Chemical shift encoding-based water-fat imaging of skeletal muscle in the presence of fat resonance shift and phase errors

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Target audience: Basic scientists and clinicians working on water-fat separation in skeletal muscle

Purpose: Chemical shift encoding-based water-fat imaging has been emerging for quantifying skeletal muscle fat content with applications in the study of myopathies [1,2], metabolic disorders [3] and other musculoskeletal pathologies (e.g. back pain [4], rotator cuff tendon injuries [5]). Recent work has shown that susceptibility-induced fat resonance shift effects can confound skeletal muscle fat quantification, but the effect is small when a complex-based water-fat separation is employed [6]. However, complex-based techniques are sensitive to phase errors, which can confound fat quantification especially in regions with low fat content [7]. Magnitude-based techniques [8] are insensitive to phase errors and have been combined with complex-based techniques to overcome phase errors in regions with low fat fraction (FF) [7]. However, recent work has shown that magnitude-based techniques can become unstable for certain combinations of echo times, when the water-fat chemical shift separation is not exactly known due to temperature variations [9]. Similarly, magnitude-based techniques would be expected to induce significant FF bias when the water-fat chemical shift separation is not exactly known due to susceptibility-induced fat resonance shift effects. Therefore, the purpose of the present study was to characterize complex-based and magnitude-based methods for water-fat separation in skeletal muscle, where both fat resonance shift and phase errors can be present.

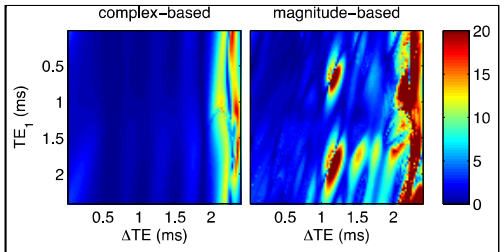

Fig. 1: Simulation results: FF bias as a function of TE_1 and ΔTE for complex-based and magnitude-based water-fat separation when x = 25 Hz at 3 T. Notice the high FF bias using the magnitude-based technique when using TE_1 = 1.8 ms and ΔTE = 1.1 ms.

Methods: Simulations: A water-fat signal model was adopted taking into consideration the presence of multiple fat peaks [8,10], a single T_2* decay [8,10] (T_2* of water and fat peaks = 25 ms) and the presence of susceptibility-induced fat resonance shift (labeled x) [6]. Synthetic data were generated for nominal FF varying between 0% and 100% in the presence of susceptibility shift (x = 25 Hz) at 3 T. Methods accounting for the presence of multiple fat peaks with x = 0, and employing a complex-based or magnitude-based water-fat separation were used to estimate the FF. The simulations were repeated for first echo time (TE_1) and echo spacing (ΔTE) values varying between 0 and 2.4 ms.

In vivo measurements: The right calf of a healthy volunteer was scanned with an 8-channel extremity coil on a 3 T Ingenia system (Philips, Best, Netherlands). A 3D time-interleaved multi-echo gradient-echo sequence acquiring six echoes with constant echo spacing in two interleaves (3 echoes per interleave) was performed with two different TE_1s: 1.80 ms and 1.45 ms; and the following common parameters: TR = 13 ms, ΔTE = 1.10 ms, FOV = 180 x 180 x 100 mm, voxel size = 1.3 x 2 x 2 mm, flip angle = 3°, bandwidth = 1223 Hz. Phase error correction estimated first phase errors using a preparation phase module before the actual sequence, acquiring the echoes without phase encoding once with the original and once with flipped readout gradient polarity. An additional phase offset was estimated based on down-sampled data, after correcting for the phase error from preparation phase data, using a formulation similar to [11] fitting for a constant phase offset for the second interleave. No noise bias correction was performed for the complex-based separation.

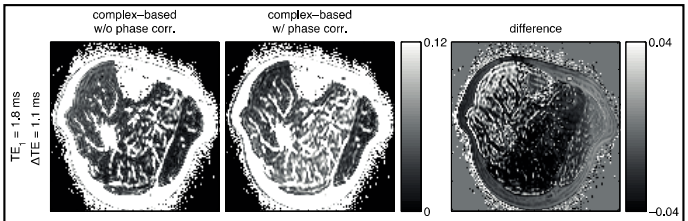

Fig. 2: *In vivo* FF maps using complex-based separation without and with phase correction. Notice the L/R variation on the difference FF map.

Results: Simulations: The complex-based method shows low FF bias at x= 25 Hz for ΔTEs up to 2 ms and TE_1s within the considered range. The magnitude-based method results in a FF bias of up to 20 % for certain ΔTE / TE1 combinations with ΔTE < 2 ms, e.g. TE_1 = 1.8 ms and ΔTE = 1.1 ms (Fig. 1).

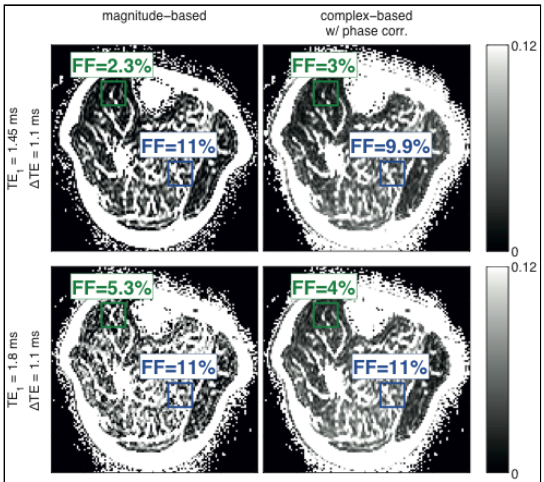

Fig. 3: *In vivo* FF maps using magnitude-based (first column) and complex-based separation with phase correction (second column) at TE_1 = 1.45 ms and ΔTE = 1.10 ms where magnitude-based separation is insensitive to x (first row) and at TE_1 = 1.8 ms and ΔTE = 1.10 ms where magnitude-based separation is sensitive to x (second row).

In vivo results: Fig. 2 shows that a systematic FF bias in the L/R direction (frequency encoding) in complex-based separation when the phase correction is not employed. Fig. 3 displays the magnitude-based and phase corrected complex-based FF maps in the first and second column, respectively, for the different TE_1s of 1.45 and 1.80 ms in the first and second row, respectively. Average FF of a ROI in soleus (blue) and tibialis anterior (green) are given in Fig. 3, while Fig. 4 shows the corresponding scatter plots for the magnitude-based FF vs. complex-based FF. Scatter points cluster close to the line of equality for TE_1 of 1.45 ms. For TE_1 = 1.8 ms, the magnitude-based estimated FF differs strongly from the complex-based FF.

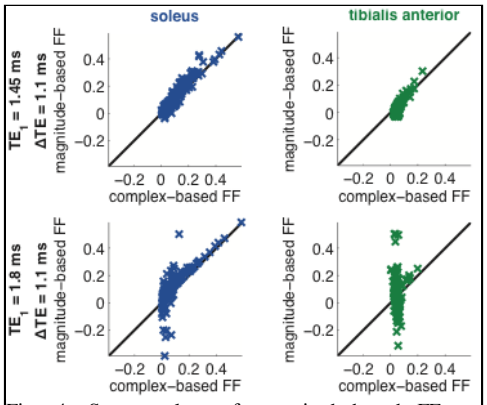

Fig. 4: Scatter plots of magnitude-based FF vs. complex-based FF for the soleus (blue) and tibialis anterior (green) ROIs shown in Fig. 3.

Discussion & Conclusion: The TE_1 / ΔTE dependent FF bias due to resonance shifts in magnitude-based separation could be measured *in vivo* as predicted by the simulations. The magnitude-based method is insensitive to phase errors but sensitive to x and can be unstable for certain combinations of TE_1 and ΔTE (Figs. 1 and 4). The complex-based method is sensitive to phase errors (Fig. 2) but insensitive to x (Fig. 3). The ROI results (Fig. 3) show a bias of the order of 3% for the magnitude-based separation in a healthy volunteer. However, the FF bias for the magnitude-based separation is expected to be much higher and therefore strongly clinically relevant in regions with high FF in severely fat infiltrated muscles. **In conclusion, skeletal muscle water-fat separation should use complex-based techniques combined with phase error correction techniques to be insensitive to both susceptibility shift and and phase error effects.**

References: [1] Wokke, J Magn Reson Imag 38:619, 2013, [2] Triplett, Magn Reson Med doi: 10.1002/mrm.24917, [3] Karampinos, J Magn Reson Imag 35:899, 2012, [4] Fischer, Radiology 266:555, 2013, [5] Nardo, J Magn Reson Imag 39:1178, 2014, [6] Karampinos, Magn Reson Med 68:1495, 2012, [7] Yu, Magn Reson Med 66:199, 2011, [8] Bydder, Magn Reson Imag 26:347, 2008, [9] Hernando, Magn Reson Med 72:464, 2014, [10] Yu, Magn Reson Med 60:1122, 2008, [11] Eggers, Proc ISMRM 2008, p. 1364.

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