SENSITIVE AND SELECTIVE NEURAL CONTROL USING AN INTRANEURAL MULTI ELECTRODE STIMULATION DEVICE IN SILICON TECHNOLOGY

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ABSTRACT

The ideal neural stimulatory information transducer must be able to activate individual neural fibres within a fascicular bundle, for example in a sensory or motor nerve. In a local approach using microelectrodes it is sufficient to apply current pulses to one neural node in order to reach the stimulatory threshold of the socalled activating functions [2]. To this end, a multi electrode array in silicon technology is being inserted into a fascicle. It is one out of several possible approaches using silicon technology [3]. This report focuses on two aspects: sensitivity and selectivity of such a neuro electronic interface, using monopolar cathodic stimulation pulses at one or two electrodes. A test for selectivity has been developed, using refractory properties. One conclusion is that beyond an electrode separation of 250 μm selectivity becomes maximal.

MATERIALS AND METHODS

The intraneural stimulation device

Figure 1 shows a schematic drawing of the tip of the silicon device, the twelve Platinum stimulation sites upon it and the positioning of the device in a fascicle. Not shown is the Si_3N_4 insulation cover layer over the tip (except over the Platinum surfaces). The tip length is 840 μm, its thickness 45 μm. The length dimension has been chosen on basis of the fascicle diameter of about 0.5 to 1.0 mm in man as well as in rat. The interelectrode distance (50 μm) follows from the fibre diameter of about 10 to 20 μm and the number of about 300 to 600 efferent motoric α fibres in a population of 1000 to 2000 fibres in an average fascicle of the Peroneus Communis Nerve of the rat [4].

The tip was inserted in the exposed peroneal nerve of the anaesthetised rat during acute experiments in order to stimulate the Extensor Digitorum Longus muscle of the right hindleg. After insertion the nerve was immersed in parafin oil or vaselin. Rectangular current pulses were used to elicit single twitch contractions of the muscle under isometric conditions. Pulse patterns (see next section) had a repetition interval of 1127 ms. Each force response was the averaged result of 16–64 twitches.

Sensitivity of a single electrode in the array

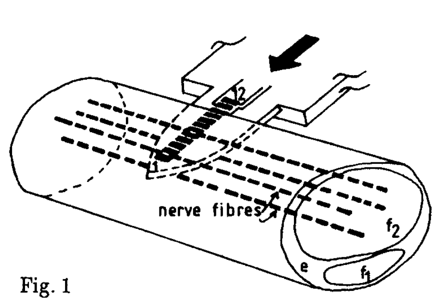

Fig. 1

In a homogeneous, isotropic medium one has for the potential at distance R $V_{e,o} = \rho_e I/4\pi R$

in which ρ_e is the resistivity of the external medium (Ωm) and I is the current.

Defining R_o as the distance from electrode to neural node beyond which no excitation occurs and for pulsewidth T=100 μs , one can derive [1,2]

$$R_o = 2K\, I_o \qquad (1)$$

with K= 6.5 m/A. I_o is the rheobase for that distance R_o.

The spherical stimulation volume with radius R_o contains $4\pi N\, R_o^3/3$ nodes, in which N is the nodal density (m^{-3}). This number of nodes excites the same amount of motor units, yielding a total twitch force amplitude of $F_t\, 4\pi N\, R_o^3/3$ (F_t is the average twitch force amplitude of a motor unit). With eq (1) this leads to a cubic force versus current relationship

$$F = 4F_t 4\pi\, N\, K^3\, I_o^3/3 \qquad (2)$$

A selectivity test for intraneural stimulation

Selectivity is maximal when each electrode excites one specific nerve fibre.In practice, with increasing current stimulus fields will expand and overlap with neighbouring fields. A measure for selectivity, which is valid within the refractory period (see below), is

$$S_{i,j} = \frac{F_{i+j}-F_j}{F_i} \text{ or } S_{j,i} = \frac{F_{i+j}-F_i}{F_j}$$

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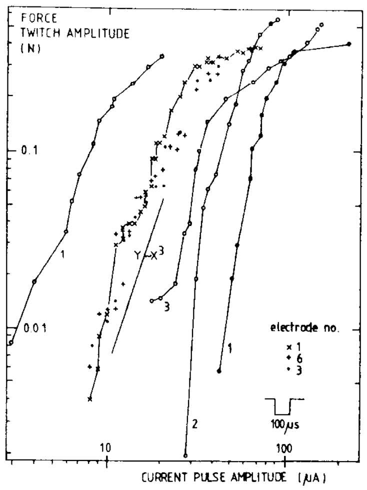

Fig. 2 Selection of recruitment curves for monopolar cathodic stimulation at electrodes no. 1, 2, 3 and 6 in several animals.

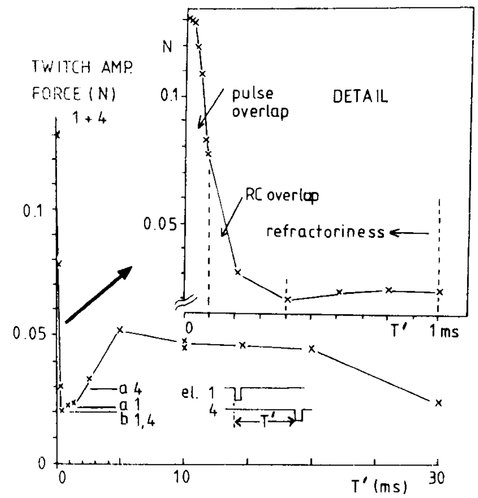

Fig. 3 Force versus time interval T' between cathodic pulses at two electrodes, 1 and 4. Force levels for stimulation at only one electrode (1 or 4) before and after the experiment (b1,4 and a1,4) are also drawn. In the inset "DETAIL" three regions are sketched: pulse overlap (0–100μs), RC overlap (100–400μs) and refractory (< 1 ms) region.

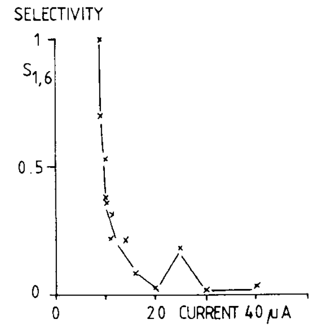

Fig. 4 Selectivity $S_{1,6}$ versus stimulus. For definitions of selectivity see the text. T' = 400 μs.

in which F_i (or F_j) is the force due to electrode i (or j) separately and F_{i+j} is the force due to stimulation at both electrodes. In the latter case S will have a value between zero and one, provided the stimulus timing fullfills three requirements. First, the pulse at electrode j must have no temporal overlap with that at electrode i. Secondly, the pulse at j must be separated in time from the pulse at i to let the membranes be fully discharged. Thirdly, the two pulses must arrive both within the absolute refractory period of 1 ms. The optimal separation must be derived from experiment.

RESULTS

Sensitivity

Experiments were performed in six rats. A representative selection of force versus current in four animals is given in figure 2. Maximum force of an EDL muscle is about 0.5 Newton. Figure 2 shows saturation of the recruitment curves to this value in all cases. Stimulation starts at the lowest attainable force level, varying between 0.002 and 0.015 Newton. These levels are probaby single motor unit levels. Recruitment curves are sampled series, no attempt was made to find all possible (discrete) force levels. For comparison the theoretically derived F versus I^3 relation (eq. 2) is drawn also in this figure. The five leftmost curves more or less obey this relationship, while the two rightmost curves are steeper in the low F range. Other experiments (not shown) in which current was fixed and pulse width T varied, yielded that τ=70 μs is a realistic experimental value. The application of equation (2) to the most sensitive curve in fig. 2, with T=100μs, K=6.5m/A and F_t=0.01N, gives an estimate for the nodal density: N = 8 x 10^{12} nodes/m^3. This implies an internode distance of 0.5 mm (nerve diameter 1 mm, fibre diameter 10 μm, a relative abundance of 30% of motoric fibres and the closest possible packing).

Selectivity

Figure 3 shows the force as a result of stimulation with fixed currents at two electrodes of the array, no. 1 and no. 4 (interdistance 150 μm) as a function of pulse separation T'. For T'=0 the combined force is 0.13 Newton which is far more than just the summation of two times 0.02 Newton, but still below a factor $2^3 = 8$ times 0.02 Newton. This indicates that the current fields of these two electrodes almost completely overlap. This is corroborated by the decrease of the force to the single electrode level at T' ≈ 400 μs. Beyond about 1 ms the stimulated nodes are no longer refractory, so mechanical addition of twitches occurs up to the maximal possible value of 0.05 Newton (apparently the force levels drift upward during the experiment, see the figure, a(fter)4 and a1). Beyond a separation of 20 ms the addition is less effective as this time interval is that of the maximum of a twitch. Beyond 100 μs and below 400 μs the membrane still contains enough charge to enable currents to raise the membranepotential above excitation threshold. This lead us to a choice of 400 μs between two pulses. Figure 3 is representative for the bad selectivity we obtained, also at low stimulus levels, up to electrode separations of 200 μm. Only beyond 250 μm selectivity reaches values of one, at low currents (figure 4).

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