Acute Peripheral Nerve Recording Characteristics of Polymer-Based Longitudinal Intrafascicular Electrodes

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***Abstract*—We examined the recording characteristics of two different types of polymer-based longitudinal intrafascicular electrodes (LIFEs) in peripheral nerve: single-stranded (*s-poly*LIFEs) and multistranded (*m-poly*LIFEs). Recordings were also made from Pt–Ir wire-based electrodes (*PtIr*LIFEs) as a control. The electrodes were implanted in either tibial or medial gastrocnemius branches of the rabbit sciatic nerve, and in the sciatic nerve of rats. Recorded neural activity induced by manually elicited afferent neural activity showed that both *poly*LIFE versions performed comparably to *PtIr*LIFEs.**

***Index Terms*—Intrafascicular electrodes, peripheral nerve recording.**

I. Introduction

AN INTEREST in greater recording and stimulation selectivity with peripheral nerve electrodes has led to the development of various intrafascicular designs [1]–[8]. This attribute of high selectivity will potentially allow researchers to provide more discrete control and more natural feedback for functional electrical stimulation and neural prosthetic devices. Acute animal studies with longitudinal intrafascicular electrodes (LIFEs) constructed from Teflon-coated 25-μm-diameter Pt–Ir wire (*PtIr*LIFEs) have demonstrated topologically selective stimulation of and recording from restricted subsets of fibers [9]–[13]. Recordings from sensory afferents can supply stable feedback to functional electrical stimulation systems, allowing linear closed loop control over joint angle [14]. Although long-term implantation of *PtIr*LIFEs in feline radial nerves demonstrated minimal neural damage and sustained recording selectivity for up to six months, continued differential motion of the electrode within the fascicle caused both a gradual drift in the recorded nerve fiber population and a reduction in the signal-to-noise ratios (SNRs) [15], [16]. The gradual differential movement was attributed to the relatively greater stiffness of the *PtIr*LIFE as compared to the surrounding neural tissue.

A more flexible LIFE electrode was subsequently developed to reduce this mechanical mismatch by metallizing a single 12-μm-diameter Kevlar fiber and insulating it with medical grade silicone. This polymer-based, longitudinal intrafascicular electrode (*poly*LIFE) was over 60 times more flexible than the solid metal *PtIr*LIFE and demonstrated similar acute recording characteristics [17]. Long-term implantation of *poly*LIFEs in feline dorsal rootlets and rabbit peripheral nerve demonstrated a higher degree of biocompatibility and reduced differential motion within fascicles. Specifically, chronic implantation of *poly*LIFEs caused less change to axonal size distribution within implanted and neighboring fascicles and thinner capsule formation around the implant than chronic implantation of *PtIr*LIFEs [18], [19]. The improved biocompatibility was attributed to the *poly*LIFE's greater flexibility.

In terms of the *poly*LIFE's functionality, experience with the developmental versions demonstrated several mechanical weaknesses thought to be related to the manufacturing processes. As a result, the original manufacturing processes have been modified to improve: 1) metal adhesion and fatigue resistance; 2) insulation adhesion; and 3) electrode tensile strength. Using the modified manufacturing processes, two *poly*LIFE designs were constructed that demonstrated improved mechanical properties according to adhesion, fatigue, and tensile testing [20]. Three of those process modifications were shown to affect the electrical properties of the interface: 1) sputtering parameter adjustment to prevent thermal stress during deposition of the metal film; 2) post deposition heating above 130 °C to fully cure the adhesion-promoting silicone; and 3) multiple metallized fiber winding to increase electrical redundancy and tensile strength. For example, use of an insulation cure temperature of 150 °C increased the interfacial impedance by 350% [20]. Therefore, as substantial changes to the original manufacturing processes may have significantly altered the electrical properties of the interface, it was our goal to characterize the acute (with hours of implantation) recording properties of the two mechanically improved *poly*LIFE designs compared to the more traditional *PtIr*LIFEs.

II. Methods

Peripheral nerve recording characteristics of the improved *poly*LIFEs were tested in two animal groups consisting of female White New Zealand rabbits ($n = 5$) and male White Sprague Dawley rats ($n = 4$). All rabbits were handled according to The Danish Committee for the Ethical Use of Animals in Research, while all rats were handled according to protocols specified by *Guide for the Care and Use of Laboratory*

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Animals (Washington, DC: National Academy Press, 1996) and protocols approved by the University of Utah Animal Care and Use Committee. Recordings were finished within a few hours of completion of the implantation procedure.

A. Electrodes

Two versions of the improved *poly*LIFEs were evaluated, namely, a single-stranded version (*s-poly*LIFE) and a multistranded version (*m-poly*LIFE). The *s-poly*LIFE was constructed from a 12-μm-diameter Kevlar fiber that had been metallized with three layers (Ti, Au, and Pt) and subsequently insulated with a thin layer of medical-grade silicone. The *m-poly*LIFE, a version with greater tensile strength, was constructed by winding three individually metallized Kevlar fibers together, and subsequently insulating them with medical-grade silicone. During the insulation process for both the *s-poly*LIFE and the *m-poly*LIFE, a 1- to 1.5-mm-long section was left uninsulated and will be referred to as the active recording zone. The *PtIr*LIFEs were constructed from Teflon insulated 25-μm-diameter 90%Pt-10%Ir wire, where the active recording zone was produced by deinsulating a ~0.5-mm-long section. Manufacturing details of the *poly*LIFE's and *Pt-Ir*LIFE's have been published elsewhere [16], [17], [20], [21].

B. Surgical Procedures

Rabbits were used to characterize the acute recording properties of *s-poly*LIFEs and *PtIr*LIFEs, while rats were used to characterize *m-poly*LIFEs.

Under aseptic conditions, the rabbits were anesthetized and maintained by intramuscular injections of a mixture containing 0.15 mg/kg Midazolam (Dormicum TM, Alpharma A/S), 0.03 mg/kg Fetanyl, and 1 mg/kg Fluranison (combined Hypnorm TM, Janssen Pharmaceutica). The left sciatic nerve of each animal was implanted with one or two *s-poly*LIFEs and three *PtIr*LIFEs. The *s-poly*LIFEs were threaded longitudinally into one fascicle of the lateral or medial gastrocnemius branches (chosen at random). Two of the *PtIr*LIFEs were then threaded into one fascicle from the other branch. The third *PtIr*LIFE was placed adjacent to the nerve at the same level of the intrafascicular implants and served as an extrafascicular reference electrode for bipolar, differential recordings. A ground electrode, consisting of a deinsulated stainless steel wire, was positioned at the base of the spine and served as the reference for monopolar recordings. Further details on the implantation procedure for *PtIr*LIFE electrodes can be found elsewhere [22].

Under aseptic conditions, the rats were anesthetized and maintained with a ketamine/xylozene cocktail (1 mg/kg). The right or left sciatic nerve of each animal was implanted with up to three *m-poly*LIFEs. One or two *m-poly*LIFEs were implanted within separate fascicles of the sciatic nerve, while one *m-poly*LIFE was placed adjacent to the nerve at the same level as the intrafascicular implant(s) and served as an extrafascicular reference electrode for bipolar recordings. Further details on the implantation procedure for *poly*LIFE electrodes can be found elsewhere [17].

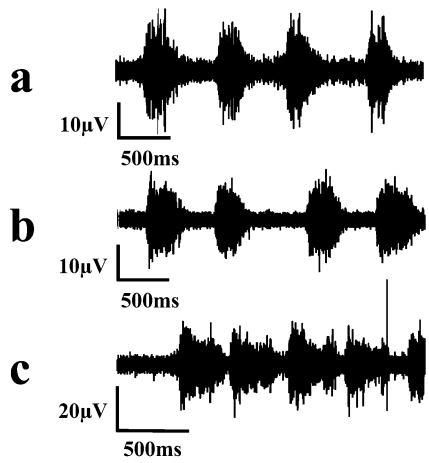

Fig. 1. Typical examples of recorded signals. (a) Monopolar recording with a *PtIr*LIFE. (b) Monopolar recording with an *s-poly*LIFE. (c) Bipolar recording with *m-poly*LIFEs. Activities in (a) and (b) were recorded from electrodes implanted in the lateral or medial branch of the rabbit sciatic nerve and was elicited by repeated manual flexion and extension of the foot. Activity in (c) was recorded from electrodes implanted in the rat sciatic nerve and was elicited by dynamic squeezing of the footpad.

C. Recordings

In rabbits, monopolar recordings of neural activity were made from both *s-poly*LIFE's and *PtIr*LIFE's, and bipolar recordings were made between an intrafascicular and extrafascicular *PtIr*LIFE. Afferent neural activity was elicited by repeated manual flexion and extension of the ankle joint. The recorded signals were amplified by a factor of 10^4, sampled at 48 kHz, and subsequently filtered offline (fourth order Butterworth bandpass filter with upper and lower cutoffs of 0.8 and 10 kHz, respectively). In rats, bipolar recordings of neural activity were made between an intrafascicular and extrafascicular *m-poly*LIFE, where the signals were amplified by a factor of 1.2×10^4, bandpass filtered between 325 and 4000 Hz, and sampled at 10 kHz. In this case, afferent neural activity was elicited by dynamic squeezing of the rat's footpad.

The SNRs of all the implanted intrafascicular electrodes were estimated by averaging the peak-to-peak values of six of the largest identifiable units and dividing by the peak-to-peak noise (see [11]). The electrode impedance was measured by application of a 1-kHz constant current sine wave where the return electrode's impedance was below the sensitivity of the measurement system and, hence, did not contribute to the effective electrode impedance. Current applied to the implanted electrodes was controlled to less than 100 nA to prevent damage to neural tissue.

III. Results

Fig. 1 shows a typical recorded signals for each electrode type. Table I shows calculated SNRs and measured electrode impedances. In measuring SNRs, characterization of a "identifiable unit" was based on examining expanded displays of the recordings and selecting potentials that had repeated appearances with a fixed amplitude (given the level of variability expected from the background noise level as displayed between bursts of activity as shown in Fig. 1) and roughly constant shape.

TABLE I
RECORDING AND ELECTRICAL CHARACTERISTICS OF LIFE ELECTRODES

Electrode type	S/N (mean ± s.d.)	Impedance (mean±s.d.)
PtIr (monopolar)	3.8 ± 0.4 (n = 8)	7.4 ± 5.5 kΩ
PtIr (bipolar)	3.7 ± 0.4 (n = 8)	7.4 ± 5.5 kΩ
s-poly (monopolar)	3.6 ± 0.5 (n = 6)	13.2 ± 3.5 kΩ
m-poly (bipolar)	2.8 ± 0.2 (n = 6)	18.7 ± 4.4 kΩ

Thus, the large spikes seen in trace a of Fig. 1 qualified, whereas the very large potential seen at the end of trace (c) was deemed to be an artifact, and was not included.

Note that, for reasons not completely understood, the *m-poly*LIFEs tended to have higher impedances than the *s-poly*LIFEs, although this difference was not statistically significant.

IV. DISCUSSION AND CONCLUSION

Because recording zone length, animal model used, method of evoking afferent activity, and signal filtering characteristics were not independently varied for each of the three electrode types, statistical analysis of the effect of electrode type on recording characteristics is not possible. However, such an analysis was not the intent of this study. Rather, we sought to examine the extent to which, under typical electrode fabrication procedures and recording conditions, polymer-based LIFEs produced useable recordings of neural activity in peripheral nerves. This was important because such a study had not been previously conducted.

Qualitative examination of Fig. 1 and the data in Table I show that mono- and bipolar recordings (at least with *PtIr*LIFEs) are equally good. The *s-poly*LIFEs produced recordings comparable to those seen with *PtIr*LIFEs, including the apparent number of units recorded from based on the overall level of activity seen in the recordings, even though they had somewhat higher impedances. Noting the scale change for trace (c) in Fig. 1, it is clear that the signals from the *m-poly*LIFE recordings were as good or better than that seen with the other electrodes, but the SNRs were lower due to an increase in baseline noise. A decrease in SNR does not necessarily imply a change in selectivity (i.e., the number of units being recorded from) but does make it more difficult to distinguish when individual units are firing. Baseline noise levels in intrafascicular electrode recordings are always higher than that seen with a resistor of equal value to the measured electrode impedance placed across the input of the amplifier. In our laboratory, we attribute this to background activity, but the complex impedance characteristics of metal electrodes in body tissue make it impossible to rule out other contributions.

The two different recording conditions (mono- versus bipolar) were selected to represent the two common options for making intrafascicular recordings, depending on the extent to which common mode rejection of external signals is critical in the application for which the electrodes are being used. Either method gives comparable results, in the absence of large, extraneural signals. The *m-poly*LIFEs were included because they are stronger and may be more suitable for clinical applications where a more rugged electrode is needed during the implantation procedure [20].

Since all three types of electrodes perform comparably, the choice of a suitable LIFE design should be decided by weighing the relative importance of four factors: recording characteristics, tensile strength, flexibility, and manufacturability. For instance, the *PtIr*LIFEs are significantly stiffer than both *poly*LIFE versions, yet their simple design allows for much easier manufacture [17], [20]. The *s-poly*LIFE's record with equivalent characteristics to the *PtIr*LIFEs, but are significantly more fragile than the *m-poly*LIFEs. Thus, if one's main concerns are flexibility and tensile strength, the *m-poly*LIFE would provide the best compromise; with medium flexibility, it demonstrates the highest tensile strength with at most only a slight additional cost in SNR and manufacturability.

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