FUNCTIONAL ELECTRICAL STIMULATION OF DENERVATED MUSCLES

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Summary

The goal of the preliminary experiments on the denervated muscle was to obtain a minimum functional movement by means of electrical excitation on denervated muscle. Surface electrodes were applied and a voltage source of the stimulating pulses was used. The results reported here present a comparative study of the skin response, torque and angle of the ankle joint to four different waveforms: simple monophasic, simple biphasic, chopped monophasic and chopped biphasic. The measurements were performed on 6 normal subjects and 4 subjects with complete denervation of the muscle tibialis anterior. The redness of skin was estimated visualy in three levels. The results of the investigations showed that the redness is minimal with chopped biphasic waveforms.
Isometric torque of ankle joint has been the largest with the chopped biphasic waveform on normal innervated muscle but has been the largest with simple biphasic waveform on the complete denervated muscle.

Introduction

Electrical stimulation of the nervous tissue has found clinical use in a wide variety of orthotic and therapeutic applications in patients with central nervous system injuries. It is generally beliaved that the denervated muscle may be directly excited by a special range of electrical waveforms, all of which elicit a non tetanic physiological response. Typical parameters are: pulse duration of a few tens miliseconds and frequency from 0,5 to 1 Hz and of relatively strong currents (=20-40 mA). The reaction of the skin under a surface electrode, however, shows a marked dependance on the parameters of the stimulating waveforms /1-10/. Contradictions to be related to electrically induced tissue and skin damage are observable in the references.

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The major goals of our investigations are:

- Detailed study the phenomena which arise from electrostimulation of the denervated muscle,
- Development of clinical useful functional electrical stimulation (FES) method for patient with lower motor neurone lesions,
- Optimization of electrotherapy for patient with denervated muscles,
- New knowledge about electrophysiology of denervated muscle,
- Minimization the various waveform parameters which are related to electrically induced redness such as current and voltage levels, energy, power, injected electrical charge and timing parameters of electrical stimuli.

Basic experiment and methodology

The goal of first preliminary experiment on denervated muscle was obtained a minimum functional movement by means of electrical exitation on denervated muscle. The patient is 5 months after spinal cord injury of lower motor neuron region, no spasticity and no voluntary movement of lower extremities was observed and no excitability on typical tetanic stimulation was obtained.

Experiment showed, that the functional movement is possible by stimulation with surface electrodes in the region of tibialis muscles group and in quadriceps with square wave form pulses of voltage 100 - 120 V, duration 50 - 80 ms and f = 7 - 10 Hz. The movements of ankle joint in the plantar flexion direction and of knee joint in the knee flexion direction were clearly observed.

After dismounting of electrodes (4 cm^2) there has been a slight redness erithema appeared on region which has been covered by electrodes during the stimulation. The erithema vanished after few hours.
The redness phenomena is the reason why this kind of stimulation parameters are unacceptable for chronic FES of denervated muscle.

This has led to efforts to minimize various waveform parameters which are related to electrically induced redness such as current electrical and voltage levels, energy, power, injucted charge and timing parameters.

Electrically induced redness may be of thermal or electrochemical origin. Electrochemical reactions products are directly related to the charge per unit area of electrode surface delivered by the stimulus /12/. Thermal reactions are related to the skin and tissue electrical properties and energy changes inside the skin /11/.
Minimization of injucted charge and of energy changes may be achieved by the use of short duration current pulses and smaller current and voltage levels /12/.

The purpose of the second experiment reported here was to investigate the response of the skin to four different waveforms: A - simple monophasic, B - simple biphasic, C - chopped monophasic and D - chopped biphasic. The waveforms of stimuli are shown in Figure 1.

The experiment was realized in five healthy subjects and in set of five patients with complete denervated muscle tibialis anterior.

Time and current parameters have been fixed. The current was 5 mA, pulse duration T_1 = 30 ms, pulse frequency f = 16,6 Hz and chopping frequency 500 Hz.

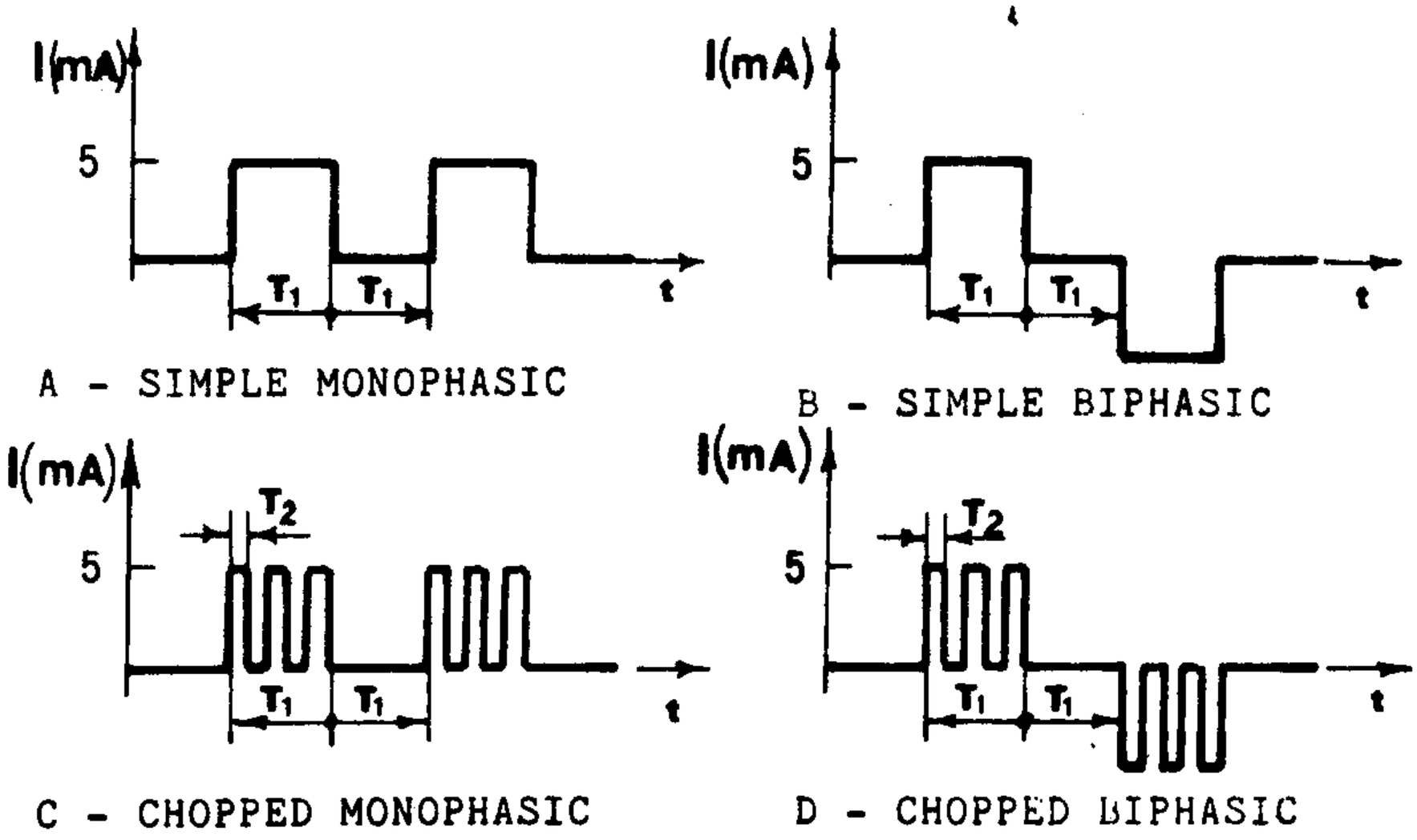

Figure 1. Waveforms of stimuli

The voltage level was regulated, adjusted and measured in correspondence to the fixed current I = 5 mA.

Also the temperature of the skin was detected with contact thermometer. The redness was visually estimated at three levels; 0,1 and 2 means no redness, slight redness and strong redness respectively. Six normal subjects were stimulated continuously for ten minutes with 4 x 4 cm large surface electrodes on the forearm region. The patients were stimulated continuously for five minutes with some electrodes on muscle tibialis anterior region.

By stimulation in the tibialis anterior muscle of normal and pathological subjects the isometric torque in dorsal flexion direction of ankle joint was measured.

Results - normal subjects

Table I shows the average and standard deviations (in parenthsis) of results were measured U_s - voltage of stimuli. The source of waveforms was practically ideal voltage source! Q_1 - electrical charge of stimuli train, E - estimation of arethema and T - maximal temperature difference during experiment. All parameters are measured for different waveforms A,B,C and D.

Waveform	A	B	C	D
U_s (V)	19,4 (2,9)	16,8 (8,9)	22,1 (4,6)	22,3 (5,5)
Q_1 (As)	3,2 (0,48)	2,9 (0,63)	5,8 (1,3)	5,8 (1,4)
E- Estimation	2 (0,25)	1,5 (0,68)	1,9 (1,10)	1,6 (0,49)
ΔT	1,5 (0,25)	1,5 (0,68)	1,9 (1,10)	1,6 (0,49)

Table I. Results of measurements on normal subjects.

Table II shows the results of measurement of isometric torque in ankle joint depending on waveforms for six normal subjects.

Maximal temperature differences depended on waveforms. $\Delta T = 1,5 - 1,9^{o}C$ were not significantly

From the measurement and visual observation we can conclude that the redness essentially diminished at chopped biphasic stimulation pulses (D). The isometric torque of ankle joint was approximately three times greater in chopped than in simple waveforms (C and D).

Subject No.	Current I (mA)	Isometric torque waveforms M (Nm)			
		A	B	C	D
1	4	5,5	4,5	6,0	6,5
2	4	2,0	1,3	6,0	6,5
3	4	2,5	1,0	3,8	5,0
4	4	0,5	0,3	2,0	2,3
5	10	5,5	4,5	6,0	7,0
6	12	1,5	1,0	5,0	6,0
Average		2,9	2,1	4,8	5,6
Standard deviation		1,9	1,7	1,5	1,6

Table II Dependance of isometric torque on waveforms A,B,C and D

Results - denervated muscles

An additional experiment was performed using the same waveforms stimulation in the denervated tibialis anterior muscle. The four patients with complete peripheral lesion of peroneal nerve were treated. The neurological and muscular status was found out objectively with I/T curve, and EMG measurements and the muscle test. The patients have no voluntary movements of ankle joint in the dorsal flexion. Because the patients' skin is more sensitive, the time of stimulation was five minutes. The isometric torque was measured with greater current 25 - 40 mA. The results of mea-

surement are collected in the tables III and IV.

Waveforms	A	B	C	D
U_s (V)	20,0 (1,40)	20,3 (2,2)	22,1 (1,6)	24,3 (2,8)
Q_1 (As)	3,3 (0,31)	3,3 (0,40)	5,9 (1,4)	6,2 (3,1)
Estimation E	0,94 (0,46)	0,40(0,33)	0,33(0,34	0,43(0,67)
ΔT (^{o}C)	1,2 (1,19)	0,90(0,61)	1,0 (0,79)	0,86(0,64)

Table III. Results of measurements on denervated muscles.

Subject No.	Current (mA)	Isometric torque M (Nm) (Waveforms)			
		A	B	C	D
1	30	0,8	0,9	0,4	0,4
2	38	1,4	2,1	1,5	1,4
3	25	0,6	1,1	0,6	0,3
4	40	1,5	2,6	0,6	0,5

Table IV. Isometric torque in dependance on waveforms of stimuli

The estimation of redness is minimal in average between 0,3 and 0,9. The diferences of temperature between 0,9 and 1,2^{o}C, are minimal by stimulation with the chopped biphasic waveform (D). Isometric torques are minimal by waveform D and essentialy greater by simple biphasic waveform of the stimuli (B).

The functionality of movement was measured with electrogoniometer. The angle of ankle joint $\varphi(^{o})$ was measured in dependance of the stimulation current I (mA). Results are collected in table V. The voltages V (V) of the stimulation pulses were also detected.

Waveforms	I (mA)	5	10	15	20	25
A	U (V)	22	32	36	42	42
	φ (°)	0	5	10	14	15
B	U (V)	20	30	34	36	40
	φ (°)	0	7	9	16	28
C	U (V)	22	33	40	43	44
	φ (°)	0	2	3	4	5
D	U (V)	24	34	38	39	44
	φ (°)	0	3	6	6	4

Table V. The dependance of ankle joint angle φ(°) and voltage U(V) of stimulation from current I (mA).

Conclusions

The investigation of problems of electrical stimulation for patients with lower motor neurone lesions shows some possibilities of optimization of electrotherapy and definy the FES to these patients. The redness and the movements are related to the waveforms of stimulation pulses. The stimulation response was better at simple monophasic and simple biphasic waveforms. The redness was essentially diminished at chopped biphasic stimulation pulses. There is also possibility that the generator of source stimulation pulses is current. Investigations in this direction are running at present.

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