FES of lower extremities: 
Comparison of rehabilitation strategies and stimulation equipment in patients with upper / lower motor neuron lesion

Bijak M¹, Mödlin M², Hofer C², Rakos M³, Kern H², Mayr W¹

¹ Center for Biomedical Engineering and Physics, Medical University of Vienna, Austria
² Department of Physical Medicine and Rehabilitation, Wilhelminenspital, Vienna, Austria
³ Otto Bock Healthcare Products GmbH, Vienna, Austria

manfred.bijak@meduniwien.ac.at

Abstract

Functional Electrical Stimulation (FES) of lower extremities in patients suffering from paraplegia can be used to restore standing up from the wheelchair, standing, walking / stepping and sitting down. Usually only patients with an intact lower motor neuron (spastic paraplegia) can benefit while patients with flaccid paralysis are excluded due to the inexistent or very weak force response to electrical stimulation.

The European Union (EU) supported project “Rise” investigated FES to recover long term denervated degenerated muscles (DDM). It turned out that this patient group can achieve similar goals like spastic paraplegics but require a longer rehabilitation course and stimulation parameters beyond the current EU regulations.

1. INTRODUCTION

Since Kantrowitz [5] demonstrated in the early sixties standing of paraplegic subjects by quadriceps stimulation various groups and researches worked on rehabilitation strategies and technical equipment to restore lower limb function. Stimulation either with surface electrodes or implantable devices is state of the art. Quadriceps muscles are stimulated for knee extension, gluteus muscles for hip stability and peroneal reflex is used for flexion functions. Other muscle groups are added according to the requirements and the technical possibilities like the available number of independent stimulation channels.

Practically all established clinical FES applications are based on direct excitation of neural structures and in case of muscle functions indirect activation of the muscles. So patients who wanted to benefit from a FES program for lower extremities had to have an intact lower motor neuron.

Individuals with conus cauda lesion have denervated lower limb muscles and suffer from severe muscle atrophy. After some years the major part of the muscle tissue is replaced by fat and connective tissue. The trophic situation of the paralyzed limbs worsens rapidly causing problems like decubital ulcers, dysfunction of wound healing and osteoporosis. Although early denervation has been widely studied the long term effects received much less attention since the general believe is that all myofibers disappear within several month of denervation. Thus FES was not seen as a proper tool for recovering and strengthening of long term denervated degenerated muscles (DDM).

For patients with intact lower motor neuron a clinical trial is ongoing in Vienna to find a rehabilitation strategy to achieve standing up and walking by means of FES in a short time.

The European Union (EU) Commission Shared Cost Project RISE, with 9 project partners, 3 additional partners and 6 subcontractors all from 6 countries started in November 2001 and is established to create a systematic body of basic scientific knowledge about the restorative effects of electrical stimulation DDM and related topics.

In the following the differences in the treatment of these two patient groups will be summarised.

2. METHODS

Up to now 20 patients with upper motor neuron lesion participated in the FES walking project.

For this group of patients an eight channel stimulator mainly intended for stimulation of lower extremities was developed [1] (Fig. 1). If after a twelve weeks lasting FES trainings program with increasing intensity for muscle strengthening [3] the knee torque was above 30Nm a stand up, sit down and balancing
training was implemented in a 6 days per week trainings regime.

After 4-8 weeks FES supported walking was practiced. First in a parallel bar frame with wheels and then with a walker. Stimulation parameters are biphasic rectangular pulses with duration of 1ms up to 2ms and a frequency of 27 Hz. The voltage was adjusted to achieve strong contractions; over stimulation was avoided to reduce fatigue. Stimulation timing was optimised for comfortable and smooth stepping in close cooperation between therapists and patient [2].

For reactivation of DDM pilot studies showed that the technical requirements are completely different. Very long impulses and high currents beyond the allowed limits had to be used. A special allowance has been given to stimulate the twenty seven subjects participating in the RISE project with long impulses and high currents.

Since appropriate stimulators are not available on the market a custom device has been build [4]. In comparison to standard FES devices the stimulator for DDM requires stronger batteries and a more powerful output stage, resulting in a bigger device (Fig. 1).

3. RESULTS

All patients with upper motor neuron lesion could perform standing up and do at least a few steps within 6 month if the described trainings regime was obeyed. The required stimulation amplitude was in the range of ±30V to ±60V.

In comparison patients from the RISE project required impulse durations between 10 and 150 ms and after severe degeneration up to 200ms. Consequently also the amplitude values are significantly higher than in nerve stimulation and require up to ±100V (±200mA) resulting in an energy of 4J per pulse delivered to the tissue. Since those energies are potentially dangerous for the skin special care had to be taken to avoid burns. Initially large conductive silicone rubber electrodes were applied to the skin via a wet sponge cloth and later, when the skin had adapted to the high currents via gel. The flexible electrodes had to fit closely to uneven skin surface to provide homogenous distribution of the electric field.

A four phase rehabilitation program was worked out: Training started in the first phase with single twitch stimulation using 150ms-200ms pulses at 2Hz. The progressively increasing muscle excitability permitted an increase in daily trainings duration. During the following 3 months pulse duration could be shortened to 80ms to 100ms (phase 2). After approximately a half year in phase 3 twitch stimulation was replaced with burst stimulation - 40ms pulses delivered at 20Hz. In the fourth phase (month 9-12) force trainings sessions where introduced with 70 to 80% of maximum force. Initially knee stretching was performed against gravity and later with increasing load around the ankles of up to 5kg. The progressive FES training increased mass and force of thigh muscles (Fig. 1) that allowed FES supported standing up and standing [8].
A comparison between the two groups of patients is summarized in Table 1.

### Table 1: Comparison of some stimulation issues for lower extremities for patients with upper and lower motor neuron lesion

<table>
<thead>
<tr>
<th></th>
<th>Patients with Upper motor neuron lesion</th>
<th>Patients with Lower motor neuron lesion</th>
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</thead>
<tbody>
<tr>
<td>Training before standing up</td>
<td>3 month</td>
<td>&gt;1 year</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>1.2ms</td>
<td>10ms … 150ms</td>
</tr>
<tr>
<td>Stimulation frequency</td>
<td>25Hz … 70Hz</td>
<td>1Hz … 20Hz</td>
</tr>
<tr>
<td>Stimulation intensity</td>
<td>Up to ±60V</td>
<td>Up to ±100V (±200mA)</td>
</tr>
<tr>
<td>Energy per pulse</td>
<td>Up to 14mJ</td>
<td>Up to 4J</td>
</tr>
<tr>
<td>Electrodes</td>
<td>Hydrogel Electrodes</td>
<td>Silicone rubber with wet sponge/ gel</td>
</tr>
<tr>
<td>Risk of skin burn</td>
<td>Very low</td>
<td>High</td>
</tr>
<tr>
<td>Flexion reflex</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

### 4. DISCUSSION AND CONCLUSIONS

Subjects with upper motor neuron lesion could reach FES supported standing up and walking/stepping within 6 month. Further FES training improves walking distance, maintains muscle mass and skin trophic and improves general health. Stimulation parameters are within usual FES ranges.

In the scope of RISE project it could be demonstrated that patients with conus cauda lesion syndrome even with long term DDM can also benefit from FES training. [6; 7] describe more details of the observed muscle regeneration.

Due to the absence of the neuromuscular junction and decomposition of motor units muscular contractions can only be elicited by depolarizing the cellular membrane of each single muscle fiber. The electrical membrane sensitivity strongly depends on the state of degeneration or recovery of the muscle cell, but in any case it is much lower than the sensitivity of a nerve cell. To achieve muscle fiber activation much longer stimulation impulses and higher current as in patients with intact lower motor neuron are required. The recent EU regulations allow not more than 0.3J of energy per pulse delivered to the tissue but up to 4J are required for DDM.

To bring the benefits of FES for patients with lower motor neuron lesion to clinical practise appropriate certified stimulators have to be commercially available. But therefore the regulations regarding the output energy per pulse have to be revised. A related proposal, supported by the outcome of the RISE project is in preparation and will be sent to the EU bodies.

### References


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