Effects of stimulation parameters on modification of spinal spasticity

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Abstract—*Various electrical stimuli with frequencies from 10 Hz to 1000 Hz and pulse widths from 10 μs to 1000 μs were applied to seven spinal-cord injured patients with spasticity of the knee muscles. Spasticity was assessed with the pendulum test and EMG activity in the quadriceps and hamstrings. No universal optimum combination of stimulation parameters could be established, but stimuli of 100 Hz and 100 μs pulse width were more effective than other combinations. Subjective remarks of patients regarding the effects over 24 h did not always correlate with measured data obtained within one hour after stimulation.*

Keywords—*Electrical stimulation, Parameters, Spasticity*

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1 Introduction

EFFORTS to modify spasticity by electrical stimulation can be traced back to at least 1752 when Benjamin Franklin—apparently quite successfully—relieved a young girl from 'convulsions and cramps' (MCNEAL, 1977). Since then reports on the beneficial effects of stimulation for various symptoms of spasticity have continued and were reviewed by VODOVNIK *et al.* (1984*a*). In spite of the large number of clinical observations the method is far from being used as a routine in physical medicine. The reason for such reluctance in accepting a simple, inexpensive method, which has no known adverse side-effects, seems to be a rather widespread inconsistency of the therapeutic results, difficulties in objective assessment of possible benefits and a variety of locations for stimulation. In addition almost every investigator applies a different stimulation regimen with some 'specific' parameters.

Some of these problems have been discussed in our recent paper (BAJD *et al.* 1985), and so the present report will concentrate on the role of stimulation parameters in relieving spasticity. In all reports of spasticity relief with electrical stimulation using skin electrodes, a given set of parameters was applied to all patients within the study. On the other hand, in spinal cord stimulation (SCS) the motor response and in particular spasticity have been found to be dependent on pulse width and frequency (COOK and NIDZGORSKI, 1984). Similarly, Neuromed, a Florida-based SCS producer, suggested that spinal-cord stimulation should be applied at frequencies from 10 Hz to 1500 Hz with 50 Hz increments to find the optimal response.

Assuming that some mechanisms of spasticity relief due to skin stimulation are identical in spinal-cord stimulation it seemed worthwhile to search for optimum parameters in cutaneous stimulation too.

2 Method

Seven spinal-cord injured patients with clinically complete lesions and spasticity of the knee joint muscles were included in the program. To test the majority of stimulation frequencies and pulse widths reported in the literature the following parameter combinations of monophasic rectangular current trains were investigated on five patients: 100 Hz/1000 μs, 100 Hz/100 μs, 100 Hz/10 μs, 1000 Hz/100 μs, 1000 Hz/10 μs, 10 Hz/1000 μs, 10 Hz/100 μs and 10 Hz/10 μs. Stimulation was applied over the quadriceps through 10 cm × 6 cm skin electrodes with a distance between electrodes of about 20 cm. The current amplitude was adjusted to a level which produced a non-painful contraction or muscle twitching. This was obtained with a current of up to 30 mA. Stimulation was delivered cyclically with the stimulation train 4 s on and 4 s off.

Because the effects of short-term stimulation do not seem to last longer than 24 h (VODOVNIK *et al.*, 1984*a*; WALKER, 1982) the patients received each day a different set of stimulation parameters.

The following measurement procedure was adopted. The patient lay in a relaxed supine position and EMG electrodes were attached to the quadriceps and hamstring. Spasticity was quantitatively assessed with the pendulum test as reported by BAJD and VODOVNIK (1984), BAJD *et al.* (1985) and VODOVNIK *et al.* (1984*b*). For this test the patient lies supine on a tilt-table with both legs bent over the edge of the table and hanging free at the knee. The examiner grasps the patient's foot and brings the leg to a horizontal position. The limb is allowed to fall freely as the knee angle is recorded with an electrogoniometer.

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The first test was performed immediately to determine the initial level of spasticity (test 1). After 5 min of inactivity the test was repeated (test 2). For the next 20 min electrical stimulation with a given set of parameters was delivered to the quadriceps. Thereafter followed test 3. To observe effects lasting up to 1 h after stimulation, tests 4, 5 and 6 were performed every 20 min. On the following day another set of parameters was tested. As eight parameter combinations were evaluated, each patient participated in the programme for 8 days.

Because of our former work on electrical stimulation of spastic patients (Vodovnik *et al.*, 1984*a*; Bajd *et al.*, 1985) we were aware that subjective comments of patients regarding the effect of stimulation represent rather valuable data, especially for the period exceeding the measurement time. Therefore the day after a given combination was applied each patient was carefully questioned about the effect the stimulation has had on his spasticity through the whole past day. A '+' was noted when the patient reported better relaxation, fewer spasms through the afternoon, warmth in the legs etc. If the patient complained about increased discomfort after stimulation, a '−' was recorded, and '0' was inserted if comments were neutral. Thus quantitative and fairly precise data were obtained for the first hour after stimulation and a descriptive report for the next 24 h period.

The measurements were quite time consuming and somewhat uncomfortable for the patients. It was therefore impractical to test all patients several times regarding the reproducibility of the obtained results. After analysing the results from five patients it was decided to repeat part of the protocol (the first four tests) on two patients. Each of them was tested on different days three times for 10 Hz and three times for 100 Hz, all at 100 μs pulse width. Finally, on both of these patients a control measurement was performed with the same protocol as in other experiments except that the stimulator was not switched on.

From each test the relaxation index R was calculated. This index represents the quotient between the initial drop and the resting angle divided by 1·6. With such a definition for extreme spasticity $R = 0$ is obtained and $R = 1$ for nonspastic normals. Details regarding the relaxation index were reported by Bajd and Vodovnik (1984). Since each experiment at a given day consisted of six tests the average relaxation index $\overline{R1}$ of the first two tests was taken as a measure of prestimulation spasticity and the average relaxation index $\overline{R2}$ of the following four tests as a measure of spasticity after stimulation.

3 Results

In Fig. 1 a typical set of data from patient F is presented. The two upper recordings show prestimulation spasticity. Strong EMG activity during extension of the leg and intense bursts in the quadriceps during the pendulum test are a common pattern usually observed in spastic patients. The lower two graphs show the same variables immediately after stimulation (frequency 100 Hz, pulse width 100 μs) and 20 minutes later. EMG activity practically disappeared in the hamstrings and was drastically reduced in the quadriceps. The goniogram shows damped oscillations very close to patterns observed in normal subjects.

A summary of data obtained from all patients is presented in Table 1. The changes in spasticity are denoted as changes in the relaxation index $\Delta R = \overline{R2} - \overline{R1}$. For patients F and G the numbers in the table are averages of ΔR over three measurements at different days. Each ΔR has also an additional +, − or 0 representing the subjective observations of the patients as described in the methodology. Data from the first five patients show that the largest ΔR were obtained at 100 Hz but with various pulse widths.

To test the reproducibility of the results the measurement was repeated three times for 10 Hz/100 μs, three times for 100 Hz/100 μs and once for control with electrodes attached but no stimulation. The data are shown in Table 2. It can be seen that the same parameters on the same patient do not have reproducible effects on different days. One of the reasons for the variability is the fact that the initial spasticity of the same patient varies substantially

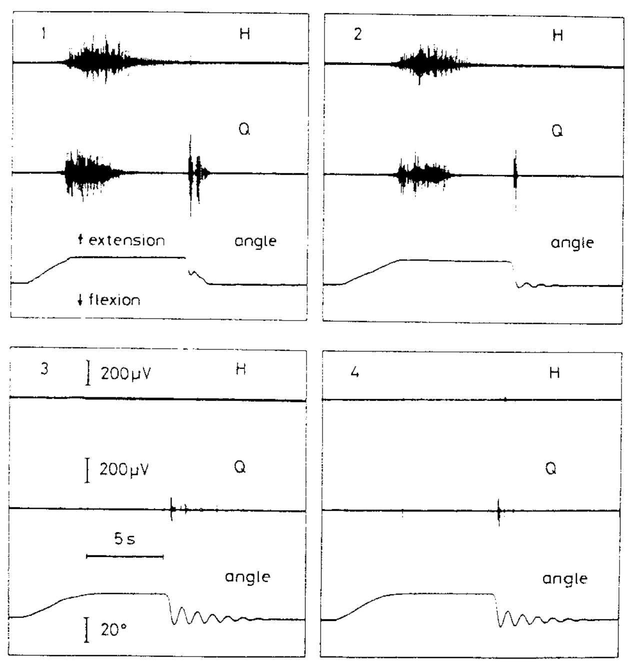

Fig. 1 *Set of pendulum tests of patient F before stimulation (test 1 and 2), immediately after stimulation (frequency 100 Hz, pulse width 100 µs, test 3) and 20 min later (test 4)*

Table 1 Effects of electrical stimulation with various parameters on seven patients. The bold values are the largest for a particular patient. For details see the text

				Frequency (Hz)/width (μs)							
				100/100	100/10	100/1000	1000/100	1000/10	10/100	10/10	10/1000
P	Age	Lesion	T	ΔR	ΔR	ΔR	ΔR	ΔR	ΔR	ΔR	ΔR
A	27	C-6, 7	8	$0{\cdot}31^{+}$	$\mathbf{0{\cdot}32}^{0}$	$0{\cdot}23^{0}$	$0{\cdot}05^{0}$	$0{\cdot}11^{+}$	$0{\cdot}11^{+}$	$0{\cdot}09^{+}$	$0{\cdot}11^{+}$
B	24	C-5	60	$0{\cdot}36^{+}$	$0{\cdot}36^{+}$	$\mathbf{0{\cdot}45}^{+}$	$0{\cdot}15^{+}$	$0{\cdot}16^{0}$	$0{\cdot}37^{+}$	$0{\cdot}43^{+}$	$0{\cdot}37^{+}$
C	23	C-7	4	$0{\cdot}05^{+}$	$\mathbf{0{\cdot}17}^{+}$	$0{\cdot}12^{0}$	$0{\cdot}08^{-}$	$0{\cdot}04^{0}$	$0{\cdot}06^{0}$	$0{\cdot}07^{-}$	$0{\cdot}02^{+}$
D	35	T-8, 9	5	$0{\cdot}03^{+}$	$-0{\cdot}11^{0}$	$\mathbf{0{\cdot}21}$	$0{\cdot}14^{+}$	$-0{\cdot}08^{+}$	$0{\cdot}06^{-}$	$0{\cdot}02^{0}$	$-0{\cdot}01^{0}$
E	22	T-4-6	7	$\mathbf{0{\cdot}175}^{0}$	$0{\cdot}11^{0}$	$0{\cdot}05$	$0{\cdot}15^{-}$	$0{\cdot}17^{+}$	$0{\cdot}09^{-}$	$0{\cdot}04^{+}$	$0{\cdot}11^{0}$
F	26	T-5	40	$\mathbf{0{\cdot}06}^{+}$	—	—	—	—	$0{\cdot}01^{0}$	—	—
G	23	T-10	36	$\mathbf{0{\cdot}18}^{+}$	—	—	—	—	$0{\cdot}13^{0}$	—	—

P – patient, T – time past injury (months).

from day to day. Thus, for example, patient G had initial relaxation indexes from 0·45 to 0·79 and any effect due to stimulation would be more pronounced when the patient was very spastic ($\overline{R1} = 0{\cdot}45$) than when he was practically without spasticity ($\overline{R1} = 0{\cdot}79$). To enhance the effect of stimulation at a high initial relaxation index a factor for relative effectiveness of therapy E was introduced. This factor is defined as:

$$E = \Delta R \, . \, R_m/(R_m - \overline{R1})$$

where R_m denotes the highest possible relaxation index. According to our definition of R its largest value is 1, therefore:

$$E = \Delta R/(1 - \overline{R1})$$

The values for E in Table 2 were calculated according to this formula. Using this method some of the data become more consistent. Let us for example look at the set of 100 Hz measurements on patient G. The ΔR were 0·23, 0·23 and 0·08. But at the last measurement the patient had a high $\overline{R1}$ of 0·79 and there was not much to be improved. When E was calculated the figures 0·55, 0·52 and 0·38 were obtained, which represent a much more consistent set of data. In general, however, the results obtained from all seven patients were too scattered and inconsistent to warrant any reliable and meaningful statistical analysis.

Table 2 Reproducibility measurements of stimulation effects on two patients

	Patient F				Patient G			
Hz/μs	$\overline{R}_1$	$\overline{R}_2$	ΔR	E	$\overline{R}_1$	$\overline{R}_2$	ΔR	E
10/100	0·77	0·82	0·05	0·22	0·45	0·74	0·29	0·52
10/100	0·75	0·72	−0·03	−0·12	0·75	0·82	0·07	0·28
10/100	0·78	0·76	−0·02	−0·09	0·74	0·79	0·05	0·19
100/100	0·71	0·83	0·12	0·14	0·58	0·82	0·23	0·55
100/100	0·68	0·78	0·08	0·25	0·56	0·79	0·23	0·52
100/100	0·85	0·82	−0·03	−0·2	0·79	0·87	0·08	0·38
Control	0·69	0·73	0·04	0·14	0·78	0·78	0·00	0·00

4 Discussion

In spite of all the difficulties in obtaining reproducible data, Table 1 reveals that 100 Hz is a more effective stimulation frequency than 10 Hz or 1000 Hz and that the pulse width seems to be less critical. This is in agreement with parameters found in several stimulators for pain suppression (e.g. GERSH *et al.*, 1980) while systems for functional electrical stimulation are using lower frequencies—between 25 and 50 Hz (VODOVNIK *et al.*, 1981). It is encouraging that our results are comparable to data obtained in pain research, particularly since an increasing amount of evidence points to a close relationship between pain and spasticity. ROLAND (1986) analysed the pain-spasm-pain cycle in spinal disorders and suggested that a large body of evidence is consistent with the existence of such a cycle.

The pathological syndromes of spasticity vary from patient to patient and even in a given patient they vary with time. COOK and NIDZGORSKI (1984) found that changes in function occurred with changes in stimulation parameters. However, he concluded that for any given time and patient there is no certain stimulation parameter that would consistently modify motor performance. It is therefore quite possible that parameters have to be adjusted individually and in the same patient they might change with time.

Since the mechanisms of spasticity with its many symptoms are still not well understood it is even more difficult to discuss the effects of electrical stimulation on a spastic neuromuscular system. Frequency dependence of responses has been observed on a short-term basis as well as over periods of hours. BURKE (1977) noted that activation of simple systems in the mammalian CNS at frequencies above 2 Hz may produce depression, enhancement or little change in postsynaptic potentials, depending on the system under study. WACHTEL and KANDEL (1971) showed that some monosynaptic systems exist in molluscan ganglia that produce excitatory postsynaptic potentials when operating at relatively low rates while at higher rates the same terminals liberating the same transmitter, produce inhibitory postsynaptic potentials. This qualitative shift in synaptic efficacy due to change in frequency might be due to two different sets of postsynaptic receptors associated with the same terminal.

Similar evidence for frequency-dependent responses was found by CHENG and POMERANZ (1979). They performed electroacupuncture in mice and found two types of pain-relieving mechanisms—one which was triggered at 4 Hz and mediated by endorphins and a second one which was obtained at 200 Hz and is probably due to serotonin. Clinically a frequency dependence of analgesia has also been observed. CHENG and POMERANZ (1979) therefore suggest that pain relief for certain diseases can be accomplished only by triggering a particular pain-relieving mechanism. This may be achieved by varying the frequencies of stimulation during electroacupuncture or transcutaneous electrical nerve stimulation (TENS).

The duration of effects of electrical stimulation may be roughly divided into three time domains: short-term effects, lasting up to minutes, longer-term effects with a duration up to hours (BURKE, 1977) and long-term effects which last for days or weeks (PETTE, 1983). It seems that the duration of the effect is proportional to the stimulation times. Our stimulation regimen of 20 min per day would then suggest that only short- and longer-term effects could be expected. The time course of the response after stimulation might take various forms starting with a decrease (post-tetanic depression and a later increase (post-tetanic potentiation) (ROSENTHAL, 1969). Our clinical observations where no or even adverse effect immediately after stimulation was found but improvement of spasticity occurred several hours later, might thus be comparable to the above study which attributed these variations to different amounts of calcium ions available for synaptic transmission.

A general pharmacokinetic model which attempts to ellucidate the observed phenomena was proposed by VODOVNIK *et al.* (1984*c*). The observation that electrical stimulation usually decreases spasticity and very seldom has adverse effects was discussed using the 'balance hypothesis' between excitation and inhibition in the neuromuscular system (VODOVNIK, 1981). To explain failures in therapy it was suggested that stimulation might not reach inhibitory synapses due to destruction of neurons caused by the lesion. Another reason might be the fact that pathological neural connections which were established during the development of spasticity prevented action potentials generated by stimulation from reaching the appropriate synapses (GOTTLIEB *et al.*, 1982).

5 Conclusion

Owing to the extremely individual manifestations of spasticity there seems to be no optimum stimulation parameter combination valid for a number of patients over a longer period of time. It is therefore quite possible that the 'best' parameters should be adjusted individually for each patient. Since especially in the first months after injury spasticity changes its symptoms within weeks, an optimum of stimulation parameters might be time dependent. Among the tested parameters the combination 100 Hz/100 μs was more effective than other combinations.

One complex or several simpler mechanisms must exist to account for the varied dynamics of the observed phenomena. The nature of the mechanisms must be neurochemical, since changes are observed in time scales ranging from minutes to hours. The sites where the supposed mechanisms are active are probably synapses of the motoneurone of the spastic muscle, its antagonistic or of interneurons in the spinal cord.

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