NERVE CUFF ELECTRODES FOR PROSTHETIC AND RESEARCH APPLICATIONS

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ABSTRACT

A new generation of nerve cuffs suitable for stimulation, recording and modulation of nerve activity has been tested in our laboratory and elsewhere. The walls are molded of low-durometer silicone and incorporate flexible electrodes, Teflon®-coated stainless steel leads and an interlocking opening/closing system. Stimulation and recording cuffs can be either single-channel or multi-channel. Single-channel cuffs have coiled circumferential electrodes. Multi-channel cuffs have internal chambers and up to 24 laser-positioned electrodes. Modulation cuffs include catheters for local delivery of pharmacological agents. The cuffs are produced and distributed by NeuroStream Technologies, Anmore, B.C., Canada.

Over 100 single-channel, 30 multi-channel and 20 modulation cuff prototypes have been implanted in laboratory animals, typically for 6 months. Electrode impedances and nerve compound action potentials were periodically monitored. Individual electrodes in multi-channel cuffs could selectively recruit different limb muscles and record distinct cutaneous fields. A morphological study of nerves inside cuffs indicated no loss of axons and only small changes in axon diameters and myelin thickness. NeuroStream cuffs are now available for testing in a variety of intended clinical FES applications.

Keywords: nerve cuff, electrical stimulation, nerve signal recording, neuromodulation, pharmacology

INTRODUCTION

Among the various types of implantable electrical and mechanical interfaces with nerves or muscles that were developed in the past two decades, nerve cuffs are uniquely capable of providing stable, reliable signals over extended periods (Hoffer and Loeb, 1980; Hoffer, 1990). In particular, nerve cuff signals is far more stable than intra-fascicular electrode signals (Hoffer and Haugland, 1992; Hoffer et al., 1997) because a cuff that surrounds a nerve cannot drift away from it, and the currents generated inside a cuff are constrained to flow within a fixed volume enclosed by the insulating wall.

Nerve cuffs have three main applications: stimulation of nerves and muscles, recording of nerve activity, and modulation of nerve activity by local infusion of pharmacological agents. Pioneering uses of phrenic nerve stimulation cuffs for diaphragm pacing (Glenn and Phelps, 1985) have successfully kept disabled individuals alive for decades. Pilot human trials of recording cuffs implanted in upper and lower limbs are showing the power of sensory feedback for FES control (Sinkjaer et al., in press).

Until now, widespread use of nerve cuffs has been limited. One reason for the slow development of clinical applications may have been a lack of serially fabricated, commercially available nerve cuffs. In our laboratory we have recently developed a family of new nerve cuff designs and fabrication procedures intended for serial production of cuffs that will meet industrial standards. We summarize here results of in-vivo testing of prototype cuffs for nerve stimulation, recording and modulation.

METHODS

General design features: All cuffs have thin walls (250-500 μm) molded of low-durometer silicone for flexibility and ease of installation. An integral piano-hinge opening/closing system (Kallesøe et al., 1996) ensures that the lumen will remain invariant and the cuff will remain well sealed (Fig. 1).

Stimulation and recording cuffs are of two types: single-channel (Fig. 2) or multi-channel (Fig. 3).

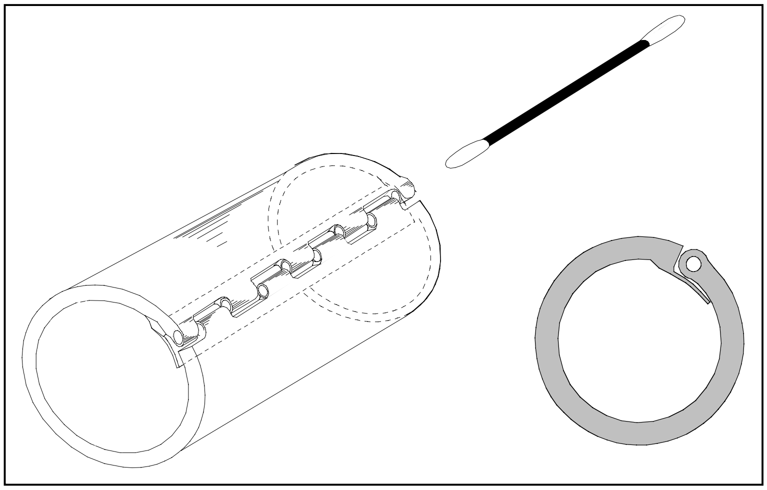


Figure 1. All cuffs have flexible walls with an integral opening/closing system (Kallesøe et al., 1996) that facilitates surgical installation and guarantees the invariance of the cuff lumen after installation.

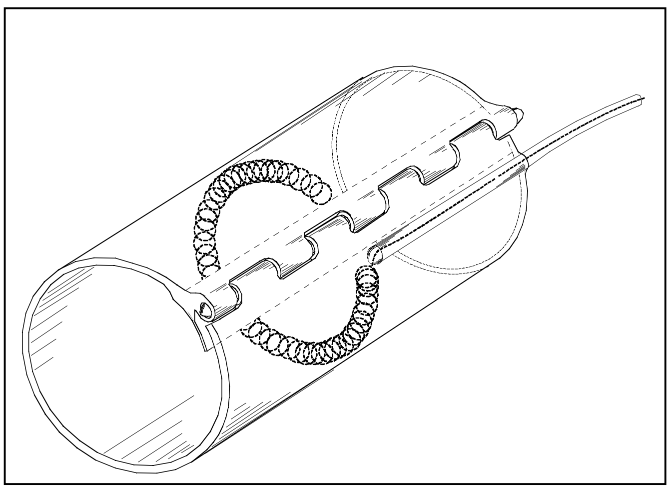
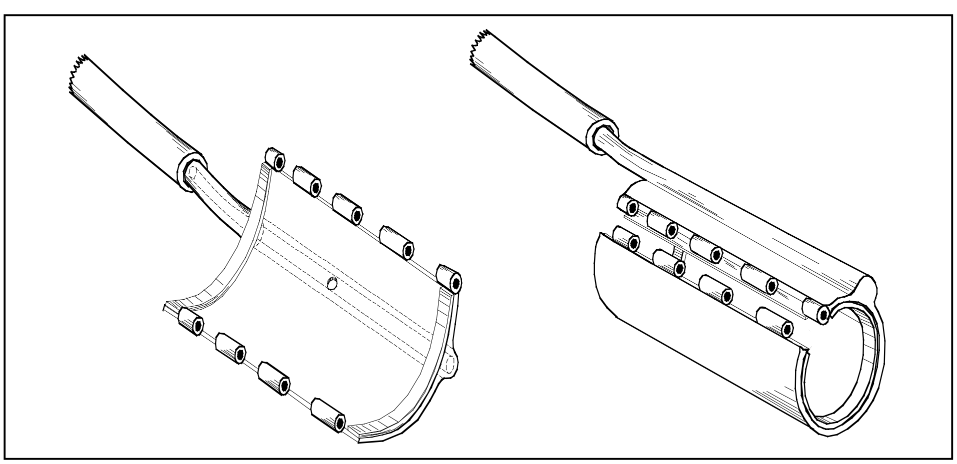


Figure 2. (Left). Single-channel cuffs include one or more coiled circumferential electrodes. The cuff lumen can be made as small as 0.9 mm I.D.

Figure 3. (Right). Multi-channel cuffs have extraneural chambers defined by longitudinal ridges. When electrodes are located in separate chambers, the selectivity of stimulation and recording is increased (Chen et al., 1997; Hoffer et al., 1997, 1998). For cat sciatic nerves we used 3-3.5 mm I.D., 8-channel cuffs that included over 40 electrodes, each precisely placed using a laser (Hoffer et al., 1999).



RESULTS

In our laboratory we implanted over 100 single-channel and 36 multi-channel recording/stimulating cuffs in a cat forelimb or hindlimb, and tested the electrodes and nerves for typically 6-12 months.

Nerve compound action potential amplitudes, latencies and electrode impedances were periodically monitored under anesthesia. These values tended to fluctuate in the initial weeks, typically stabilized after one month, and thereafter remained largely invariant (Hoffer et al., 1997).

Under general anesthesia, multi-channel stimulation allowed the selective recruitment of individual limb muscles (Chen et al., 1997) using low amplitude stimuli (typical threshold current = 200 µA x 100 µs). Some electrodes recruited several muscles with fairly similar thresholds, but other electrodes recruited a second muscle at 2-5 times higher threshold currents than for the first recruited muscle.

Multi-channel recordings from forelimb nerves allowed identification of distinct cutaneous fields (Strange et al., 1997) and accurate identification of which of the five digits was mechanically contacted at any one time by a computer-controlled probe array (Christensen et al., 1997).

Modulation cuffs have been used to administer lidocaine to peripheral nerves in limbs of moving animals in order to transiently block conduction in small-diameter axons only (Hoffer & Loeb, 1982), to transiently block conduction in all axons (Strange & Hoffer, in press) and to treat regenerating rat nerves with pharmacological substances delivered by osmotic pumps (viz., Brown et al., 1998).

A morphological study of median nerves inside single-channel recording/stimulationg cuffs that incorporated the interlocking closing system and an earlier type of circumferential electrodes indicated no changes in the numbers of axons and only small changes in axon diameters and myelin thickness (Crouch et al., 1997). Gross morphological inspection of nerves inside explanted multi-channel cuffs revealed that a thin layer of connective tissue neatly surrounded the nerve but the connective tissue did not entirely occupy the cuff chamber spaces, which remained fluid-filled.

It was noted that using these designs, the nerves were not very tightly attached to the electrodes and the cuffs could be easily removed at the end of experiments. In two cases where damage to external wires caused a need to replace an implanted cuff, this replacement was simple to perform and did not affect the nerve compound action potential parameters measured before and after the repair surgery.

DISCUSSION

The nerve cuffs described here constitute a new generation of interfaces designed for serial fabrication according to industrial standards. Prototype cuffs tested in animals were shown to be safe and effective when proper sizing and installation procedures were followed. NeuroStream Technologies, Inc. (Anmore, B.C., Canada) is now making cuffs available for clinical trials and research applications.

In addition to the more traditionally envisioned nerve stimulation and recording applications for the restoration of voluntary use of paralyzed limb muscles and for bladder control with FES (Sinkjaer et al., in press), new areas of clinical use may be made possible. For example, the fields of pain control, neuromodulation and nerve regeneration may be advanced by the commercial availability of cuffs with catheters to infuse substances directly to nerves.

Multi-channel stimulation cuffs may allow to selectively recruit previously unavailable muscles since surgical access to parent nerve trunks is usually easier than access to the fine, more delicate branches that innervate single muscles. Multi-channel stimulation cuffs may also be effective for independent stimulation of bladder and sphincter musculature, and penile erection (viz., Creasey, 1993).

Multi-channel recording cuffs placed on nerve trunks in a forearm or leg may be used to monitor skin contact information arising from each digit (Christensen et al., 1997), or differential loading of regions of the foot sole, to better control limb movements with FES. Similar cuffs placed on posterior sacral roots may monitor bladder presssure independently from signals arising from other pelvic

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