Mapping functional electrical stimulation in denervated thigh muscles of paraplegic patients with T2 parameter imaging

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Introduction

Functional electrical stimulation (FES) for paraplegic patients has long been subject of research with the long-term goal of restoring lost muscle functions. It has several additional positive therapeutic effects and can further be seen as a sports activity [1]. In contrast to healthy muscle, where all regions supplied by an excited nerve are activated, fibers of denervated muscles need to be activated directly by the external electrical field, which is generated via two large surface electrodes. The activation pattern follows the geometric distribution of the electrical field which can be modeled in simulations showing where activation would occur at locations of fiber endings as well as along the length of a fiber [2]. Experimental validation of these results, however, has not yet been established. T_2 parameter MRI can be used to study the short-term effects of muscle stimulation and their spatial distribution.

Materials and Methods

Subjects: 9 paraplegic patients with flaccid paraplegia and denervation of the leg muscles were studied. The patients, who had participated in an FES program for several years, were scanned before and after performing their individual regular FES training, consisting of leg extensions, sitting outside the magnet. For comparison, three healthy subjects, performing a similar FES exercise, were scanned. Patients were divided into two groups, based on their response to functional electrical stimulation. The electrodes were placed on the anterior side of the right thigh. Functional electrical stimulation was carried out with biphasic rectangular impulses and a maximum intensity of 160 V_{pp} for the patients and 40 V_{pp} for healthy subjects.

NMR protocol: T_2 parameter images were calculated from transversal multi-slice multi-echo (MSME) images using a 3 T Bruker whole body scanner with a quadrature receive/transmit birdcage RF coil. Six spin echoes (CPMG scheme) were acquired at 25 - 150 ms, in steps of 25 ms. T_2 parameter images were calculated by fitting mono exponential curves to the even echoes, to reduce effects of RF pulse imperfections across the slice cross section and profile. Post exercise images were acquired ~6.1 min after the last FES pulse.

Data processing: Data acquired before and after exercise were realigned and normalized using minc tools, to enable processing of data on a per-pixel basis. Calculation of T_2 parameter images was done with ImageJ, performing a nonlinear least squares fit of a mono exponential T_2 dephasing curve, employing a simplex algorithm. Activation images were calculated pixel-by-pixel as relative T_2 increase [3] by subtraction of pre exercise T_2 maps from post exercise data, and dividing by pre exercise T_2s (i.e. $\Delta T_2/T_2$). Anatomically matched regions of interest were placed well within in the individual thigh muscles to evaluate activation and absolute T_2 pre and post exercise.

Results

Activation images ($\Delta T_2/T_2$) of thigh muscles of a paraplegic patient and a healthy control subject after FES are shown in Fig. 1. Generally, activation is more distributed in thigh muscles of paraplegic patients than in the healthy controls, where distinct muscles, mainly rectus femoris (RF), vastus medialis (VM) and vastus lateralis (VL), are activated (Fig. 1 d-f). Using T_2 increase as an index, muscles of well trained patients (group A) are activated to the same or even larger extent than healthy muscles, while activation remains lower in patient group B. Both patient groups, however, show activation in the posterior muscles (adductors, m. semimembranosus and biceps femoris), where healthy subjects do not show any T_2 increase. In patient group A, activation increases in slices between the electrodes compared to the position below the distal electrode in RF (24 vs. 15 %) and vastus intermedialis (15 vs. 11 %) and is activated equally in VL and VM. T_2 of reference test objects was very reproducible and varied only within 0.7 ± 3.2 % (mean ± SD) between pre- and post exercise scans.

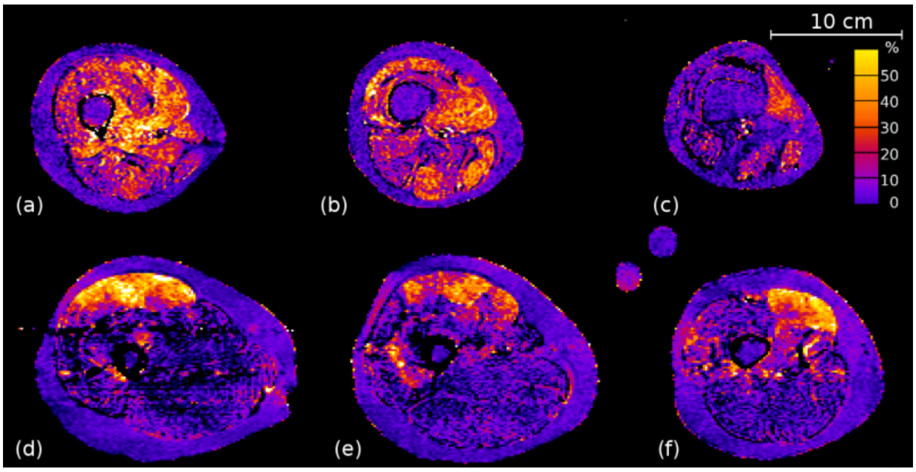

Fig. 1: Relative T_2 change ($\Delta T_2/T_2$) after functional electrical stimulation in three slices of a paraplegic patient (a-c) and a healthy control (d-f).

Discussion and Conclusion

Our results demonstrate that activation after FES of denervated muscles of patients with a conus cauda lesion can be mapped by T_2 parameter images acquired with a multi-slice multi-spin-echo MR sequence. The activated areas were roughly delineated by muscle boundaries and activation was relatively homogeneous across the muscle cross section, although the examined muscles of all paraplegic patients were denervated and thus are activated by direct stimulation of the muscle fibers, rather than by distributing activation via nerve branches across the muscle. The reason for this finding is likely to be the difference in electrical properties of muscles, fat between the muscles, and fasciae. As expected, activation was found predominantly in anterior muscles, but also its extension into posterior muscle groups is consistent with the long-term training effects of FES in denervated muscles [4]. In conclusion, our results show that electrically induced activation of muscle tissue of denervated paraplegic patients, who regularly perform FES, can be visualized by T_2 parameter imaging. T_2 changes after FES were found in denervated muscles as well as in healthy controls, with characteristic differences in distribution and intensity of activation, caused by the different techniques (i.e. electrode size, pulse lengths, -frequency and peak voltage) necessary for functional electrical stimulation of denervated and healthy muscles. The findings may be used to refine models of the electrical field of FES in muscle and fiber activation in the future.

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