Stimulation selectivity of an interfascicular electrode in the sciatic nerve of rabbits

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Abstract

The choice of electrode for functional electrical stimulation systems is a compromise between selectivity and invasiveness; high selectivity is desirable to obtain maximum functional control, but if the surgical procedure induces too high risk the electrode will not be acceptable for human use. Current literature on peripheral nerve electrodes has focused mainly on extra-neural and intrafascicular electrodes. The current study presents a new interfascicular electrode that could simplify implantation of the electrode because it does not require the nerve to be freed of blood vessels and connective tissue. The electrode was implanted in the sciatic nerve of nine rabbits and was capable of fully activating the tibial and peroneal nerve branches with high selectivity (SI = 0.98±0.02, mean±SD) in all animals. Implantation of the electrode was simple and the interfascicular electrode could be an interesting alternative in applications where freeing the nerve is complicated by blood vessels e.g. the vagal nerve. Further studies are needed to investigate the stability and safety of the electrode in chronic experiments.

Keywords*: Interfascicular electrode, nerve stimulation, stimulation selectivity, peripheral nerves, animal experiments.*

Introduction

Neural prosthetic devices utilizing stimulation of peripheral nerves are in use for multiple applications today, including vagal nerve stimulation to treat epilepsy, sacral nerve stimulation to treat urinary and faecal incontinence, phrenic nerve stimulation for ventilator assistance, and peroneal nerve stimulation for correction of foot-drop [1, 2]. A large variety of electrodes have been developed to provide the interface of these systems to the nerve, ranging in invasiveness from percutaneous to extra-neural, intraneural and even regenerative electrodes [2].

The most successful electrode for peripheral nerve stimulation has been the cuff electrode, which has been used for many research and rehabilitation applications for several decades, but also intrafascicular electrodes have received considerable interest over the last two decades. The intermediate stage between the cuff electrode and the intrafascicular electrode, i.e. electrode placement among the fascicles, has received less interest.

In a modelling study it was found that an electrode placed in the epineurium just outside a fascicle of the human deep peroneal nerve was unable to stimulate this fascicle selectively with respect to neighbouring fascicles [3]. This is a rather intuitive result since several fascicles were within a relative short distance of the electrode and the impedance of the perineurium must be overcome before the fascicle can be activated. Tyler and Durand 1997 did, however, show that a solution to this problem could be to include a passive element in the electrode that shields non-target fascicles from the stimulating contact [4].

From a surgical point of view implanting cuff electrodes can be cumbersome in some locations due to the requirement to free the nerve of surrounding tissue such as blood vessels, while implantation of intrafascicular electrodes is a relatively invasive procedure as well, requiring the penetration of the perineurium with a sharp needle. An electrode designed to be pushed into the relative soft epineurium without lifting the nerve could provide a relatively less invasive means of placing electrode contacts in close proximity of the nerve fibres. This should provide a current consumption low enough for an implanted system and selectivity at least to the level of activating a single nerve.

In the current study a four-contact interfascicular electrode was developed and tested in the sciatic nerve of nine rabbits. The electrode contained two pairs of contacts, placed on opposite sides of the electrode, shielded from each other by the nylon frame of the electrode. Orienting the electrode so that one contact pair faced the tibial fascicle of the sciatic nerve and the other the peroneal fascicle the electrode demonstrated excellent selectivity in recruitment of the tibial vs. peroneal nerve.

Material and Methods

Surgery

Nine rabbits weighing 3894±216 g (mean±SD) were anaesthetized, the skin was opened in a line from the hip to the knee of the left hind leg and the femoral biceps and semitendinous muscles were split from each other to expose the underlying nerves. The interfascicular electrode was implanted in the sciatic nerve distal of the muscular branch with one pair of contacts facing the tibial fascicle and the other pair facing the peroneal fascicle. This insertion was made using a blunt glass needle to pierce the nerve after which the electrode could be pulled through the channel created by the needle using the nylon suture attached to the electrode. The tibial and peroneal nerves were freed and a cuff electrode was placed around each nerve for recording.

Electrodes

The interfascicular electrode developed for the experiment is illustrated in Fig. 1. It consisted of an 8 mm long piece of flattened 0.63 mm outer diameter Nylon tube with a Nylon suture, used for pulling the electrode into the nerve, and four circular Ag contacts of approximately 0.5 mm diameter. Silver was used for the contacts because it is relatively easy to manipulate and because we sought to investigate electrode properties, not biocompatibility. The contacts were placed in pairs on each side of the flattened tube with 2 mm between the middle of each contact of the pair. The total width of the electrode was less than 1 mm. The suture was fixated with a knot inside the tube, the contacts were glued to the tube wall, and the electrode was filled with silicone. The lead wires were coiled for strain-relieve and soldered onto the four wires of a shielded lead cable.

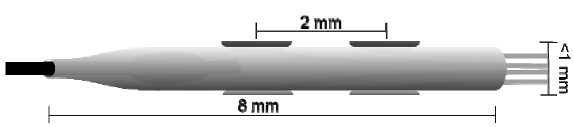

Fig. 1: Illustration of interfascicular electrode with four Ag contacts. Not drawn to scale.

Cuff electrodes for recording were produced according to the technique described by Haugland [5]. The cuffs were 12 mm long and contained three 1 mm wide Pt ring contacts placed with 5 mm between each ring.

Stimulation

Mono-phasic constant current square pulses of 50 µs were delivered by a SD9 stimulator with a PSIU6X isolation unit (Grass Technologies). Recruitment curves were obtained by computer triggered stimulation with 10 single pulses at each stimulation intensity for several intensities, from below recruitment threshold to above full recruitment of the first recruited nerve branch. Stimulation current was calculated from the linear relationship between the voltage output of the SD9 and the constant current output of the PSIU6X.

Recording

Recorded nerve signals were preamplified, amplified, filtered, and further amplified using two AI402 SmartProbes and a CyberAmp 380 (Axon Instruments Inc.). The gain was chosen depending on signal amplitude. The signals were high-pass filtered using a first-order filter with -3 dB frequency of 0.1 Hz and low-pass filtered using a fourth-order Bessel filter with a -3 dB frequency of 10 kHz. In some rabbits it was necessary to increase the corner frequency of the high-pass filter to 1 Hz because of high amplitude low frequency noise. The signals were then digitized at 50 kHz using a PCI-6221 ”M series DAQ” with a BNC-2110 connector block (National Instruments) and stored on a computer for further analysis.

Data analysis

Data analysis was performed off-line using Matlab® (The MathWorks™). A time-average was generated for each set of 10 stimuli with equal stimulation intensity and the peak-to-peak response (V_{pp}) of the direct nerve volley was calculated from this time average. Each V_{pp} was normalized in each of the nerve branches with respect to the largest V_{pp} obtained during the experiment to express the response as a fraction (f) of full nerve activation.

For each stimulation intensity (I) the selectivity index (S) was calculated as the response of the target nerve branch (b) divided by the sum of the responses of both nerve branches:

$$S_b(I) = \frac{f_b(I)}{f_{tibial}(I) + f_{peroneal}(I)} \qquad (1)$$

in accordance with e.g. [6, 7]. To get a single number to measure the selectivity of the electrode, it was calculated as the mean of the highest achieved selectivity in recruitment of each nerve branch while activating the branch to at least 70% of its maximum, i.e.:

$$\hat{S} = \frac{1}{2}\sum_{i=1}^{2} \max\left\{ S_i(I) \mid f_i(I) \geq 0.7 \right\} \qquad (2)$$

Adapting the definition provided by Yoo et al [7], a nerve branch was regarded as selectively activated in a functionally relevant way if both the criteria $S_b(I)>0.7$ and $f_b(I)>0.7$ were satisfied.

In addition, the maximally achieved f and the threshold current ($I_{10\%}$), required to produce 10% activation of the nerve branch were obtained.

Results

The interfascicular electrode achieved functional selective stimulation of all 18 nerve branches tested in the experiment with $\hat{S}$ = 0.98±0.02 (mean±SD) and with f up to 0.98±0.04. The selectivity was slightly higher for the peroneal nerve than for the tibial nerve (1.00±0.00 vs. 0.97±0.04, $p=0.009$ by Mann-Whitney Test) whereas the maximal selective response did not differ significantly (f_{tibial} = 1.00±0.01, $f_{peroneal}$ = 0.96±0.05, $p=0.292$). The threshold current for stimulating the nerves was $I_{10\%}$ = 415±210µA (0.02µC per stimulus pulse) with the peroneal nerve requiring significantly lower current than the tibial nerve (287±111µA vs. 542±213µA, $p=0.003$).

Discussion and Conclusions

Electrodes for stimulating of or recording from peripheral nerves have been extensively researched, but designs have focused on either extra-neural electrodes or the more invasive intrafascicular electrodes, while interfascicular electrodes have received very little interest. In this study a new electrode was designed to be easily implanted between the fascicles without isolating parts of the nerve and to provide fascicle selectivity. Implantation of the electrode was smooth; the epineurium was easily penetrated by the blunt needle while the perineurium was left intact. Once a channel was created by the needle the electrode could be pulled into the nerve without much resistance.

The results of the present study demonstrate that the interfascicular electrode presented here is capable of fully activating two fascicles separated by the nylon tube of the electrode with remarkable selectivity ($\hat{S}$ = 0.98±0.02, max(f) = 0.98±0.04).

In the present study the electrode was inserted into the nerve without any difficulty, but it was difficult to see the electrode inside the nerve and therefore also to asses if it still had the desired orientation. The results and observations during explanation do, however, show that electrode placement was successful. In this experiment the electrode was fixated only by the fascicles pushing on the sides of the electrode. No electrode movement was observed in the current experiment, but it remains to be investigated if this passive fixation is sufficient in a chronic environment.

It should be noted that stimulation of multi-fascicle nerves would require a very different design than for a nerve with just two fascicles e.g. topological sectioning of the nerve into more than just two chambers.

For chronic studies it is necessary to develop a non-silver electrode and perhaps to include some means of fixation, e.g. tiles. The presented electrode design should, however, otherwise provide a stable and safe interface to the nerve since it does not penetrate the protective boundary of the nerve, the perineurium, and does not confine the nerve to a limited space, which could lead to pressure damage.

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Acknowledgements

The authors thank the staff at Aalborg Hospital for their assistance. This study was supported by the Danish National Advanced Technology Foundation.

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