Rapid and Simultaneous Measurements of T1, T2 and Relative Proton Density (M0) for Dynamic Musculoskeletal Studies

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Introduction: Skeletal muscle functional imaging can provide valuable information on the physiological changes accompanying muscle activation Because skeletal muscle physiological adaptations can simultaneously impact several NMR physical parameters (T_1, T_2, T_2*, relative spin density (M_0), etc), mono-parametric NMR imaging may not be able to describe adequately the complex behavior of stressed or exercised muscle. In the present work, we investigated the feasibility of fast simultaneous measurements of T_1, T_2 and M_0 using an Inversion Recovery TrueFISP (IR-TrueFISP) sequence [1]. The main advantage of this method is the possibility of performing dynamic T_1, T_2 and M_0 measurements in a single multi-parametric acquisition protocol, with relatively high temporal resolution. Additional advantages of the IR-TrueFISP approach studies are expected including low power deposition compared to standard spin echo techniques and low spatial distortion compared to rapid echo planar imaging (EPI). In the present work we illustrate the potential of this method for dynamic skeletal muscle application through an experiment showing multi parametric variations.

Theory: an analytical description of IR-TrueFISP is given In [1]. It has been theoretically and experimentally demonstrated that when equal and coherent RF pulses are periodically applied to the spin system after an inversion pulse, the steady state is built up exponentially with a time constant T_1* (T_1* ≤ T_1, T_2) dependent on T_1 and T_2: $S(t) = S_{stst}(1 - INV \cdot \exp(-t/T_1^*))$, where S_{stst} is the transverse magnetization during driven equilibrium (the steady-state signal) [2]. The parameter INV is related to the equilibrium magnetization M_0 through $INV = 1 + S_0/S_{stst}$ with $S_0 = M_0 \sin(\theta/2)$. By a three-parameter fitting of an experimental IR-TrueFISP data set, T_1, T_2 and M_0 can be simultaneously calculated using the following equations [1]: $T_1 = T_1^* \cdot (INV - 1) \cdot \cos(\theta/2)$, $T_2 = T_1^* \cdot (1 - \cos(\theta/2)/(INV-1))^{-1} \cdot \sin(\theta/2)$ and $M_0 = S_{stst} \cdot (INV-1)/\sin(\theta/2)$.

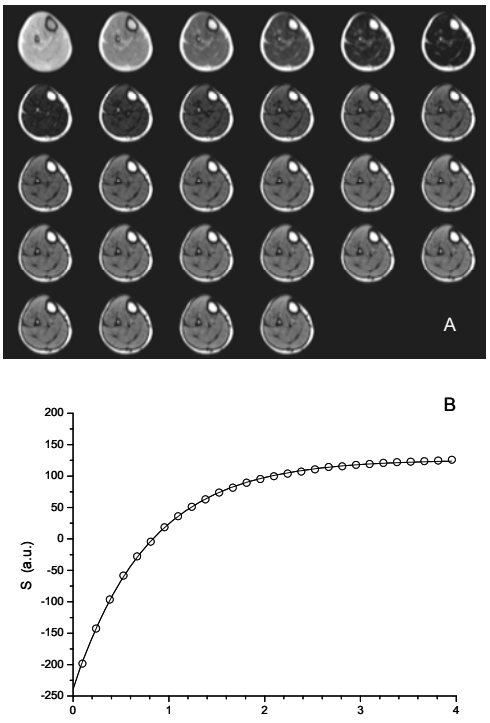

figure 1: (Up) (A) Typical image series obtained from an IR-TrueFISP experiment in human calf. The total acquisition time for this series was 4 s. ***(B)*** *IR-TrueFISP recovery signal obtained from a region of interest traced in the m. gastrocnemius medialis.*

Methods: (IR-TrueFISP sequence) Experimental data were acquired on a 3.0 T whole-body scanner (Siemens Tim Trio, Erlangen, Germany). TR was minimized to 3.4 ms to reduce off-resonance effects. Only one slice was selected on the broadest part of the right calf. Spatial resolution in the reading direction (2.5 mm) was imposed by the maximal available acquisition bandwidth (1560 Hz/pixel) and the minimum TR. Identical resolution was set up to the phase direction to assure a high sampling of the signal recovery (142.8 ms/image, 28 images/acquisition). Each image was comprised of 42 phase-encoding steps (Partial phase Fourier = 6/8) acquired in linear order encoding. Slice thickness = 8 mm. Acquisition time for a TrueFISP image was 142.8 ms. After adiabatic non-selective inversion and spoiling of the residual transverse magnetization, a train of 28 images was acquired. The total acquisition time during magnetization recovery to the driven equilibrium was 4 s. The rf flip angle (FA) θ was set to 20° (the "optimal" flip angle [2]) A slice selective prepulse of θ/2 was applied immediately after the inversion pulse to reduce the transient response during the transition to driven equilibrium. Spectral fat saturation was applied just before the θ/2 prepulse to reduce the off-resonance artifacts in the transient response. A delay of 8.5 s was introduced between the end of each acquisition block and the next inversion pulse to allow for complete relaxation of the longitudinal magnetization. In this study the body coil was used as transmit coil in order to improve B_1+ homogeneity. A B_1+ mapping using standard double angle method was carried out just before IR-TrueFISP experiments to correct FA error in derived IR-TrueFISP parameters estimation. Phased-array surface coils were used for signal reception.

(Protocol) IR-TrueFISP experiments were preliminarily carried out in 10 healthy volunteers to determinate the T_1 and T_2 values at rest. One untrained volunteer was asked to participate in an exercise protocol, which consisted of successive submaximal plantar flexions performed in the regular intervals (~ 4 s) during about 11 minutes in supine position. The subject was asked to perform this exercise until exhaustion. IR-TrueFISP acquisition was carried out at rest (5 min baseline), stopped during exercise and restarted immediately after exercise.

Results: Fig. 1a shows a typical example of the 28 acquired IR-TrueFISP images used for multi-parameter quantification in the calf muscle at rest. The total acquisition time for this series was 4 s. Fig. 1b shows the signal recovery to the driven equilibrium, obtained from a region of interest traced in the muscle gastrocnemius medialis. In homogeneous muscle regions, the signal courses were well characterized by the monoexponential three-parameter fit function. High determination coefficients (R^2 > 0.999) were obtained for all IR-TrueFISP signal recovery fitting in muscle regions. At rest, average muscle T_1 and T_2 values (1.36 ± 0.13 s and 47 ± 5 ms, respectively, mean ± standard deviation, N = 10 subjects) obtained from the IR-TrueFISP experiments, fit well into the range of literature values [3]. Our results for one subject indicate concomitant changes in T_1, T_2 and M_0 for tibialis anterior, peroneus and gastrocnemius lateralis and no significant paradigm-related changes for the muscles soleus and gastrocnemius medialis (fig. 2).

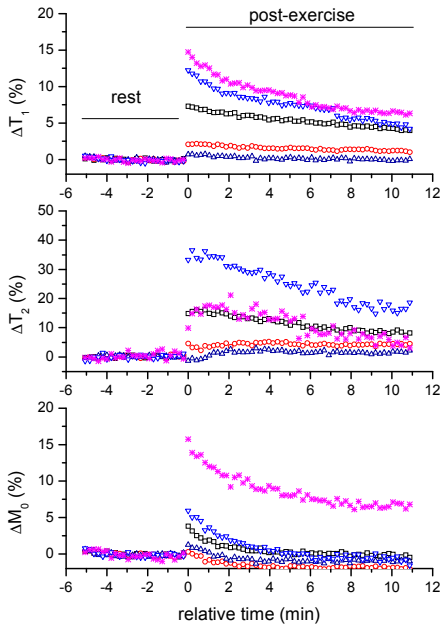

figure 2 *Individual time course of T_1, T_2 and M_0 changes following exercise. Multiparametric values were estimated for the m. soleus (diamond), gastrocnemius medialis (down triangle), gastrocnemius lateralis (up triangle), tibialis anterior (right triangle) and peroneus (left triangle).*

Discussion: IR-TrueFISP was sufficiently fast and sensitive to detect small and transitory T_1, T_2 and M_0 changes in the calf muscles resulting from exercise. Limitations for this method are the imprecise knowledge of FA and non-uniform excitation across the slice profile. In this work, post-processing was used to compensate for FA errors. Non-uniform excitation profile error was minimized using a FA close to the optimal flip angle [4]. Benefiting from an adequate time resolution for kinetic studies of exercising muscle, IR-TrueFISP could be interleaved with other NMR techniques (1H and 31P-NMRS, ASL imaging, BOLD-GRE imaging, etc) and generate additional relevant information in comprehensive muscle physiology protocols. **References**: [1] Schmitt et al, MRM 2004, [2] Kronenbitter and Schwenk, JMR 1977, [3] Stanisz et al, MRM 2005, [4] Coolen et al MRI 2009