Selective Recording of Electroneurograms from the Sciatic Nerve of a Dog with Multi-Electrode Spiral Cuffs

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Abstract: Electroneurograms (ENGs) from superficial regions of the sciatic nerve of a Beagle dog were recorded selectively with a chronically implanted 33-electrode spiral cuff (cuff). By delivering stimulating pulses to groups of three electrodes (GTEs) within the cuff we could define the relative positions of the particular superficial regions that selectively innervated the tibialis anterior (TA) and gastrocnemius muscles (GM). GTEs with and without contractions of the TA and GM muscles were selected and connected to a 4-channel ENG system designed to amplify ENGs by 100,000 times and to pass frequencies between 500 Hz and 10 kHz. In our study, 12 experiments were conducted on three Beagle dogs with a cuff implanted for up to 2 years. We present the results obtained in four experiments conducted on one animal. With the implanted leg mounted in a special electronic brace we applied extending forces to the ankle, rotating it by up to 37° according to the neutral position, eliciting torque to stretch the TA muscle. Only the ENG from a GTE eliciting maximum contraction of the TA muscle showed activities corresponding to the trajectory of the mechanical load of the muscle. Next, we dissected the calcanean tendon (CT) of the implanted leg and applied repetitive pull forces to the CT. Only the ENG from the GTE elicitng maximum contraction of the GM muscle was activated in correspondence to the trajectory of the mechanical load applied on the CT. The results suggest that the cuff, implanted chronically on the sciatic nerve, is useful to record ENGs of the afferent fibers from TA and GM muscles selectively and that the technique could be extended for human use in the field of rehabilitation for paralysis. [Japanese Journal of Physiology, 50, 509–514, 2000]

Key words: multielectrode spiral nerve cuff, ENG, sciatic nerve, skeletal muscle.

Control of paralyzed limbs and muscles through functional neuromuscular stimulation (FNS) has been an area of active research for many years. Sensing neural signals to control assistive devices for FNS was suggested a number of years ago [1]. Recently, it has been possible to record afferent signals using the microneurography technique developed by Vallbo and Hagbarth [2]. The drawbacks of this technique are that the population of units which can be sampled is relatively small and that the recording electrode is easily dislodged if any significant movement of the surrounding tissue occurs [3–5]. These limitations can be circumvented when using tripolar nerve cuffs [6]. They give a more global picture of neural activity where nerve cuff signals feature considerable spatial and temporal averaging [7–10]. However, when recording an electroneurogram (ENG) from natural sensors in the presence of muscle activity, one must exclude electromyographic activity (EMG) and other noise sources that can be several orders of magnitude larger than the neural signals [6]. In rejecting the unwanted signals in the registration of ENG, the outer
Electrodes of the tripolar nerve cuffs are shunted together and a bipolar amplifier is employed to measure the potential difference between the middle and outer electrodes. The described arrangement of electrodes is referred to as a “quasi-tripolar” configuration [11]. In a typical tripolar nerve recording cuff, the three electrodes are mounted on the inside of a cylinder made of an insulating material, thus additionally reducing the EMG pick-up as well as other unwanted signals. None the less, nerve cuffs implanted on cutaneous nerves have proven to provide useful and reproducible whole-nerve recordings [6, 12]. Published results in Nikolić et al. [6] and Haugland and Sinkjær [12] demonstrate a functional use of cutaneous mechanoreceptors recorded by an implantable whole-nerve cuff recording electrode. However, whole-nerve recordings provide only one channel of information from the aggregate activity of many nerve fibers [7, 12]. The lack of spatial information could be circumvented by using cuffs with spatially arranged groups of three electrodes (GTEs) providing information from different superficial regions of the nerve [13].

Muscle spindles and Golgi tendon organs relay muscle length and tendon force information from the limb through the peripheral nerves to the central nervous system [14–16]. Signals from the muscle and tendon receptors serve only or almost only for muscle control, and they act completely subconsciously. They send a great amount of data to the spinal cord and cerebellum and even to the brain to ensure muscle control.

The use of this information recorded selectively with the multielectrode spiral cuff would be an effective method for the assessment of a closed-loop control of muscle force [17]. Namely, published results in Yoshida and Horch [17] describe a closed-loop functional neuromuscular stimulation system that uses afferent neural activity from muscle spindle fibers as feedback for controlling the position of the cat ankle joint.

The present study addressed the hypothesis that a certain superficial region of the peripheral nerve is composed mainly of fibers innervating one or more synergistic muscles where afferent and efferent fibers from a specific part of the muscle appear to run close to each other in the bundle [18]. The goal of this study was to determine whether a 33-electrode spiral cuff could be used to selectively collect the sensory information from the sciatic nerve of a dog. In particular, we wanted to know if an ENG could be recorded selectively from nerve fibers within superficial regions of a dog’s sciatic nerve innervating mainly muscle spindles and Golgi tendon organs of the tibialis anterior (TA) and gastrocnemius (GM) muscles [19].

**MATERIALS AND METHODS**

A cuff was made by bonding two 0.1 mm–thick silicone sheets together [13, 20]. One sheet stretched and fixed in that position was covered by a layer of adhesive (NuSil, MED-1511). A second unstretched sheet was placed on the adhesive and the composite was compressed to a thickness of 0.3 mm. When released, the composite curled into a spiral tube as the stretched sheet contracted to its natural length. Thirty-three electrodes (0.6×1.5 mm) made of 0.05 mm–thick platinum ribbon connected to lead wires (Cooner Wire, AS 631) were mounted on the third silicone sheet. They were arranged in three parallel spiral groups, each containing 11 electrodes at a distance of 0.5 mm. The distance between the spiral groups was 6 mm. Electrodes of the central group were connected to lead wires individually, while the corresponding outer electrodes were shunted to each other and then connected to lead wires. The silicone sheet with electrodes was bonded on the inner side of the cuff. The cuff, with an inner diameter of 2.5 mm, was trimmed to a length of 20 mm as shown in Fig. 1. The lead wires were connected to the connector to be implanted within the lateral subcutaneous tissue for the time between recordings.

The research was performed on four Beagle dogs. They were premedicated with 40 μg/kg medetomidine I.M. (Domitor, Orion Corp.) and 0.2 mg/kg methadone S.C. (Heptanon, Pliva). Induction was performed with 1.0 to 2.0 mg/kg propofol I.V. (Diprivan, Zeneca Pharmaceuticals Ltd.). General anaesthesia was maintained with 0.8 to 1.5 vol.% isoflurane (Forane, 510 Japanese Journal of Physiology Vol. 50, No. 5, 2000

Fig. 1. A 33-electrode spiral cuff for selective recording of ENGs from superficial regions of peripheral nerves.
Abbott) in 100% O₂. The skin over the left sciatic nerve was shaved, cleaned and disinfected. A sterile technique was used to expose the sciatic nerve in the leg from the mid-thigh to the popliteal fossa. The multi-electrode spiral cuff was then installed on the nerve just above its bifurcation in the tibial and peroneal nerve. The cuff’s leads were passed along the muscles within their soft connective tissues to common subcutaneous points on the upper lateral sides of the legs. Analgesia during surgery was sustained with 0.5 to 2.0 mg/kg ketamine I.V. (Ketamine, Veyx-Pharma GmbH) when necessary. Antibiotics (cefazolin 20 mg/kg I.V.; Cefamezin, Krka) were administered perioperatively. Analgesia during the early recovery period was provided with 0.3 to 0.5 mg/kg methadone S.C. TID. Eight milligrams/kg Tramadol S.C. TID (Tramal, Grünenthal GmbH) was administered for an additional 2 d. To allow the devices to stabilize, the first experiment was performed 30 d after the implantation. Considering the dimensions of the nerve and the dimensions of the cuff containing 11 GTEs, the geometric model of the cuff fitted on the nerve, presented in Fig. 2, was developed [13, 21]. In the model, each of the 11 GTEs was denoted by a consecutive number as shown in the previous figure. Then the relative positions of GTEs closest to the superficial regions of the sciatic nerve innervating the TA and GM muscles were determined experimentally. This was done by delivering stimulating pulses to each of the GTEs within the cuff. During each stimulating/recording session, the dog was anesthetized according to the aforementioned procedure. To remove the contribution to the ENG arising from hair receptors, the foot was thoroughly shaved, treated with depilatory cream and washed. The subcutaneously implanted connector was removed from the tissue, cleaned and dried. Rectangular, biphasic, charge-balanced current pulses with an intensity of 1.2 mA and a frequency of 20 Hz were delivered monopolarly on the central electrode of each individual GTE within the cuff. As a neutral electrode, a hypodermic needle was inserted in the subcutaneous tissue of the thigh, slightly proximal to the cuff. When a contraction of muscles occurred, the current amplitude was adjusted so that an isometric torque in the ankle joint of about 10% below the maximum was obtained. This was performed using the electronic brace by measuring the isometric torque elicited in the ankle joint by the TA muscle. The electronic brace designed especially for this study is shown in Fig. 3a.

The GTEs that elicited the largest peak force in the TA and GM muscles were indicated as relevant for the ENG of interest. In a specimen experiment, the isometric torque elicited by the TA muscle reached the peak value (0.81 N m) when the muscle was stimulated with GTE No. 8. Similarly, the isometric torque elicited by the GM muscle reached the peak value (0.84 N m) when the muscle was stimulated with GTE No. 5.

Outer electrodes of the two defined GTEs and outer electrodes of the two GTEs, the latter eliciting no contraction of the TA and GM muscles, were connected
to one input end of a 4-channel custom-designed differential ENG preamplifier while corresponding central electrodes were connected to the other ends. As a ground electrode, connected to the ENG preamplifier common, a hypodermic needle inserted previously was used. The total gain of all four ENG preamplifiers was set to $A=10,000$. In the main amplifier with a gain of $A=10$, the ENG was bandpass-filtered between 500 Hz and 10 kHz to additionally reduce the EMG pick-up. Therefore, total amplification of the system was $A=100,000$. Amplified ENGS were then fed to a high-performance data acquisition system (DigiPack 1200, Axon Instruments).

In the first recording, the implanted leg was mounted again in the electronic brace. The brace was unlocked so it could turn around together with the ankle of the dog. The ankle joint position induced by mechanical force was continuously measured with a goniometer coupled to the electronic brace. Extending forces were applied manually to the ankle, which elicited its rotation by about $37^\circ$ according to the neutral position, thus producing a torque in the ankle of about 1.2 Nm, and consequently stretching the TA.

In the second recording, the CT was surgically insulated and transected at about 1.5 cm above the tubular calcanei and attached to a force transducer as schematically shown in Fig. 3b. Repetitive pull forces of about 12 N were then applied to the proximal end of the CT.

In both recordings, the ENG increased as the muscles were being stretched but essentially ceased when they were shortened. It was shown previously that the ENG of a mixed peripheral nerve has most energy in the range from 1 to 3 kHz [12]. Since the ENG contains frequencies ranging from 1 to 10 kHz, the sampling ENG directly required a sampling frequency of 20 kHz.

RESULTS

The results of a 7-year study, where 12 experiments were conducted on three Beagle dogs, show almost the same degree of selectivity in ENG recordings. However, during the study, the complete measuring setup and methodology were improved constantly. Therefore, we present the results obtained in four experiments conducted in the last of three animals implanted during the 7-year study.

The top trace of Fig. 4 shows the rotations of an ankle, and thus tensions in the TA muscle. Trace a shows the ENG recorded by GTE No. 8; trace b shows the ENG recorded by GTE No. 2, which actually elicited no contraction of the TA and GM muscles; trace c shows the ENG recorded by GTE No. 11, which also elicited no contraction of the TA and GM muscles; and trace d shows the ENG recorded by GTE No. 5, which actually elicited a contraction of the TA muscle. In particular, trace a shows the ENG recorded by the GTE situated close to the superficial region innervating the TA muscle.

As can be seen in Fig. 4, only the ENG recorded with GTE No. 8 corresponds to the trajectory of the mechanical load/rotation of the ankle. ENGS recorded by GTE Nos. 2 and 11 show no consistency with the mechanical stretch of the TA muscle, while the ENG recorded by GTE No. 5 shows some consistency. However, the ratio between the useful information and the background is very low. Besides, this weak consistency could be attributed to the antagonistic GM muscle, which was also exposed to the rotations of the ankle. Namely, in nerves with many fascicles, certain portions of nerve fibers belonging to different muscles are distributed among the fascicles [18]. Therefore, the ENGS of antagonistic TA and GM muscles could also be in phase with each other.

Similarly, Fig. 5 shows four ENGS recorded when pulsing pull forces were applied to the CT, and thus to the GM muscle. A trace representing applied pulsing pull forces is shown in the most upper part of the fig-
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Fig. 5. ENGs recorded by 4 of 10 GTEs while pull forces were applied to the CT, and thus to the GM muscle. Top trace: The course of pull forces.

ure. Trace a shows the ENG recorded by GTE No. 11, which actually elicited no contraction of the TA and GM muscles; trace b shows the ENG recorded by GTE No. 1, which also elicited no contraction of the TA and GM muscles; trace c shows the ENG recorded by GTE No. 8; and trace d shows the ENG recorded by GTE No. 5. Particularly, trace c shows the ENG recorded by the GTE situated close to the superficial region innervating the GM. As can be seen in Fig. 5, only the ENG recorded with GTE No. 5 corresponds to the course of applied pulsing pull forces. The ENG recorded by GTE No. 8 still shows some consistency, while the ENGs recorded by GTE Nos. 1 and 11 show very weak or almost no consistency. In both ENGs, and especially in the latter, the ratio between useful information and the background is very low.

DISCUSSION

This study is the first demonstrating that natural sensory activity in peripheral nerves containing somatic sensory information from muscle spindles and Golgi tendon organs can be selectively recorded from a certain superficial region of the nerve with an implanted multi-electrode spiral cuff. We show in this study that natural sensory activity in superficial regions of the sciatic nerve innervating the TA and GM muscles of a dog, arising most probably from muscle spindles and Golgi tendon organs and recorded selectively with chronically implanted 33-electrode spiral cuff, contains useful information about the force applied on the TA and GM muscles. The cuff has yielded reliable and reproducible recordings for more than 24 months. Recent work with glabrous skin mechanoreceptors using whole-nerve cuffs has shown that sufficient information can be extracted from an ENG to compensate for slip on the cat’s footpad [6]. The same technique has been applied experimentally to a hemiplegic patient to provide feedback to control an FNS stimulator to correct footdrop using a chronic cuff implanted around the sural and peroneal nerves [12]. The remaining question as to whether intrafascicular recording electrodes with greater recording selectivity than extraneural electrodes have additional benefits that can be exploited under a FNS application was answered by Yoshida and Horch [17]. However, the problem of the dislodging of recording electrodes during any significant movement remained unsolved. Based on the hypothesis that a certain superficial region of the peripheral nerve comprises mainly fibers of one or more synergistic muscles and that afferent and efferent fibers run close to each other and aforementioned experiences, our study was aimed at demonstrating that an ENG recorded selectively with a multi-electrode cuff can be useful as a potential feedback signal for control of a muscle stimulator.

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REFERENCES


