Application of Functional Electrical Stimulation (FES) for Training in Long-Term Space Flights

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Introduction

Long-term flights in microgravity cause atrophy and morphological changes of skeletal muscles. Extensive daily physical training using mechanical devices raises the caloric intake, shortens the operational activities and requires extreme motivation of the crew members. The limitation for an active muscle training during a long-term space mission in terms of time and space needs the consideration of an automatic support. Functional Electrical Stimulation (FES) is well established in terrestrial rehabilitation and sport training since years. It has a high potential to serve as an efficient counter-measure that avoids most of the cited impairments, as long as the equipment is comfortable and easy to handle under space conditions.

To investigate the effectiveness and practicability of FES as a countermeasure mean, a co-operation with IBPM in Moscow was established and led to the recent first two successful applications on board of MIR space station

Methods

Principle of training: FES is applied to 4 muscle groups of both lower extremities. Electrodes are placed on the skin above the quadriceps femoris muscles, the hamstrings, the tibialis anterior- and peroneal muscles, and the triceps surae muscles. Synchronous stimulation of antagonistic muscle groups prevents from unwanted joint movements.

The training is performed during 6 hours per day with 1 sec "on" and 2 sec "off" trains at intensity levels of 20 - 30% of maximum tetanic force (MTF). Besides this extensive training mode an additional intensive training mode with a limited number of high intensity tetanic contractions is implemented.

Equipment and parameters: The technical equipment consists of electrode trousers carrying EMG and stimulation electrodes for the eight channels, and two interconnected 4-channel stimulators carried on a belt. After donning the system a programming routine checks the electrode impedance and detects all threshold and saturation levels by amplitude variation of single stimulation impulses and recording of the evoked EMG reaction (M-wave). This procedure makes use of the correlation between M-wave amplitude and muscle tension and allows to determine the intensity levels for extensive (20-30 % MTF) as well as intensive training (100 % MTF) automatically for all 8 channels. After this initialization the system begins with automatic training with a default stimulation frequency of 25 Hz in extensive and 50 Hz in intensive mode. Electrode impedance and M-wave are monitored permanently to identify potential electrode problems or early signs of muscle fatigue.

Evaluation: Evaluation is done in accordance with the standard protocol of the Moscow IBMP, which is routinely used to investigate the effectiveness of various countermeasure means. The protocol contains physiological as well as morphological preflight and postflight examinations, and ergometric tests during flight. In addition the stimulation device records and stores stimulation intensity, M-wave and impedance data.

Results

The work of the Vienna research team was focused on technical and technological research and development. A practical solution was found for the electrode trousers (Fig.1). Placement of the electrodes to the skin is simplified by a patented construction of two flexible flaps, carrying the electrodes and corresponding protection foils, that are alternatively exposed to the skin. The developed stimulation equipment consists of the circuitry for M-wave and impedance-recording, the stimulation output stage, micro-controllers for impulse generation and measurement purposes (one for each channel), a coordinating micro-controller, the power supply, the graphical display, control elements and a bus-interface. The 8-channel stimulator is divided into two 4-channel modules interconnected by an I²C-bus (Fig.2). All stimulation and training parameters can be set by a personal computer (PC) via an RS232 link. The training protocol is transferred weekly to the PC via the RS232 link and stored in a database.
The equipment was successfully applied by two cosmonauts between Dec. 98 and Feb. 99 and between March and August 99 respectively. Both cosmonauts went to MIR station in August 98 and used the equipment in a later phase of their flight and then continuously till their landing. Up to now only data of the first of the two applications are available.

During this first pilot application MYOSTIM was used for 3 hours per day at intensity levels of 20-30 % MTF additionally to the routine physical training program. 4 control cosmonauts from different missions with similar flight duration performed only the routine on-board countermeasure training and no FES. The compliance of training in volume and intensity was between 80 and 100 %.

The Russian documentation, which was sent to us recently, showed promising results of the first MYOSTIM application during a long-term space flight. It has provided us with data of both handling of the equipment in microgravity and effectiveness of FES muscle training in space. However, we have only pilot results and further systematic investigations are absolutely required.

In comparison to the control cosmonauts of crew 26 and crew 27, who used only the routine countermeasure physical exercise program, the commander of crew 26, who used in addition MYOSTIM, was in much better condition during flight and after landing. This was the significant outcome of the ergometric locomotion tests performed pre- and post-flight and during flight, where he showed, in comparison to his colleagues, much lower heart rate and lactate levels in all phases.

Muscle contraction dynamics, investigated with tendometry and dynamometry, showed clearly better values in post-flight investigations. The histo-morphological investigations did show a similar reduction of fiber cross sectional area (CSA), when compared with the control results, but the typical atrophy-related increase of interfascicular connective tissue did not appear in the FES trained muscle. In contrary a decrease from 11% to 6% was observed. Cytochrome-C-oxidase indicated a substantial increase of aerobic metabolism of both type 1 (+152%) and type 2 fibers (+131%), an effect that was emphasized by an increase of capillary density by +174.5 %.

The positive influence of additional FES training was further confirmed in the posture stability tests and in reflex tests, that showed significantly better results and a much earlier recovery.

The subjective judgement of both cosmonauts was extremely positive: There were no complains concerning daily handling of the equipment over month and practicability of the training during work, except seldom extremely fine-motorial tasks, when they had to switch of the stimulation temporarily. The reported improved fitness and wellbeing, the feeling of "complete muscle integrity" and the lack of previously experienced muscle pain.

**Figure 1**: Principle of electrode and cable integration (left) and application in 0-gravity (wright).
Discussion

Morphologically microgravity causes a loss of muscle mass and a reduction of type I muscle fibers, which are responsible for muscle tone and posture above all. It is common knowledge that extensive FES training tends to transform type II to type I fibers, an effect that seems to be useful to compensate the type I fiber loss in microgravity. The level of 20 to 30% of MTF was chosen to achieve substantial training at minimal sensible inconvenience. The first test under space conditions showed, that this isometric low level training is comfortable and does not interfere with daily operational activities.

An exact simulation of terrestrial muscular activity cannot be expected from stimulation via surface electrodes. Distribution of fiber types in an FES trained muscle will always differ from a normal muscle. This effect is known to be totally reversible within several weeks after end of stimulation training under normal muscular activity, i.e. under terrestrial conditions.

The results of the functional tests, the faster functional recovery and the subjective judgement of the cosmonaut, who had already experienced a long-term flight without FES training previously, lead to the assumption, that - besides pure muscle preservation - a major benefit of daily extensive low level FES training lies in the stimulation of the proprioceptive system and induction of afferent activity.

The first applications in space have provided us with data of both handling of the equipment in microgravity and effectiveness of FES muscle training in space. However, we have only pilot results, that call for further systematic investigations. Provided that the technique further proves to be effective, the application should be extended to the trunk and neck muscles to preserve posture of the cosmonauts.

Profit for terrestrial applications in medicine can be expected, as long-term immobilization causes morphological changes in skeletal muscles, similar to those in microgravity.

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