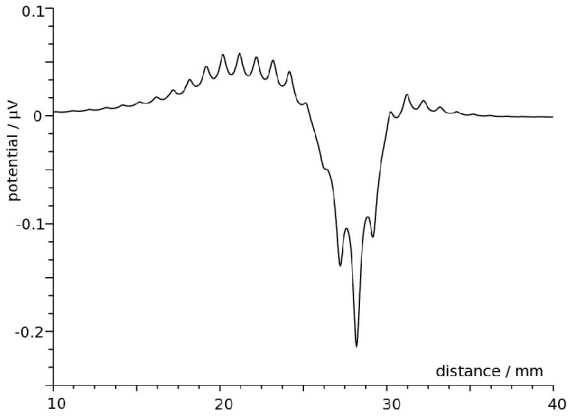

Figure 2: Extracellular potential plotted along the axon's axis at a distance of 200 µm from the membrane. The nodes of Ranvier are separated by l_{my} = 1 mm.

2.2. Analysis of extracellular potential

A typical result is shown in fig. 2. We can clearly distinguish the pseudo-periodical variations due to the discontinuities along the myelin shield. These variations are specific to the neuro-signal and can be highlighted by spatial frequency analysis.

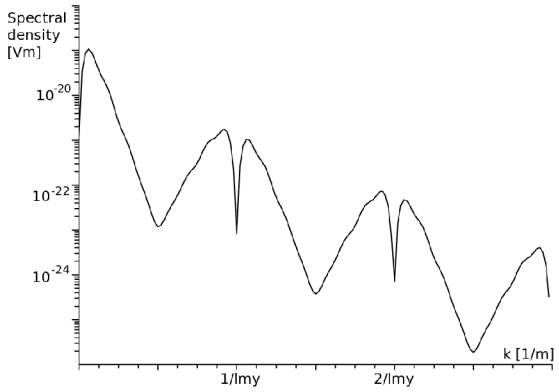

Figure 3: Typical spectrum of extracellular potential with regard to the spatial frequency in the direction of the axon's axis.

Fig. 3 gives a typical spectrum in the spatial frequency domain. The frequencies for the highest amplitude value are clearly linked to the internode distance l_{my} and occur for wave-numbers equal to

$$k_n = n/l_{my} \qquad (1)$$

whereas the low frequency energy denotes the global variations due to signal propagation along the axon.

2.3. Filtering

The classical preprocessing used for ENG recording consists in calculating the difference between the potential on a central pole and the average of the potential on outer poles [8, 9]. This method, known as *Laplacian* filtering can be generalized to multipolar configuration and has proven to be very efficient for EMG rejection [10].

We have recently prove that this kind of filter exhibit a bandwidth between *1/4h* and *3/4h*, *h* being the interpole distance [11]. The first maximum of the ENG spectrum is centered on $k = 1/l_{my}$ (fig. 3) for 0.5 mm < l_{my} < 1.5 mm. To fit the bandpass of the filter for all kind of fiber (fig. 4), the optimal inter-pole distance should simply be h = 375 µm.

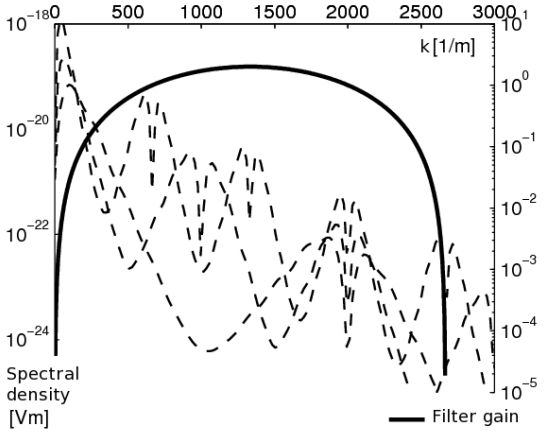

Figure 4: Typical ENG spectra for l_{my} = 0.5, 1 and 1.5 mm and optimal Laplacian filter gain.

3. Selectivity results

The selectivity of the electrode is the ability to discriminate signal generated by different fascicles in the nerve. In the ideal case, each recording channel, after filtering, would convey information from a single fascicle, thus from a single location of sensory organs. To evaluate the selectivity, we use the method exposed by Yoo *et al.* [4] to compute the selectivity index (SI). This quantity denotes the relative contribution of two distinct sources over the different channels. In the case of perfect separation, SI = 1.

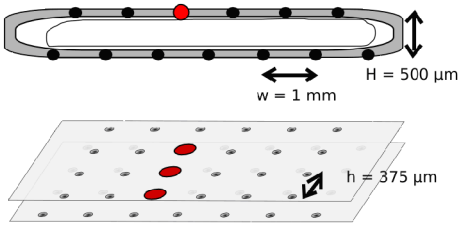

Figure 5: Flat electrode layout with highlight on three poles used to compute Laplacian (one recording channel).

In order to get a realistic model of the flat cuff electrode, we used the layout presented in fig. 5. The poles have a width of 250 µm and are regularly distributed on the whole surface. We compute the SI for each possible location of two axons inside the nerve. The fig. 6 shows the average SI as a function of the distance between the two sources, along with the standard deviation. The result is compared to the multipolar electrode presented in [4] with a more typical interpole distance of h = 5 mm and a width of 500 µm.

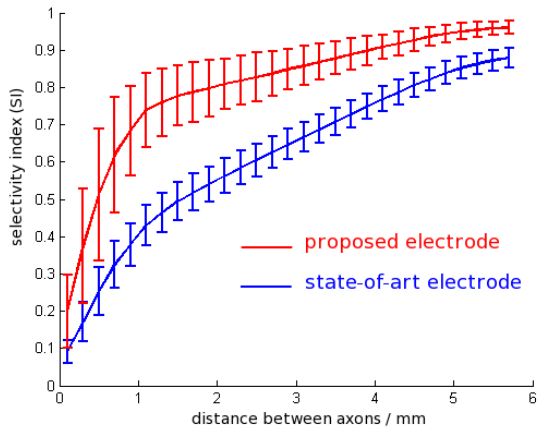

Figure 6: The selectivity index of the proposed electrode versus a state of art multipolar electrode.

4. Discussion and Conclusions

These first results tend to indicate that the proposed layout with smaller than usual inter-pole distance always exhibits a better selectivity regarding the ENG sources. This conclusion must be moderated regarding two points.

1. First, this better selectivity implies some loss in the signal power, due to the filtering. Simulations show that attenuation of 6 dB has to be expected. Moreover, this issue can be overcome by the multiplication of recording channels.
2. Second, the use of smaller poles will degrade the impedances of the bio-electronic interface. Very high input impedance low-noise pre-amplifiers are thus needed to get a useful signal.

These remarks put in evidence that a specific multichannel pre-amplifier is necessary for the new electrode presented here. The most obvious solution will be in the form of an ASIC performing analog low-level filtering (see [11] for an implementation example).

This paper has presented a new approach in the design of ENG recording multipolar electrodes. It points the importance of the physiological conformation in the signal characteristics and shows they can be used to optimize electrode layout. It proposes the use of signal analysis in the space-frequency domain as a design tool. Together with the development of a dedicated ASIC, future works will include validation of the concepts presented here through animal experiments.

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