LONG TERM RECORDING OF ACTION POTENTIALS IN PERIPHERAL NERVES USING INTRAFASCICULAR ELECTRODES

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ABSTRACT

It was demonstrated that 25 μm diameter electrodes implanted longitudinally into fascicles of peripheral nerves in the cat can be used to record action potentials for up to 6 months. Such recording could be used for feedback control in paralyzed individuals. A single intrafascicular electrode typically records from an average of 10 separately identifiable sensory nerve fibers (range 2 to 25) with an average signal-to-noise ratio of 3 (range of 1.4 to 12). The average signal-to-noise ratio remains constant at approximately 3.0 during the first 2 to 3 months of recording. This parameter, which may be related to how close the recording site is to the individual axons, declines to an average of 2.7 and 2.2 in months 4 and 6, respectively. Encapsulation amounting to a thickness of several electrode diameters was seen in histological sections of the nerve. It was possible to identify and track individual unit activity over several months. However, an average gain and loss of approximately 20 units per electrode over the 6 month period was observed. This suggests slow movement of the electrode relative to the axons or some axonal damage and regeneration near the recording site. Six of eight electrodes, using the latest design, remained functional at 6 months.

KEY WORDS: nerve, chronic, recording, electrode, neuroprosthesis

INTRODUCTION AND BACKGROUND

The motivation for this study is the need to provide force and position feedback for control of functional electrical stimulation of paralyzed muscles [1,2,3]. The idea is to record from peripheral nerves that carry somatosensory information from skin tactile sensors as well as from muscle spindles and tendon organs. Several studies have shown that cuff electrodes can be used to extract tactile information chronically from peripheral nerves [4,5]. Recently Hoffer [5] has shown that such electrodes can be used to estimate force levels applied to the footpads in the cat. An inherent limitation of cuff electrodes is that they record a composite signal from various types of slow and fast adapting receptors. This makes extraction of accurate dynamic and static force information difficult [5]. Others [6,7] have experimented with recording from smaller subunits of peripheral nerve by inserting electrodes inside nerves. Edell has had some success in chronic recording inside rabbit peripheral nerves using silicon based comb-like microelectrodes. However, problems with long-term mechanical stability and effective insulation of the microcircuits persist. Janssens et al [7] showed that large signals including individual action potentials could be recorded by small wires inserted longitudinally inside fascicles of peripheral nerve. Our own studies have elaborated on this approach. Several years ago we proposed to record such information chronically by inserting very small wires (25μm diameter) into fascicles of peripheral nerves. Previous publications have described the early work to optimize electrode recording parameters [2,3] and develop methods of extracting action potentials from the complex multi-unit recordings and tracking individual units over several months [8,9]. The present paper describes the results with electrodes implanted for 6 months in the radial nerve of cats.

METHODS

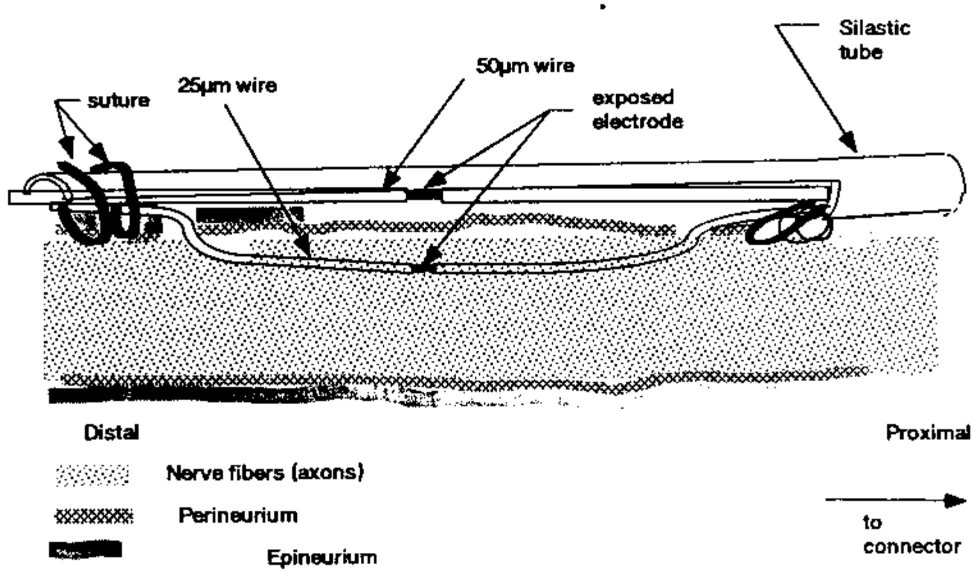

Figure 1. Drawing of nerve fascicle showing electrode placement and attachment to nerve for Method 3 bipolar electrodes.

Electrodes: The latest electrode design and nerve attachment method, used for the most successful 6 month implantations, is shown in figure 1. It consists of an intrafascicular electrode made from 25μm diameter 90% Platinum-10% Iridium wire insulated with quadruple coated Teflon . The reference electrode, made with 50μm diameter wire of the same alloy, is placed outside the fascicle. Both wires are wound around a non-absorbable suture and this assembly is inserted and glued into a thin Silastic - rubber tube. Half of this tube is cut away in the area of the recording site, leaving a flexible rubber flap for attachment to the fascicle by sutures as shown in the figure. The two wires are attached only distally to the recording site. This attachment method and electrode design (method 3) minimizes the stress on the delicate wires by transferring part of any mechanical tension to the rubber tube. An earlier method (method 2) was the same as method 3 except that the rubber flap was not used. The earliest method (method 1) used a smaller 25μm diameter wire for the external reference electrode and did not use the rubber flap. In method 1 the fascicle was dissected from the underlying nerve in the area of the electrode insertion.

Electrode Insertion: The electrodes were inserted into single fascicles of the radial nerves of anesthetized cats. The nerve was exposed for 2 to 3 cm midway between wrist and elbow. The perineureum was carefully teased away to expose individual fascicles. Two of the larger fascicles were then selected for implantation. The epineurium was removed from the top surface of the fascicle to reduce the mechanical resistance to insertion. The insertion was accomplished by the method described previously [3] using a sharpened 50μm diameter Tungsten needle attached to the electrode wire with cyanoacrylate adhesive. The needle was threaded longitudinally into the fascicle for about 1 cm and then pulled through until the 1 mm recording site was well within the fascicle. The electrode wire was then cut at the distal end and the needle was discarded. Typically 4 electrodes were implanted per animal.

Instrumentation and Measurements of Unit Activity: The bipolar electrodes were connected to a high input impedance differential amplifier with an overall gain of 10 000 and a bandpass of 400 to 6000 Hz. Neural activity was displayed on a storage oscilloscope and recorded on an FM tape recorder. Identification of individual units was accomplished by a method previously described [8]. Receptive field locations were determined for single units by applying threshold-level mechanical stimuli to selectively activate units. Only those action potentials which had amplitudes 40% above the background noise level, corresponding to a signal to noise ratio of 1.4, were selected for measurement. The neural activity was recorded on tape and locations of receptive fields noted. Between 2 and 25 such units (average 10) were recorded for each fascicle. These measurements were repeated at 0.5, 1, 2, 4 and 6 months after implantation. A unit was considered to be the same as in a previous recording session if the receptive field location and receptor type was of the same as determined by the method of Horch, et al. [10].

Histology: Six months after implantation, the cats were deeply anesthetized and perfused with a 0.1 M PO_4 buffered solution of glutaraldehyde and paraformaldehyde. The implanted sections of the nerve were then excised, stained and embedded in plastic for semi-thin sectioning and preparation for light microscopy.

RESULTS

Electrode Survival: Method 3 of electrode design and implantation which was performed on 2 cats for a total of 8 electrodes proved to be the most successful. Six of the eight electrodes (75%) continued to function at 6 months (figure 2). The other methods of electrode insertion and attachment showed a much greater failure rate with only one of 11 from method 1 and 8 of 24 from method 2 surviving at 6 months after implantation.

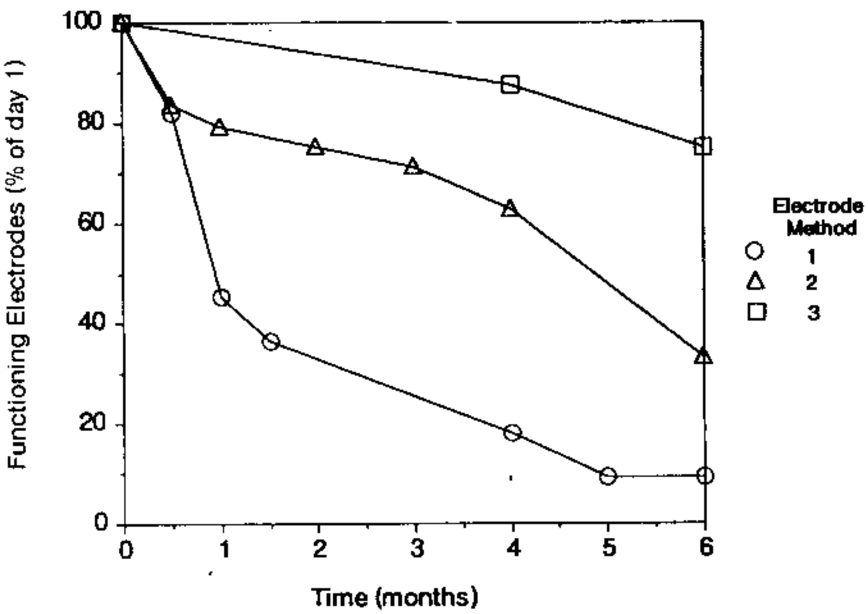

Figure 2. Functional electrodes as % of implanted electrodes which were functioning on day 1, showing differences in survival of three electrode design and attachment methods.

Stability of Recording: The number of nerve fibers in the recordings varied over the six month period in a complex way (see figure 3). For method 3 there was a significant decrease in the number of recorded units during the first 2 to 3 weeks after implantation. Between 4 and 8 weeks there is usually a large rebound in the number of active units per electrode (up to 200% of the number on day 1). Thereafter a gradual decrease from the maximum is seen to values that average 100% of initial numbers with values ranging between 140% to 40% of day 1. A second pattern was also seen in at least three electrodes which is characterized by very few active units at implant time. Thereafter there is a substantial increase in number of identifiable units over the 6 month period. This later mode is consistent with local damage to the nerve at implantation and subsequent recovery of axonal function.

Persistence of the Same Units: During the recording period there was a significant turnover of axons that were seen by the recording electrodes. The average number of units stayed the same. However, on average, only a third of the units present at 1 month after implantation could still be identified at 6 months. Figure 4 depicts the decline in the percent of sensory units which were present at 1 month.

Variability of Signal-To-Noise Ratio: Figure 5 shows the average signal-to-noise ratio measured in 9 intrafascicular electrodes as a function of time after implantation. The average remained constant at 3.0 for the first 2 months. There was a gradual decrease in this value at 4 and 6 months and also a decrease in the scatter of the values of individual units. Each small data point on the plot represents the signal-to-noise ratio of a single unit.

DISCUSSION AND CONCLUSIONS

It was demonstrated that intrafascicular electrodes are a viable method of recording from 5 to 10 sensory axons during a 6 month period. A number of issues

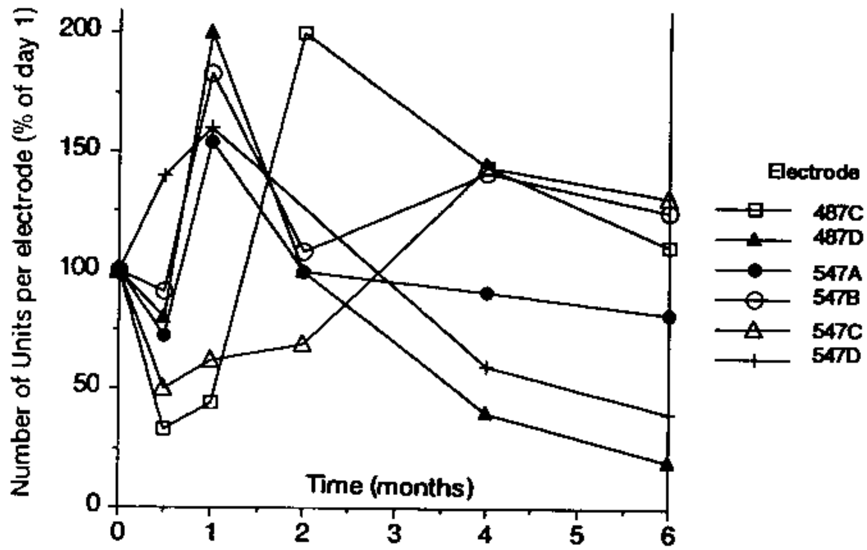

Figure 3. The number of identifiable units as % of the number identified on the day of implantation as a function of time for 6 electrodes. For 5 of the 6 electrodes there is an initial decrease, a rise to a maximum during the first 2 months and then a gradual decrease in number of active units during the last two months.

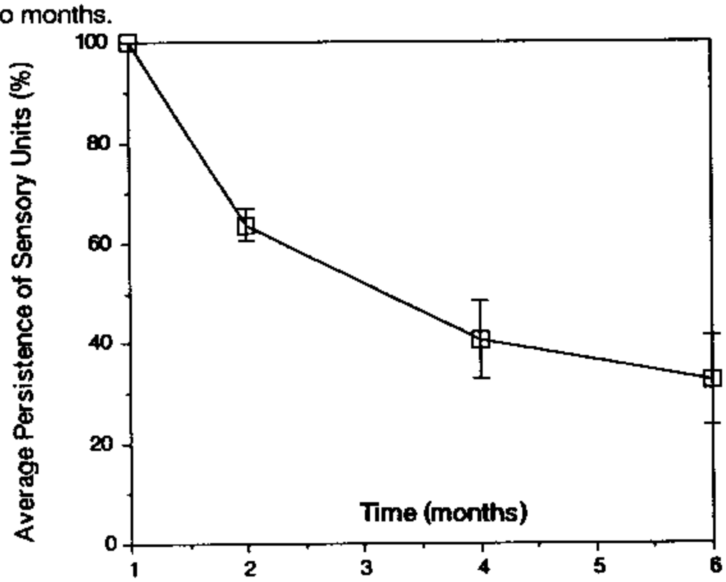

Figure 4. Average persistence of sensory single units as percent of those identified 1 month after implantation of the electrode. Bars indicate standard error of the mean. (Data from Lefurge, Goodall and Horch, "Information contained in sensory nerve recordings made with intrafascicular electrodes", submitted for publication)

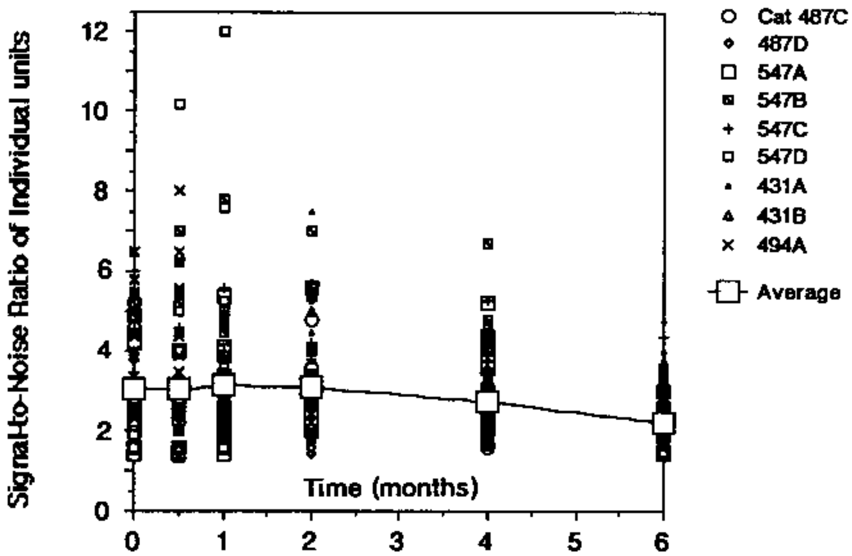

Figure 5. The signal-to-noise ratio of individual units as a function of time. No significant change in the amplitude of action potentials occurred during the first 4 months and a slight decrease occurred at 6 months.

such as electrode life, and the time required for stabilization of the recordings remain to be resolved before clinical application can be considered.

Several improvements in electrode attachment and design were required before acceptable electrode failure rates were achieved. Our experience shows that 25μm diameter 90% Platinum - 10% Iridium alloy wires used for the electrode material do not tolerate large or repeated stresses. The type 1 electrode used in early cat experiments, consisting of a bipolar pair of 25μm diameter wire, had a half life of less than 1 month. Replacing the reference electrode with a much stronger 50μm diameter wire (type 2 electrode) extended the half life to approximately 4 months. We assume that the stronger external wire reduced the stresses on the smaller intrafascicular wire. The latest design which involves stress relief with the protective silastic tube results in a half-life of greater than 6 months. Further testing of this electrode configuration is needed to establish survival longer than 6 months.

The gradual decline in signal-to-noise ratio and the continuing slow turnover in identifiable units that are in the recording field of the electrode indicate that the electrode-nerve interface is not completely stable after six months. Several processes may be responsible for the observed changes. The movement of the cat's leg may produce slight movement of the electrode inside the fascicle. This can damage the delicate axons and produce a loss of fibers surrounding the electrode. A second process of slow encapsulation may also be occurring as well.

The histologic sections of the implanted fascicles generally show encapsulation at the level of the implant of thickness 25 to 50 μm. Figure 6 shows the cross section of a fascicle with the electrode (upper left) encapsulated after 6 months. The number

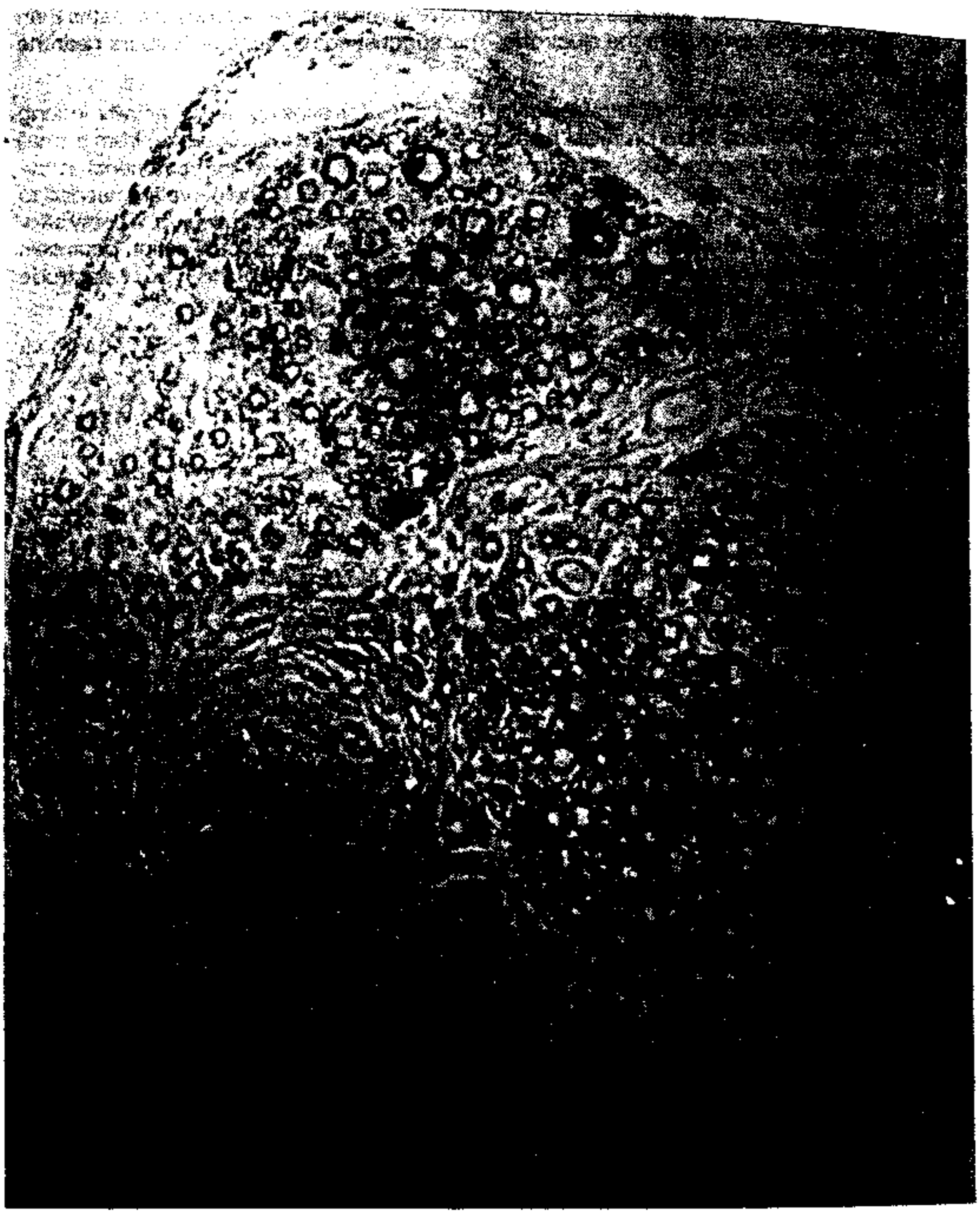

Figure 6. Section of a nerve fascicle in the area of an implanted recording electrode showing a moderate amount of damage and encapsulation of the electrode 6 months after implantation.

of myelinated axons per unit area near the electrode appears to be reduced, and those axons that are near the capsule appear to have somewhat thinner myelin sheaths than axons further away from the electrode. This suggest some damage of fibers near the electrode.

We conclude that intrafascicular electrodes for sensing neural activity in long term applications show promise. It has been demonstrated that recording from a small population of axons is possible for up to six months. Further improvements in the mechanical characteristics and attachment of the electrode to the nerve are needed to reduce damage and encapsulation. Further work in this area is continuing. A separately funded project is developing better methods of extracting individual action potentials from multi-unit recordings. Another project is exploring the use of this type of electrode for intrafascicular stimulation.

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