DEVELOPMENT OF THE THIN-FILM LONGITUDINAL INTRA-FASCICULAR ELECTRODE

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Abstract – Longitudinal Intra-Fascicular Electrodes (LIFE) are implantable fine wire based electrodes designed to provide a relatively selective interface to the nervous system. In an effort to create LIFEs with smaller, more precise, and more reproducible active sites, we have turned to modern microfabrication techniques. A flexible micromachined polymer structure was designed to replace the key component of the electrode, the fine wire in contact with the endoneural tissue that forms the neural interface of the electrode. Electrodes were constructed and implanted into the medial gastrocnemius nerve of rabbits to test their in-vivo impedance and recording characteristics. We found that the thin film structures could be implanted without damaging the electrode. Their active sites impedances were very consistent with the inter-site impedance variation less than 15%. Moreover, we were able to record from muscle afferents with a signal to noise ratio of between 2 and 8.

Keywords: Neural interface, thin polymer film electrode, microfabrication, impedance, action potential

1. Introduction

The chronically stable, biocompatible, and highly selective neural interface is the ultimate goal in the field of neural interfaces. If available, such an electrode implanted in the peripheral nerve and used with FES could be used to achieve finer and more elegant motor control using natural sensor feedback, and deliver selective nerve stimulation. Longitudinal intra-fascicular electrodes (LIFE), fine wire electrodes implanted within the body of the peripheral nerve, have shown promise to achieve these goals [1-4].

Multi-unit peripheral nerve recordings with 8-16 differentiatable afferent units have been possible using LIFEs constructed out of Teflon insulated 25 µm Pt-Ir wire with 1 mm long recording sites [5,6] in anaesthetized experimental preparations. Since individual spikes can be resolved in these records, the mass interspike interval from natural sensors can be interpreted and used to provide meaningful feedback to FES systems[3]. LIFEs tested chronically in the awake walking cat were able to achieve multi-unit neural recordings. Unfortunately, single afferent units could be resolved only during phases of gait with relatively low levels of activity. During other phases of gait, the records were mixed with both afferent and efferent units. The number of units in such recordings precludes the practical use of single unit information without the use of computationally intensive advanced spike sorting algorithms [7]. Achieving greater recording selectivity requires that the active site be reduced in size by at least an order of magnitude. Given the difficulties in consistently producing LIFEs with 250 µm long active sites with the current techniques, a shift in paradigm would be necessary.

Metal wire electrodes used to construct LIFEs are orders of magnitude mechanically stiffer than the neural tissue in which they are implanted. Appropriate strain relief can overcome breakages of the metal electrodes due to strain hardening and metal fatigue. However, the mechanical property mismatch may account for the heavy encapsulation seen around chronically implanted LIFEs [1]. These issues have lead to the development of metallised polymer fibre based electrodes [8]. However, manufacturing issues and difficulties in effectively insulating and producing precise active sites persist.

The main question addressed in the present project was to determine whether a LIFE electrode could be designed and implemented with sufficient recording selectivity to resolve single unit activity within the neural signals associated with normal activities such as gait. To achieve greater recording selectivity we have focused our efforts towards the development of a LIFE using standard photolithographic and micromachining techniques from the electronics industry. Micromanufacture offers the potential to exactly control the electrode and active site geometry, and opens up the possibility of producing multiple sites along the length of a single electrode. A novel thin film LIFE (tfLIFE) was designed and implemented. The electrodes were constructed on a thin polymer substrate to achieve better mechanical matching and better biocompatibility with the peripheral nerve. Furthermore, the thin film substrate allows histology to be made with electrodes in-situ. In the present paper we report on the construction, in-vivo characteristics and recordings of the tfLIFE.

2. Methods

The traditional LIFEs used in our work are dual channel electrodes, consisting of a fine wire segment, that are pulled into the nerve fascicle by a strand of polyaramid filament attached to a 50 µm tungsten needle (fig 1A). 7-strand stainless steel biomedical cables (Cooner Wire Co, AS631) are soldered to fine wires to
make electrical contact between the nerve and the recording instruments. The tLIFEs are designed to replace the fine 25 µm Pt-Ir wires of the traditional LIFE design with a microfabricated polymer structure. Each half of the structure has two independent 50 µm x 50 µm active sites spaced 2mm apart, traces and contact flaps. A layout of this structure is shown in fig 1B.

These tLIFE structures were constructed by surface micromachining photosensitive polyimide and gold/chromium metal layers on top of oxidized silicon wafers. Photosensitive polyimide was chosen as the electrode substrate because of its flexibility, biocompatibility, structural properties and ability to withstand a saline environment [9]. Structures were fabricated on silicon wafers, which enabled the use of standard silicon integrated circuit fabrication equipment and techniques. A three mask photolithographic process was used to pattern the layers of polyimide and metal (Au/Cr) into working structures, which were released from the supporting wafers to form the completed electrodes.

The electrode impedance spectrum (fig. 2) showed that the active sites were extremely well matched throughout the impedance spectrum. The relative standard deviation of the impedances never exceeded 15% between 2 Hz and 10 kHz.

3. Results

The electrode impedance spectrum (fig. 2) showed that the active sites were extremely well matched throughout the impedance spectrum. The relative standard deviation of the impedances never exceeded 15% between 5 Hz and 10 kHz.
A typical differential recording from the tfLIFE during various levels of activity in the medial gastrocnemius nerve is shown in figure 3A.

Fig 3: Typical differential recordings from tfLIFEs. A shows simultaneous recordings made from the two pairs of active sites on a single tfLIFE. The first panel in A shows the background activity/noise in the recording. The second and third panels show the afferent activity recorded during constant and periodic stretching of the muscle. B is the signal to noise spectrum of the recorded activity. It shows that the activity has frequency components between about 200 Hz and 10 kHz, which is consistent with nerve activity. C shows the cross covariance between I and II. The zero delay point is marked by a circle on the plot and does not correspond to the peak of the cross covariance which occurs at 32 µs delay. It indicates that the spikes are recorded in I on average 32 µs before they are picked up in II. This is consistent with a traveling action potentials propagating proximally along the nerve. Given the distance between the sites in I and II, the action potentials were conducting at between 50 and 100 m/s.

The first panel of figure 3A shows the baseline record and consists of mostly amplifier noise. Muscle afferents were activated in two modes as shown in the next two panels: Constant muscle stretch and periodic muscle stretch. These panels indicate that the level of activity in the recording can be modulated by mechanical activation of muscle mechanoreceptors. The signal to noise spectrum was determined (fig. 3B) and shows that the recorded activity has frequency components with signal to noise greater than 1 between 200 Hz and 10 kHz. The cross covariance between the record from electrode pair 1 and electrode pair 2 is shown in figure 3C. It shows that the peak cross covariance does not occur at 0 delay (denoted in figure 3C by the circle on the cross corregogram) but rather at 32 µs delay. This is consistent with traveling action potentials, which lasted between 1 and 1.5 ms recorded on both electrode pairs as they passed the recording sites. Since the recording sites of the two electrode pairs are displaced between 2-4 mm, the conduction velocity of the wave can be calculated to be roughly between 50 and 100 m/s. This is consistent with the conduction velocities of the muscle mechanoreceptor afferent axons.

4. Discussion

The aim at this stage of the study was to determine whether a flexible micromachined thin film electrode could be produced, implanted and used to record activity from the peripheral nerve. We found that the tfLIFEs could be implanted into peripheral nerve without mechanical failure. Furthermore, they were able to record activity from muscle mechanoreceptors. Despite making no effort to optimize the electrode active site surface or impedance, the records in figure 3A show that large amplitude spikes are distinctly visible above the mass activity in the background. However, due to the pad geometry and material, which made the electrode impedance relatively high, the recording stability was marginal. Nonetheless, we show here that these new structures are capable of recording neural activity from the peripheral nerve despite being in the very early stages of their development. Clearly, the next step in the development will be towards improving the interfacial impedance and the charge transfer characteristics of the electrode.

References

[3] K. Yoshida and K. Horch, Cross covariance between I and II. The zero delay point is marked by a circle on the plot and does not correspond to the peak of the cross covariance which occurs at 32 µs delay. This is consistent with a traveling action potentials propagating proximally along the nerve. Given the distance between the sites in I and II, the action potentials were conducting at between 50 and 100 m/s.

Acknowledgement: This work was funded in part by a grant from the Danish National Research Foundation, and internal support from the College of Engineering and Applied Sciences, Arizona State University.