T_1 corrected multipeak T_2*-IDEAL gradient-echo imaging for the quantification of intermuscular adipose tissue

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Introduction: Intermuscular adipose tissue (IMAT) has been recently associated with different metabolic abnormalities including obesity and insulin resistance [1]. The distribution and the total amount of IMAT have been traditionally assessed using T_1-weighted imaging [1]. However, quantification of IMAT based on T_1-weighted imaging is limited by partial volume effects and requires effective segmentation procedures [2]. IMAT fat fraction maps can be alternatively measured using chemical shift-based water-fat separation techniques [3]. IDEAL has been recently implemented to measure fat content in dystrophic skeletal muscle [4]. In order to get accurate fat content measurements with IDEAL, the spectral complexity of fat, T_2* decay and T_1 effects have to be considered. Multi-peak T_2* IDEAL based on 6 time-point measurements has been proposed to overcome the two first confounding factors [5]. Regarding the T_1 effect, the large T_1 difference (values at 3 T) between muscle (1500 ms) and fat (360 ms) can cause a significant overestimation of fat fraction [6, 7]. The use of small flip angle (SFA) has been proposed to minimize T_1 weighting [6, 7] and multiple flip angle (MFA) measurements have been used to correct for T_1 weighting [8, 9]. However, the SFA method is limited by low SNR and the MFA method suffers from prolonged scan times [6, 9]. In the present work, the use of a precalibrated T_1-corrected fat spectrum is proposed in order to correct for T_1 effects in dual flip angle (DFA) multi-peak T_2* IDEAL measurements of IMAT, considering accuracy and noise performance.

Materials and Methods: Model formulation: The multi-peak T_2* IDEAL signal model [5] is enhanced by using a precalibrated multi-peak fat spectrum that takes into account the T_1 weighting of the individual fat peaks. If $a_{p,cor}$ are the T_1-corrected relative amplitudes of the fat peaks, the enhanced signal model can be written as:

$$S(t)=\left[\rho_w\frac{(1-\exp(-TR/T_{1w}))\sin(\alpha)}{1-\exp(-TR/T_{1w})\cos(\alpha)}+\rho_f\left(\sum_{p=1}^{P}a_p\frac{(1-\exp(-TR/T_{1fp}))\sin(\alpha)}{1-\exp(-TR/T_{1fp})\cos(\alpha)}\right)\sum_{p=1}^{P}a_{p,cor}\exp(j2\pi\Delta f_p t)\right]\exp(j2\pi\psi t)\exp(-t/T_2^*)$$

$$\text{with } a_{p,cor}=\frac{\frac{a_p\sin(\alpha)(1-\exp(-TR/T_{1fp}))}{(1-\cos(\alpha)\exp(-TR/T_{1fp}))}}{\sum_{p=1}^{P}\frac{a_p\sin(\alpha)(1-\exp(-TR/T_{1fp}))}{(1-\cos(\alpha)\exp(-TR/T_{1fp}))}}$$

Single voxel spectroscopy with multiple TRs is used to measure a_p and T_{1p} as a calibration step. The double angle method based on low resolution spin-echo is used for transmit B_1 mapping in order to estimate the flip angle α. Multi-peak T_2* IDEAL is then performed for two flip angles using the T_1-corrected precalibrated spectrum. ρ_f is estimated in the least squares sense based on the two fat signal measurements. T_1 correction for the water signal is done by employing two flip angles to estimate T_{1w} and ρ_w.

MRI measurements: A water-fat phantom was constructed containing 8 vials with fat content between 2.5% and 20%, based on Intralipid 20% fat emulsion. A quadrature knee coil was used to scan the phantom and an eight-channel knee coil was used to scan the calf muscle of a healthy volunteer on a 3 T GE scanner. An investigational version of 6-point IDEAL in a 3D SPGR sequence was used with parameters: FOV= 18 cm, TR/TE/ΔTE=10/1.3/1.1 ms, flip angle= [2º 5º 20º], matrix size 180x180, 4 mm slice thickness. Single-voxel PRESS MRS data (1080 ms<TR<6000 ms, TE=28 ms) were collected in the phantom to measure T_{1fp}.

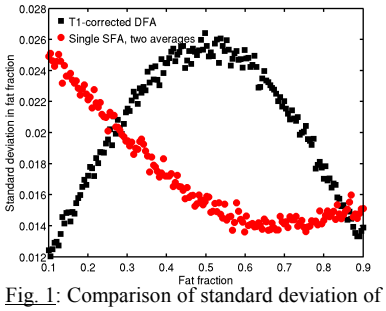

Fig. 1: Comparison of standard deviation of fat fraction between T_1-corrected DFA approach and single SFA approach with two averages.

Results and Discussion:

Noise performance: The noise performance of the T_1-corrected DFA approach (α=5º and 20º) is compared with the SFA approach (α=2º) with two averages (so that scan time is constant) using numerical simulations that take into account both the water-fat separation and the T_1-correction steps (1000 steps, T_{1w}=1500 ms, T_{1fp} and a_p as in the phantom). Imposing the constraint 1000 ms<T_{1w}<2000 ms, the mean standard deviation in the fat fraction is similar between the two techniques (Fig. 1a) and the mean SNR of the in phase signal (synthesized by water+fat) is higher with the dual flip-angle approach than with the single flip angle approach. The comparable fat fraction noise performance of the two techniques is due to the constraints imposed in T_{1w} and the precalibration of T_{1fp} that have not taken in consideration in [9]. Therefore, the DFA approach enables the noise efficient removal of T_1 bias in fat fraction (SFA approach shows a residual 2% bias at 50% fat fraction), in combination with high SNR for the in phase image.

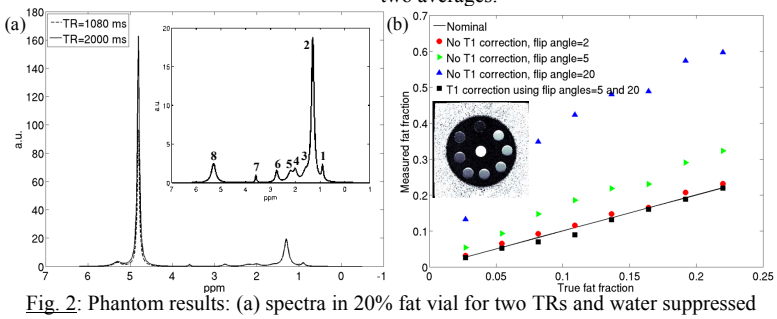

Fig. 2: Phantom results: (a) spectra in 20% fat vial for two TRs and water suppressed spectrum showing the multiple fat peaks, (b) fat fraction measurements with and without T_1 correction.

Phantom results: 7 fat resonances and 1 glycerol resonance (peak 7) are observed in the Intralipid spectrum (Fig. 2a). Based on the MRS measurements with variable TRs we measured T_{1f}=[537 2064 341 318 254 420 360 967] ms and the T_{1f} values did not vary with fat content in disagreement with [10]. The T_1-corrected DFA approach removes the T_1 bias in the fat content estimation and shows reasonable agreement with the SFA approach results. It was also noticed that the use of the same T_1 for the different fat peaks in the fat only region (at the center of the phantom) lead to an underestimation of the fat fraction by 2-3% relative to the use of different T_1s for the different fat peaks.

Fat fraction	ROI A	ROI B
α=2º	0.22	0.26
α=5º	0.27	0.33
α=20º	0.47	0.58
DFA	0.17	0.22

Table 1: *In vivo* fat fraction results for different flip angles in two ROIs.

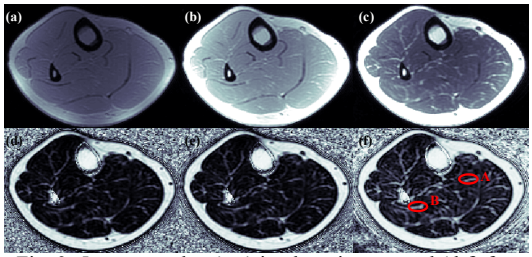

Fig. 3: *In vivo* results: (a-c) in phase images and (d-f) fat fraction maps for flip angles α=2º (a,d), 5º(b,e), 20º(c,f).

In vivo results: Fig. 3 shows the in phase images and the fat fraction maps from the mid calf slice (all with the same window level). SNR increases in both water and fat regions of the in phase image as the flip angle increases from 2º to 5º (Figs 3a, 3b), whereas the measured fat fraction is considerably increased as the flip angles increases (increase up to 100% with α=20º relative to α=2º, as shown in Table 1). The DFA approach reduces the fat fraction values with higher flip angles (T_1-weighted) to values close to the SFA approach values (proton density weighted) for two ROIs in the IMAT region (the precalibrated fat spectrum used for the *in vivo* data was the same as in [11]). More work would be required in order to validate the T_1-corrected IDEAL fat fraction measurements in the IMAT regions with single-voxel spectroscopy fat content measurements.

Conclusion: The use of a precalibrated T_1-corrected fat spectrum in dual flip angle multi-peak T_2* IDEAL enables noise efficient IMAT quantification without T_1 bias.

References: [1] Gallagher et al, AJCN 81: 903-910, 2005, [2] Boettcher et al, JMRI 29: 1340-1345, 2009, [3] Reeder et al, MRM 51: 35-45, 2004, [4] Wren et al, AJR 190: W8-W12, 2008, [5] Yu et al, MRM 60:1122-1134, 2008, [6] Liu et al, MRM 58: 354-364, 2007, [7] Bydder et al, MRI 26: 347-359, 2008, [8] Hu et al, JMRI 28: 1483-1491, 2008, [9] Wiens et al, ISMRM 2009, p. 4449, [10] Hu et al, MRM, in press, [11] Middleton et al, ISMRM 2009, p. 4331.