Simultaneous Quantification of T1, T2, Fat Fraction and Off Resonance Frequency Using Phase Sweep SSFP

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Purpose: The goal of this study was to describe and validate a new approach for simultaneous quantification of water T_1 and T_2, fat fraction (FF) and off-resonance frequency using multiple balanced steady state free precession (bSSFP) images with incremented RF pulse phase (phase sweep SSFP).

Methods: The variation in SSFP signal yield as a function of the RF pulse phase increment is a well characterized phenomenon (**Fig. 1**) [1-2], referred to here as a phase sweep profile. The phase inversion of the SSFP signal in sequential "SSFP bands" (not shown here), in combination with the profile shift as a function of resonance frequency, gives rise to constructive and destructive interference between water and fat (**Fig 1**). Additionally, the shape of the phase sweep profile is a strong function of flip angle, T_1 and T_2. We propose that simulated basis sets of SSFP phase sweep profiles for water and fat, that incorporate exact pulse sequence parameters and spectral shapes of water and fat, can be used to quantify the FF, water T_1 and T_2 values, and off-resonance frequency from the measured phase sweep profiles. We further propose that saturation recovery preparation will improve sensitivity to T_1. A custom single-shot saturation recovery SSFP pulse sequence (Siemens, Sonata) with controllable phase increment was used for data acquisition. Bloch equation simulations (incorporating all pulse sequence parameters including slice profiles and spectral line-shapes) were used to generate water and fat phase sweep basis sets that span a wide range of off-resonance, T_1 and T_2 values. ***Acquisition Parameters:*** Single-shot SSFP, TE/TR = 1.37/2.74 ms, 192 readout points, flip = 60-70°, 360x270 mm FOV, 700 ms recovery time and non-saturation acquisitions with 5 seconds of recovery, 50 phase sweep offsets spanning 450 Hz. ***Phase Sweep Fitting:*** Water T_1 and T_2, off-resonance and FF were derived using a Nelder-Mead direct search algorithm to fit the acquired phase sweep profiles with the basis profile sets. ***Simulations:*** Monte Carlo simulations were used to evaluate the effects of signal to noise on the four fit parameters (SNR = 20:10:100), and input parameters of water T_1/T_2 = 1175/50 ms, FF = 10%. ***Phantoms***: 8 NiCl/agar phantoms with a wide range of T_1 (340-1130 ms) and T_2 (42-75 ms) values, and 6 phantoms with known lipid concentrations (0% to 18%) were used for validation studies. Spin-echo and spectroscopy experiments and were used for gold standard T_1, T_2 and FF, respectively. ***In-Vivo:*** Phase sweep SSFP data (identical acquisition parameters to simulations and phantom studies) was acquired in an axial calf muscle slice, with regional analysis.

Results: Monte Carlo results (500 repetitions) in **Fig. 2** show the bias and standard deviations for FF, T_1 and T_2 as a function of SNR. Spin echo and SSFP phase sweep values were in good agreement for T_1/T_2 phantoms, R^2 = 1.00 and 0.98, respectively. Similarly, spectroscopy and SSFP phase sweep values for FF were in good agreement, R^2 = 0.99. **Fig. 3** shows single pixel phase sweep profile fitting and best fit FF, T_1 and T_2 values from 75 pixel ROIs in tibialis anterior, gastroc and soleus muscle groups.

Conclusions: It is feasible to quantify water T_1 and T_2, off-resonance frequency and FF using a saturation-recovery prepared phase sweep SSFP method. The variability in each parameter is largely independent due to the features of the saturation-recovery phase sweep profile. Specifically, FF is determined by profile asymmetry, T_2 by profile depth (shape), T_1 by saturation recovery weighting, and off-resonance by a global profile shift. Single-pixel analysis is feasible with the evaluated parameters (2x2x8 mm^3), although accelerated imaging with fewer points remains to be evaluated. Multi-parameter fitting offers more comprehensive tissue characterization, and the phase sweep approach is relevant in tissues containing lipids but in which T_1 and T_2 of the water signal, relative fat content or off-resonance frequency are targeted.

References: [1] Carr HY. Phys. Rev. **112**: 1693–1701 (1958). [2] Miller KL. Magnetic Resonance in Medicine **63**: 385-395 (2010).

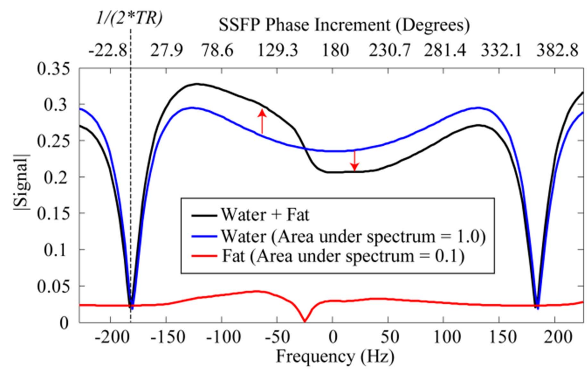

Figure 1: Sample SSFP phase sweep profile for water, fat (10% fat fraction) and their sum.

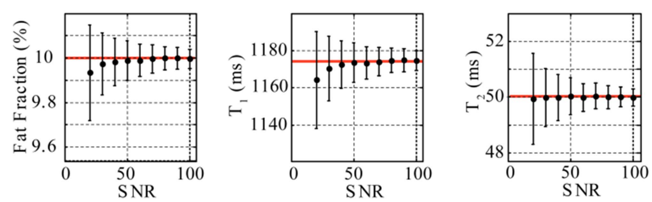

Figure 2 - Monte Carlo Simulations: mean+/-std values for best fit fat fraction and water T_1 and T_2 as a function of SNR (20:10:100) Red lines show the input (true) values.

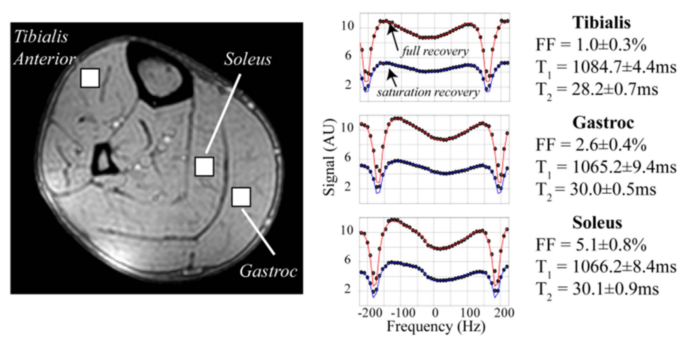

Figure 3 - InVivo Data: Sample best fit curves (solid lines) for single pixel phase sweep data (black points) from three muscle groups (tibilis anterior, gastroc, soleus), with mean±std for fat fraction (FF) ,T_1 and T_2, from 75 pixels in each muscle group.