MULTI-GROOVE ELECTRODE FOR FASCICLE SELECTIVE NERVE STIMULATION

Koole, P., Holsheimer, J.

Department of Electrical Engineering, University of Twente
Enschede, NETHERLANDS.

ABSTRACT

A multi-groove electrode for direct nerve stimulation is presented. The device has been designed for fascicle selective nerve stimulation. After dissection fascicles can be positioned in grooves and stimulated separately. Each groove is similar to an open cuff. The properties of stimulation by this electrode were investigated by computer simulations, using monopolar stimulation by a single cathode. There appeared to be no interfering cross-talk to neighbouring fascicles when the isolating partition was at least as high as the diameter of the fascicles. A small cathode appeared to be preferable, because recruitment increased more gradually as a function of stimulus amplitude at smaller dimensions. The degree of inverse recruitment was also influenced by the dimensions of the cathode. Recruitment characteristics of the fascicles were strongly affected by the electrical properties of tissues in between the cathode and the perineurium. From these simulations it can be concluded that the multi-groove electrode will be suitable for fascicle selective nerve stimulation. The model predictions will be tested in animal experiments.

KEY WORDS: fascicle selective nerve stimulation, multi-electrode, FES, recruitment

INTRODUCTION

For the electrical stimulation of paralyzed muscles or their nerves several types of electrodes have been developed. Surface electrodes have most been used clinically. However, the number of muscles that can be stimulated selectively by these electrodes is limited. Other problems are variability of the response, muscle fatiguebility and skin irritation (1).

Therefore a lot of effort is spent on the development of implantable electrodes, e.g. intramuscular (2,3), epimysial (4), nerve cuff (5,6), epineural (7) and intraneural (8,9) electrodes. Each of these electrode-types has its advantages and disadvantages depending on the specific application. Until now they are not used widely. One of the problems when using electrodes for direct nerve stimulation is that muscle selectivity has to be improved (5).

Since peripheral nerves are composed of fascicles and distally these fascicles are specific for one muscle or a group of muscles (10), we started to develop electrodes based on these anatomical properties. Two types of electrodes were investigated: intrafascicular wire electrodes and an extrafascicular multi-groove electrode.

For the intrafascicular wire electrodes it has been shown in a modeling study (11) that fascicle selectivity of nerve stimulation can be increased by decreasing the distance between electrode and nerve fibres. Using a small electrode the best selectivity could be obtained when the electrode was placed inside a fascicle. We have shown experimentally, in the rat sciatic nerve, that it is possible to stimulate a fascicle selectively by a wire electrode inside the fascicle (12). Careful chronic experiments will be necessary to evaluate the effects of injury of the perineurium by piercing wire electrodes into a fascicle and the biocompatibility of materials inside a fascicle. Other problems are the positioning of the wire electrodes inside the nerve and the fixation of the intrafascicular electrodes.

As an alternative the multi-groove electrode has been developed for fascicle selective nerve stimulation. For its application a peripheral nerve has to be split into fascicles or fascicular groups after opening the epineurium. Fascicles are put into grooves and stimulated by contacts. In clinical nerve repair opening of the epineurium seems to cause no complications and experience in the manipulation of fascicles is obtained. In order to prevent severe surgical trauma of the perineurium, carefull handling of fascicles is necessary (13).

In this paper we present a multi-groove electrode which enables the electrical separation of fascicles. Results of model simulations, used in designing the multi-groove electrode, are presented. Special attention is paid to the recruitment order and the slope of the recruitment curves, as well as cross-talk to a non-stimulated fascicle from a neighbouring groove.

MATERIALS AND METHODS

1. Multi-groove electrode

Fig. 1 shows the multi-groove electrode that has been developed. Selected fascicles lie in small grooves, each groove being similar to an open cuff. The remaining part of the nerve lies in the concavity below the grooves. The device is made of silicone rubber (Dow Corning, Silastic 734 RTV). The grooves have a circular cross-section, the diameters being equal to the diameters of the fascicles (0.5 to 2.0 mm); the length of the grooves: 8 mm. The width of

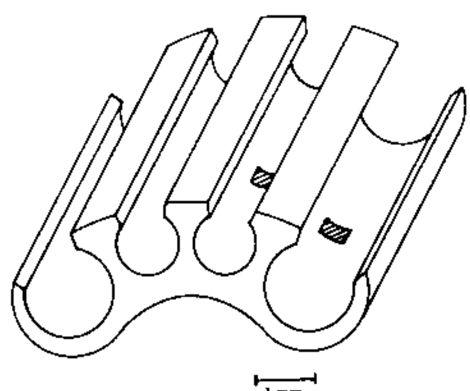

Fig.1. Multi-groove electrode with 4 grooves. The number of grooves and their dimensions can be varied. Two contacts (shaded) are visible.

the partitions between the grooves is 0.2-0.4 mm. The device keeps the fascicles isolated, mechanically as well as electrically. Flat contacts (90 % Pt, 10 % Ir, dimensions 0.5x0.5 mm^2) are fitted at the inner wall of the grooves, connecting wires (same material) enter the device as a bundle.

2. Modeling of nerve stimulation

2a. Volume-conductor model

In order to evaluate the effect of the geometry of the multi-groove device on nerve fibre excitation within a fascicle, a computer model was used which describes the geometrical and electrical properties of the tissues and materials and the excitation of myelinated nerve fibres. We used the computer model developed by Veltink et al. (11). The three-dimensional model was composed of wedge shaped volume elements (fig.2). The potential distribution within the volume-conductor model was calculated by the variational method. The equations were solved numerically by Gauss elimination and Gauss-Seidel iteration.

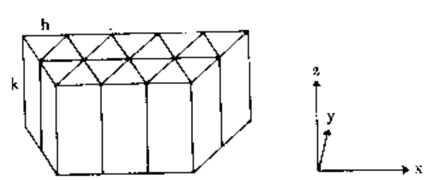

Fig.2. Part of the model, composed of wedges (see text).

The dimensions of the wedges (fig.2) are given by: the side of the equilateral triangle (h) and the length of the wedge (k). Usually h was 0.1 mm and k was 0.5 mm. The length of the model (x-direction) was taken 50 h, the width (y-direction) was $20\sqrt{3}$ h and the height (z-direction) was 41 k (=20.5 mm).

The multi-groove electrode models used for this paper only consisted of two grooves. The axes of the grooves and the nerve fibres were in the z-direction.

The contacts could be positioned anywhere in the model and their dimensions in the x,y-plane could be varied. The contacts were defined by imposing a fixed potential at the grid points (Dirichlet condition). The width of the contacts (in the z-direction) was at least one grid point. In the simulations presented in this paper monopolar cathodal stimulation was used. Zero potential was imposed at the surface of the model (Dirichlet condition), so the surface represented the anode. To diminish the influence of the finite dimensions of the model, a boundary layer was introduced, having $\sigma = 10^{-4}\,(\Omega m)^{-1}$, imitating an increased distance to the anode.

The conductivity of the fascicles was assumed to be anisotropic: $\sigma_x = \sigma_y = 0.08(\Omega m)^{-1}$ and $\sigma_z = 0.5(\Omega m)^{-1}$ (11). The conductivity of the perineurium was $8.4 \cdot 10^{-4}\,(\Omega m)^{-1}$, derived from Weerasuriya et al. (15) assuming a 40 μm thickness of the perineurium in their experiments. The thickness of the perineurium roughly equals 5 % of the diameter of a fascicle (10, page 41). In the model it was not always possible to fulfil this condition. In these cases the value of σ was corrected in such a way that the value of $\sigma \cdot$ thickness was correct.

The surrounding medium had a conductivity of $0.1(\Omega m)^{-1}$, in the range of the conductivity of muscle tissue (16). The insulating material of the multi-groove electrode was given a very low conductivity: $10^{-6}\ (\Omega m)^{-1}$.

2b. Nerve fibre model

Nerve fibre excitation was modeled using the network description of a myelinated nerve fibre in an external electrical field, introduced by McNeal (11,14). The external field was applied by monophasic rectangular pulses (pulsewidth $60\,\mu$sec). The nerve fibre model consisted of 10 internodal intervals. The 3 nodes near the electrode were described by the Frankenhaeuser-Huxley equations. The membrane impedance of the other nodes was kept constant ($c_m = 0.02\ F^{-1}m^{-2}$, $g_m = 304\ \Omega^{-1}m^{-2}$, nodal gap $= 25\ 10^{-7}$ m).

Simulations were executed using fibres with an outer diameter (D) between 9.5 and 15.5 μm. The distance between nodes of Ranvier (L) was 100 D, the ratio of the inner (d) and outer (D) diameter of the nerve fibres was 0.7.

Nerve fibre excitation depends on the distance between the cathode and the nodes of Ranvier. This distance consists of two components: the perpendicular distance between cathode and nerve fibre in the x,y-plane and a component (L_0) between the midplane of the cathode and the nearest node of Ranvier in the z-direction. L_0 varies between 0 and 0.5L.

2c. Evaluation of modeling results

Results are presented by recruitment contours and recruitment curves.

A **recruitment contour** is the boundary of the region in a fascicle where nerve fibres of a given diameter will be excited using a given stimulus amplitude. Usually two contours will be shown. One represents fibres having a node of Ranvier in the midplane of the electrode ($L_0=0$) and the other represents fibres for which $L_0 = 0.5L$ (having a higher threshold for stimulation).

Recruitment curves show the fraction of recruited fibres of a single diameter in a fascicle as a function of stimulus amplitude. It is assumed that the distribution of nerve fibres of the same diameter over the cross-section of a fascicle is uniform. The distribution of L_0-values is assumed to be uniform between 0 and 0.5 L.

Compound force recruitment curves are also shown. They represent a weighted sum of a number of recruitment curves from several fibre diameters (similar to experimental recruitment curves), normalized to maximum force. The weight factors depend on the diameter distribution of the nerve fibres and on the relation between nerve fibre diameter and twitch-force (or tetanus-force) of its motor unit.

Boyd and Davies (17) presented the diameter distribution of motor-fibres for several muscles in the cat. The maximum tetanus force (F) of a motor unit is an exponential function of the conduction velocity (v, in m/sec) of the motor nerve fibres in several fast twitch muscles (18). The experimental data can be approximated by the equation:

$$F = \text{constant} \cdot e^{0.09\,v} \qquad (1)$$

The ratio between conduction velocity (m/sec) and nerve fibre diameter (μm) is approximately 6 (17). Weight factors for the EDL (extensor digitorum longus) of the cat, based on these data, are shown in table 1.

From the recruitment curves two parameters were calculated (fig.3).

A.
$$S_D = \frac{0.2}{\log V_{60} - \log V_{40}} \qquad (2)$$

where S_D is an estimate of the slope at 50 percent of the recruitment curve for myelinated nerve fibres with outer diameter D; S_C represents the slope of the compound force recruitment curve; V_n is the stimulus amplitude at n percent of the recruitment curve.

B.
$$I_r = \frac{V_{50,10} - V_{50,10}}{V_{50,15}} \qquad (3)$$

where Ir is an estimate of recruitment order. $V_{50,10}$ and $V_{50,15}$ are stimulus amplitudes at 50 percent recruitment for D = 10 and 15μm, respectively. Physiological recruitment order would result in a negative value of I_r. Positive values, always found in this study using artificial stimulation, indicate an inverse recruitment order. A lower positive value represents a less pronounced inverse recruitment order.

D(μm)	number of α-fibres	weight factor
9-10	5	0.01
10-11	8	0.03
11-12	17	0.12
12-13	41	0.51
13-14	46	1.00
14-15	10	0.38
15-16	1	0.07

Table 1. Number of α motor fibres innervating the EDL of the cat (17). The weight factors are calculated by equation 1 and normalized to the maximum value; D is the central value of each interval and v=6 ·D.

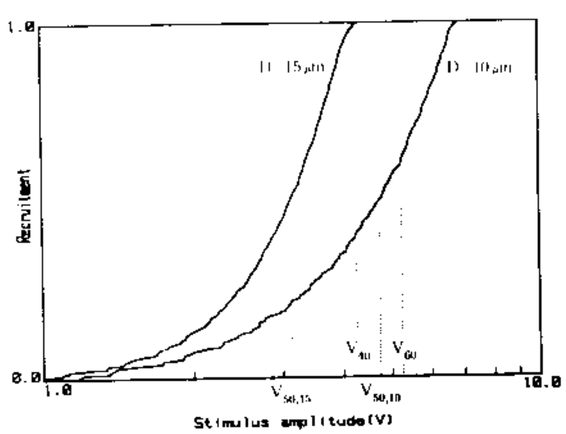

Fig.3. Recruitment curves of nerve fibres with D=10 m and D=15 m. In these simulations the cross-section of fig.5 was used, with a small cathode at the bottom of the groove. A logaritmic amplitude scale is used (also in fig.4, 6, 7 and 9). The marked stimulus amplitudes were used to calculate parameters (see text).

Cross-talk between two fascicles is quantified by the parameter

$$R = V_{2,min}/V_{1,max} \qquad (4)$$

where $V_{1,max}$ is the minimum stimulus amplitude at which all nerve fibres in fascicle 1 are excited ($10\,\mu m \le D \le 15\,\mu m$); $V_{2,min}$ is the stimulus amplitude for fibres in fascicle 2 with lowest threshold. Fascicle 1 lies in the groove with the active cathode, fascicle 2 is a neighbouring fascicle. If $R < 1$ the recruitment curves overlap.

RESULTS

At first some multi-groove electrodes with different heights of the isolating partition have been modeled (fig.4). From these simulations it appeared that the partition has to be at least as high as the fascicle diameter. When the partition height decreased from 95 % to 50 % of the fascicle diameter (0.5 mm) the parameter R decreased by 55 %. At partition heights above the fascicle diameter, R increased by only 6 %. Therefore the partition was taken as high as the fascicles in the simulations shown below.

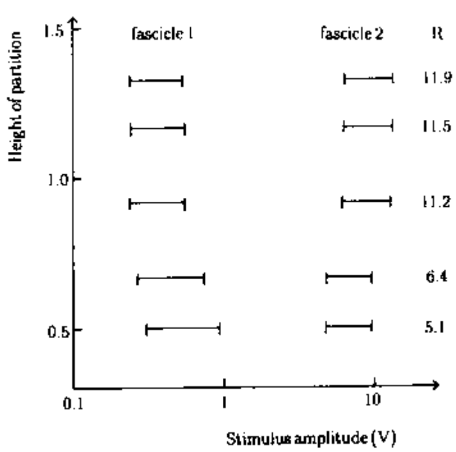

Fig.4. Cross-talk as a function of partition height (values relative to the diameter of the fascicles). Fascicle 1 stimulated by a large cathode in the groove, fascicle 2 stimulated by cross-talk. For both fascicles the interval of the stimulus amplitude is indicated where recruitment increases from 0 to 100 % ($10\,\mu m \le D \le 15\,\mu m$). Values of the cross-talk parameter R are shown at the right side. Diameter of the fascicles 0.5 mm; h=0.05 mm; k= 0.5 mm; thickness of the isolating partitions varies between 0.2 and 0.4 mm; width of the cathode, encircling a large part of the fascicle: 0.5 mm; in the lower two cases the electrode was shorter than in the upper cases.

Starting with the model of fig.5 the dimensions of the contacts have been varied. The left fascicle was stimulated by a single cathode and its recruitment characteristics were studied.

Fig. 6 shows recruitment curves for $D = 10\,\mu m$. The length (in the x,y-plane) of the cathode was varied: 27, 15 and 5 grid points, respectively (fig.5); the width (z-direction) was 0.5 mm.Recruitment curves for $D = 10$ and $15\,\mu m$, using the small contact, are shown in fig.3. Thresholds were lower for the thick fibres. The compound force recruitment curves of the three contacts are shown in fig.7. The values of the slope-parameters S_{10}, S_{15} and S_c of the large cathode were about 60 % higher than of the smaller ones (table 2). The recruitment curve of the small contact increased very gradually at a low recruitment level, as shown in fig.6 and 7. The value of the inverse-recruitment parameter I_r increased by 30 % at decreasing length of the cathode.

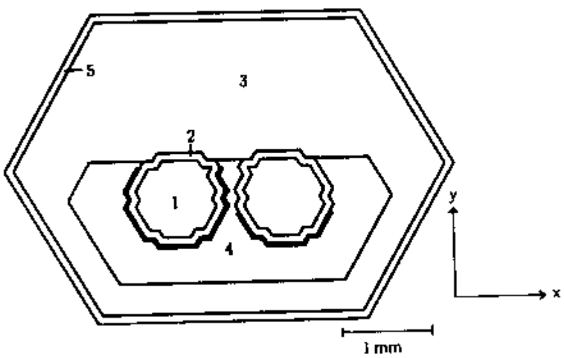

Fig.5. Cross-section of the model used to obtain the results of fig.3 and 6 to 9. Two contacts with different lengths (thick lines), used for the simulations of fig.3, 6 and 7, are drawn. The contacts are at the inner wall of the grooves. The largest contact is 27 grid points (=2.5 mm) and the intermediate one 15 (=1.3 mm). A small contact (not shown) consisted of only 5 grid points (=0.4 mm) at the bottom of the groove. h=0.1 mm; k=0.5 mm. 1. fascicle, 2. perineurium, 3. surrounding tissue, 4. silicone rubber, 5. boundary layer of the model.

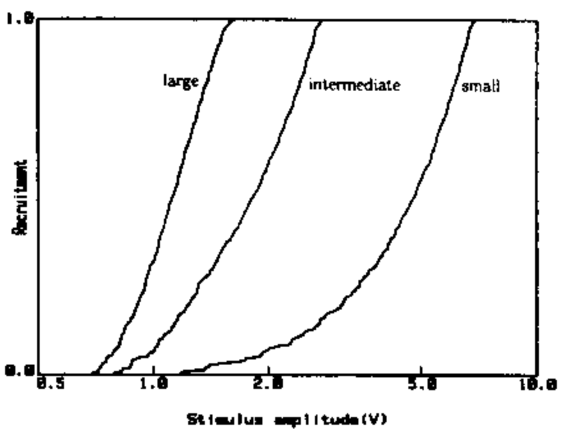

Fig.6. Recruitment curves calculated for D=10 m for three different lengths of the cathode, using the model of fig.5.

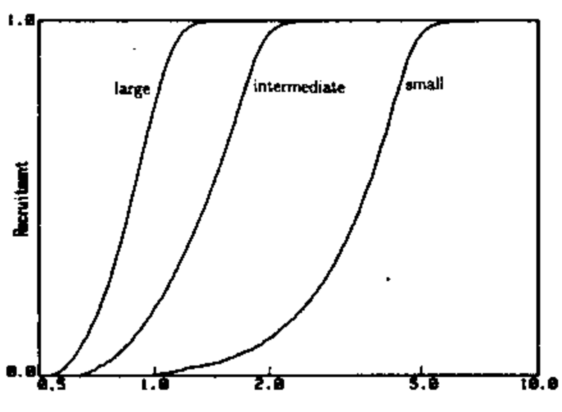

Fig.7. Compound recruitment curves for three different lengths of the cathode, as in fig.6.

The main advantage of using a smaller contact is that it will be possible to stimulate both sides of a fascicle by two different contacts, which is illustrated in fig.8. Fig. 8 shows recruitment contours using a contact at one side of the fascicle. At the stimulus amplitude chosen 50 % of the nerve fibres with diameter D=15 μm, having a node of Ranvier in the midplane of the contact, were recruited. However, when the nearest node of Ranvier was above or below the midplane of the contact or when the nerve fibre diameter was smaller, a smaller part of the fascicle was recruited, because thresholds were higher.

Electrode		S_{10}	S_{15}	S_c	I_r
large	width = 0.5 mm	3.7	4.8	4.5	0.40
intermediate		2.2	3.1	2.8	0.45
small		2.2	3.1	2.9	0.51
small	width = 0.0 mm	2.2	3.1	2.8	0.48
	width = 0.5 mm	2.2	3.1	2.9	0.51
	width = 1.0 mm	2.6	3.2	3.0	0.54
	width = 1.5 mm	2.8	3.4	3.2	0.58
small, (fig.8)		2.4	3.4	3.1	0.50
small, (fig.10)		4.2	5.2	4.4	0.57

Table 2. Slopes S_{10} and S_{15} of the recruitment curves and the inverse-recruitment parameter I_r. S_c is the slope of the compound recruitment curve. The lower two lines represent the situation of a small contact at one side of the fascicle, respectively without (fig.8) and with (fig.10) an intermediate tissue layer in between the electrode and the perineurium.

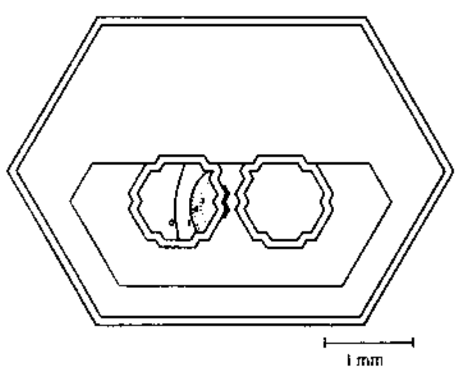

Fig.8. Recruitment contours calculated for D=15 μm (solid lines) and D=10 μm (dotted lines). The contours marked by 0 were calculated for L_0=0, the contours marked by 1 were calculated for L_0= 0.5L. Small contact (thick line) at one side of the fascicle, width of the contact was 0.5 mm.

Fig.9 shows recruitment curves of the small contact having different widths in the z-direction (0, 0.5, 1.0 and 1.5 mm). The slope changed by less than 30 % (table 2.): the curves were a little steeper for contacts with a larger width. The parameter Ir increased by 20 % when the width of the contact was increased.

In the simulations presented above the fascicle filled the whole groove. This will not always be true in an experimental situation. Therefore some simulations were done with a tissue layer in between contact and fascicle. Fig.10 shows recruitment contours when a cathode is on the right side of the fascicle. In this case it was assumed that the

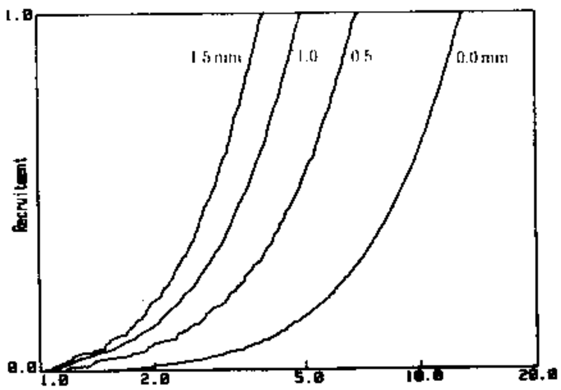

Fig.9. Recruitment curves for a small cathode at the bottom of the groove. The width of the cathode was varied (0.0 mm to 1.5 mm).

intermediate tissue layer had a much higher conductivity (σ= 0.1 (Ωm)$^{-1}$) than the perineurium. The shape of the contours changed as compared to fig.8. Unfortunately the recruitment curves became steeper and the recruitment parameter Ir increased. Thresholds of the other fascicle were much lower (R = 2.1) as compared to the situation of fig.8 (R = 13.2), because the resistance of the current path from the contact to the other fascicle was lower. The value of R increased by 80 % when the height of the partition was increased by 40 %.

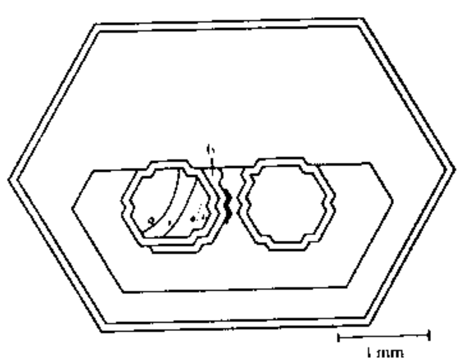

Fig.10. An intermediate tissue layer (region 6) was modeled in between the cathode and the perineurium. Small cathode (thick line) at the right side of the fascicle, width of cathode: 0.5 mm; h=0.1 mm, k=0.5 mm. Recruitment contours are shown for D=15μm (solid lines) and D=10 μm (dotted lines). The contours marked by 0 were calculated for L_0=0, the contours marked by 1 were calculated for L_0=0.5L

DISCUSSION

The multi-groove electrode presented seems to be appropriate for fascicle selective nerve stimulation.

A small contact has some advantages over a contact surrounding a large part of the fascicle: the slope of the recruitment curve is less steep and it will be possible to recruit complementary halves of the fascicle separately by two contacts, for example to reduce muscle fatigue by stimulating via these contacts alternately. Inverse recruitment, however, was somewhat more pronounced when using a small contact, but this disadvantage does not counterbalance the positive aspects.

The width of the contact did not have a large effect on the slope of the (compound) recruitment curves, but a contact with a small width should be prefered.

Although it has to be emphasized that the weight factors of table I are just rough estimates, the compound force recruitment curves support the conclusions drawn from the other recruitment curves.

The partitions have to be at least as high as the fascicles. Probably the partitions can best be chosen a little higher than the fascicles, for situations when scar tissue grows around the fascicle, because the cross-talk parameter R decreased considerably when an intermediate tissue layer with high conductivity was introduced between contact and perineurium (fig.10).

The intermediate tissue layer also resulted in a virtual enlargement of the cathode, because current spreads out in the intermediate tissue layer. It can be understood from fig.10 that two regions of the fascicle stimulated by different contacts may overlap at a lower recruitment level than in the situation of fig.8.

The possibility that action potentials will be blocked by hyperpolarization at both sides of the cathode has not been considered, because this will only occur at stimulus amplitudes of at least 5 times threshold (19, 20). Therefore it would not seriously affect our conclusions.

The predictions based on the model simulations have to be tested by animal experiments, as well as the biocompatibility of the multi-groove electrode in contact with fascicles.

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