Introduction

Implanted neuromuscular stimulators have been used to correct footdrop in 31 hemiplegic patients by stimulating the peroneal nerve and thereby activating muscles that dorsiflex the foot (Waters et al., 1975; McNeal et al., 1977). The implanted hardware comprised a passive radiofrequency receiver placed in the medial thigh with a flexible lead wire extending to a cuff electrode that was wrapped around branches of the peroneal nerve just below the knee. A review of the long-term results of this clinical series was recently completed (Waters et al., 1985). Ten units still implanted in the surviving patients were functional 9–14 years after implantation.

One problem encountered with some of these patients was excessive inversion or eversion of the foot during dorsiflexion. Four muscles innervated by the peroneal nerve normally act synergistically to dorsiflex the foot. Two of these muscles also invert the foot while the other two evert the foot during dorsiflexion. In those patients in which a problem was observed, one of these two groups of muscles was apparently stimulated excessively, resulting in unbalanced dorsiflexion. This occurred despite wrapping the cuff electrode around selected branches of the peroneal nerve and demonstrating that balanced dorsiflexion of the foot was achieved during the surgical procedure.

It was felt that this method of correcting footdrop would be significantly enhanced if there was a way to electronically balance the contribution of these two groups of muscles postimplantation. Two methods of balancing the foot were proposed. One was to use a dual-channel receiver with two electrodes, one wrapped around motor branches to the two muscles that dorsiflex and invert the foot and the other wrapped around the branches to the muscles that dorsiflex and evert the foot. By adjusting the relative intensities of the two channels, correct dorsiflexion could be achieved. The second method considered was to use a single insulating sleeve wrapped around all four motor branches with an array of small electrodes positioned inside the sleeve. Given a method for postsurgically selecting any of the electrodes to be the cathode and a second to be the anode, it should be possible to find a combination that produces the desired response.

Some results have already been reported that suggest the feasibility of the second concept. Caldwell (1971) placed up to eight electrodes (each a 0.25mm diameter, 1mm long platinum wire) around the sciatic nerve of rabbits. Electromyographic (EMG) activity of the gastrocnemius and anterior tibialis muscles (both innervated by branches of the sciatic nerve) was recorded from a pair of wires inserted into each muscle. He reported that a combination of stimulating electrodes could usually be found to produce a contraction of one muscle without activating the other. EMG data presented, however, was limited to one rabbit, and no specifics of stimulus amplitude and electrode positions were given.

A six-electrode array (three stimulating and three earth electrodes) was used by Petrofsky (1979) to selectively activate three distinct populations of neurons within cat sciatic nerve. Equipotential lines drawn from experimentally obtained data were shown to trisect the sciatic nerve into three similar pie-shaped sections; the implication being that neuronal populations in each of these sections could be selectively activated by stimulation through one of the three active electrodes. Single-fibre EMG data did indeed show that approximately one-third of 55 muscle fibres of the medial gastrocnemius were activated by each of the three stimulating electrodes with virtually no overlap; i.e. each

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motor unit was excited by stimulation through one electrode but not excited by stimulation through the other two. These results would be compatible if the motoneurons innervating the medial gastrocnemius were distributed throughout the sciatic nerve so that one-third of the neurons were within the excitation zone of each of the three stimulating electrodes; however, this is not the case. Motoneurons of the medial gastrocnemius are localised within the sciatic nerve to one or a few fascicles (see, e.g. Sunderland, 1968). This problem is not addressed by the author.

The purpose of the present study was to test the feasibility of selectively activating independent muscles with peripheral nerve stimulation using both of the methods described above. The muscles studied were those that flex and extend the ankle. Chronic and acute studies involving four dogs were conducted. Methods and results of these studies are presented. The implications of using each method to produce balanced dorsiflexion of the human foot are discussed.

2 Methods and procedure

Four mongrel dogs between 20 and 27 kg were used in this study. All animals were initially anaesthetised with intravenous Surital (sodium thiamylal) for intubation and transfered to Penthrane (methoxyflurane) for the remainder of the procedure.

In one animal, a sterile technique was used to expose the sciatic nerves bilaterally from the midthigh to the popliteal fossa. The posterior tibial and peroneal branches were identified. Two bipolar cuff electrodes were implanted in the left leg, one around the posterior tibial nerve and the other around the peroneal nerve. The electrodes were flattened multistranded platinum wire 1.5 mm in width running parallel to each other with 4 mm separation inside a silicone rubber flap that was 11 cm wide. When wrapped around the nerve, two circumferential bands were thus formed inside an insulating cuff. To guard against damaging the nerve the cuff electrodes were wrapped loosely around the nerve; the inner diameter of the electrode being approximately 50 per cent greater than the diameter of the nerve. Both electrodes were located above the knee just below the point where the nerves bifurcate from the sciatic nerve. At this location, both nerves are in close proximity to each other so that the exterior of each electrode was in contact with the adjacent nerve. Two monopolar cuff electrodes (a single multistranded wire inside a 7 mm wide flap) were positioned in the same way around the peroneal and tibial nerves in the right leg. Leads from all four electrodes were passed subcutaneously to a common point on the back. Excess lead wire was coiled and placed in a subcutaneous pocket. All incisions were closed and the animal was awakened. Twelve weeks later, the animal was reanaesthetised and the back incision was reopened for testing.

In three other dogs, who were sacrificed at the end of the procedure, a nonsterile technique was used to similarly expose only the left sciatic nerve. A cylindrical plastic sleeve containing seven electrodes (Fig. 1) was positioned around the sciatic nerve proximal to the point of bifurcation into the posterior tibial and peroneal nerves. The sleeve, machined from Delrin, was 8 mm in diameter and 18 mm long. The inner channel of the sleeve was elliptical in cross-section with dimensions of 3 x 4 mm. Six of the electrodes were circular silver electrodes 1 mm in diameter. Electrodes A, B and C were located on one half of the sleeve with a 3 mm spacing between the centres of A and B and a 6 mm spacing between the centres of B and C. Electrodes D, E and F were identically spaced on the opposite half of the sleeve. Electrode G was a silver band 1 mm wide that completely encircled the nerve when the two halves of the sleeve were sutured together around the nerve. The centre of the band was 3 mm from the centres of electrodes A and D. The multielectrode array was positioned for maximal selectivity by observing the EMG response when stimulating through selected electrode pairs. This position was determined at the beginning of the experiment and was not changed after data collection was initiated. After positioning the sleeve, the incision was closed for the duration of the experimental tests.

In all four dogs, bipolar wire electrodes were placed in each of four muscles of the leg for recording EMG activity. The wire was nylon-coated stainless steel 0.05 mm in diameter with approximately 2 mm at the tip deinsulated. Two of the muscles in which EMG was recorded, the gastrocnemius and soleus (ankle extensors), are innervated by the posterior tibial division of the sciatic nerve. The other two muscles, the anterior tibialis and peroneus longus (ankle flexors), are innervated by the peroneal branch. EMGs were recorded from all four muscles while stimulating through various combinations of electrodes. All tests were conducted while the animals were anaesthetised. In the chronic dog experiment, this was performed 12 weeks following implantation to allow tissue reaction to the cuff electrodes to stabilise.

In each case, the stimulus amplitude was increased to eight times the minimum motor threshold of the four muscles or until all four muscles were stimulated supramaximally. The pulse duration was fixed at 0.2 ms and the repetition rate was one pulse per second. The stimulator, built in our laboratory, was capacitively coupled and produced monophasic constant-current pulses.

All EMG signals were recorded using differential preamplifiers (Tektronix FM-122) and recorded on a Honeywell Visicorder. EMG responses to pulses of constant amplitude were very consistent and were either biphasic or triphasic in form. At each stimulus level, the maximum peak-to-peak value of the EMG was recorded and used as a relative measure of motor activity.

3 Results

In the chronic dog experiment, maximal stimulation of motor fibres of the nerve contained within any one of the four

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Fig. 1 Multielectrode array inside an insulating sleeve used to test the selectivity of various electrode configurations: (a) closed as it would be when placed around the nerve and (b) opened to expose the electrodes. Dimensions, materials and procedures used to position the array on the nerve are described in the text.

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