Towards accurate temperature mapping in adipose and aqueous tissue with joint T1 and PRFS using Balanced SSFP

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Target Audience The target audience comprises Magnetic Resonance (MR) physicists and methodology developers interested in MR thermometry.

Purpose MR temperature mapping provides the possibility of real-time monitoring during thermal treatments such as RF hyperthermia or thermal ablation therapies. The temperature dependent proton resonance frequency shift (PRFS) has been established as the most commonly used quantification method in water-based tissue as it is independent of tissue type and it behaves linearly within the temperature range of interest. Nevertheless, the PRFS method is insensitive to temperature change in adipose tissue[1]. T1 quantification is one alternative method to measure temperature in fatty tissue. Accurate T1 measurement methods involve the sampling of the T1 relaxation curve, but have been hampered by long image acquisition time. A variable flip angle (VFA) method employing a spoiled gradient echo sequence (SPGR) has been proposed recently which allows simultaneous T1 and PRFS measurement within clinically acceptable scan time[2]. However, the accuracy of T1 quantification suffers from systematic variables like B1 inhomogeneity, especially at 3 Tesla. Balanced steady-state free-precession sequence (bSSFP) has been used for temperature-induced PRFS measurement via multi-echo acquisition[3], sampling of the magnitude off-resonance profile, and cross-correlation of frequency offset curves acquired at different temperatures[4]. We propose to directly use the linear phase profile to additionally evaluate the temperature dependent PRFS in water-based tissues, which is extracted from difference phase images acquired in the steady state. Fast T1 mapping methods using bSSFP have been developed for cardiac MRI[5-7], and its principles may find application in fast temperature mapping. Here, a potentially more accurate hybrid sequence using bSSFP is introduced which combines T1 mapping with phase-mapping based PRFS calculation for temperature quantification in both water and fat-based tissues. Sampling of T1 relaxation curve allows a more accurate T1 quantification compared to the VFA method. bSSFP is found to be superior to SPGR regarding T1 mapping accuracy[8]. Furthermore, bSSFP benefits intrinsically from a higher signal to noise ratio (SNR) value compared to the conventionally used inversion recovery (IR) prepared SPGR. Here, both IR and saturation recovery (SR) bSSFP are compared and the transient state of a bSSFP readout is used for sampling an image at a certain inversion or saturation delay time (TI or TS).

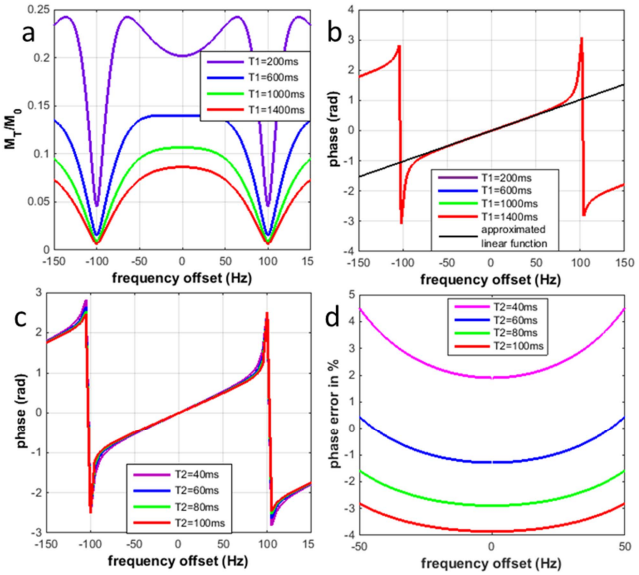

Fig. 1 Simulation results for bSSFP in steady state with TR = 5ms, TE =4ms and flip angle = 30°. a) Transverse magnetization simulated for T2 = 50ms and variable T1 values. b) Phase evolution simulated for T2 = 50ms and same variable T1 values as in a). c) Steady-state phase for T1 =300ms and variable T2 values. d) Phase errors due to temperature induced T2 variation when approximating phase evolution by a linear function (see Fig.1b)

Methods The feasibility of simultaneous PRFS quantification from a steady state image is examined with means of Bloch simulation. For the steady-state simulations shown in Fig. 1 a-d repetition time (TR) of 5ms and echo time (TE) of 4ms were chosen for adequate phase contrast. As both transverse relaxation time T2 as well as longitudinal relaxation time T1 are temperature dependent, the question arises if these parameters have an impact on the phase, truncating the PRFS estimation. Bloch equation simulations were performed to simulate the steady-state. T1 was varied in a range of 200ms to 1400ms when T2 was set on a constant value of 50ms (Fig. 1a and 1b) and T2 was varied in a range of 40ms to 100ms, while T1 was kept at 300ms (Fig. 1c and 1d). As a proof of principle for fast T1 quantification in adipose tissue, 2D T1 mapping based on MOLLI[6] and SMART1[7] is conducted in ex vivo porcine lard at a constant temperature. The measurements are conducted on a 3T GE system (GE Discovery MR750w 3.0T General Electric, Milwaukee, USA) with a flexible receive coil (GEM FlexCoil 16-M Array). Magnetization preparation was employed in combination with single-shot bSSFP readout. IR as well as SR bSSFP are investigated. In order to counter B1 inhomogeneity, an adiabatic radiofrequency (RF) pulse was applied for saturation as well as for inversion preparation. Imaging parameters: matrix size=256x256, isotropic pixel resolution 0.9375mm, flip angle=35°, TR=3.638ms, TE=1.116ms. TI for IR bSSFP were 210ms, 367ms, 525ms, 683ms, 840ms, 998ms, 1155ms, 2506ms, 2663ms and 4164ms. TS were 47ms, 281ms, 516ms, 751ms, 986ms, 2487ms, 3990ms. One additional image was acquired without saturation. Before the next saturation pulse was applied, spoiling was carried out to eliminate residual transverse magnetization. For T1 quantification, a three-parameter pixel-wise fitting to the model $Signal = A * (1 - B * \exp(-Tx/T1))$ with Tx either TI or TS, was carried out in MATLAB (The Mathworks, Inc., Natick, MA, R2013a) using a trust-region method.

Results Fig. 1a and 1b show the magnitude and phase off-resonance profiles with T2 fixed at 50ms and varying T1. The phase evolution is not affected by changes of T1 relaxation. All different T1 values result in the same phase off-resonance profile. In the pass-band area of -50Hz to 50Hz we can approximate the phase evolution with a linear function, characterized by a rise of 0.0102rad/Hz. By assuming the linear phase evolution, a phase deviation of 2.15% needs to be accepted at ±50Hz for a constant T2 of 50ms. Additional phase error due to variable T2 relaxation is shown in Fig. 1c and expressed in percent in Fig. 1d. At 3T a temperature difference of 1°C corresponds to a phase difference of 0.8° in the described setting. In comparison, a temperature difference of 1°C results in a phase shift of 2.1° for SPGR with TE=5ms. Initial experimental results for T1 mapping in adipose tissue at room temperature are shown in Fig. 3. T1 was found to be (mean±SD) 268ms±8 with IR bSSFP and 276ms±14 with the spoiled SR method in ex vivo porcine lard. In literature, 250ms was found for T2 in bovine adipose tissue at 0.5T[9]. No reliable T1 values could be identified in the areas of banding artifacts.

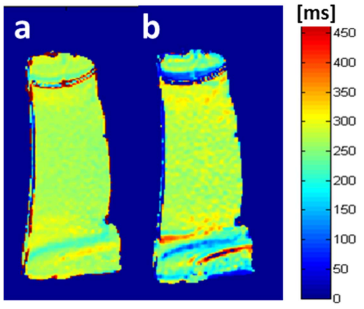

Fig. 3 Calculated T1 maps from a) IR bSSFP and b) SR bSSFP

Discussion & Conclusion It is assumed that temperature stays constant during the acquisition time for one T1 mapping sequence, which may take 10s-30s. In applications such as RF hyperthermia this is tolerable, especially at the period during which a constant temperature is maintained. Sequence-specific artifacts like banding can be avoided by a homogeneous B0-field, which could be achieved with efficient B0 shimming in the area of interest. Another possibility is to apply RF phase cycling and make another acquisition with the frequency band shifted by 1/(2*TR) and subsequently merge these images in a post-processing step. The presented work demonstrated the potential of combining fast and accurate T1 mapping for temperature quantification in fat employing fast IR and SR bSSFP and jointly using phase maps for PRFS based thermometry in water-based tissue.

References 1. Rieke V, et al. MR Thermometry. JMRI 27 (2008) 376. 2. Todd N, et al. Hybrid Proton Resonance Frequency/T1 Technique for Simultaneous Temperature Monitoring in Adipose and Aqueous Tissues. MRM 69 (2013) 62. 3. Scheffler K, et al. Fast Frequency Mapping With Balanced SSFP: Theory and Application to Proton-Resonance Frequency Shift Thermometry. MRM 51 (2004) 1205. 4. Palival V, et al. SSFP-Based MR Thermometry. MRM 52 (2004) 704. 5. Chow K, et al. Saturation Recovery Single-Shot Acquisition (SASHA) for Myocardial T1 Mapping. MRM 71 (2014) 2082. 6. Messroghli DR, et al. Modified Look-Locker Inversion Recovery (MOLLI) for High-Resolution T1 Mapping of the Heart. MRM 52 (2004) 141. 7. Slavin GS, et al. True T1 mapping with SMART1Map: a comparison with MOLLI JCMR 15 (2013). 8. Scheffler K, et al. T1 Quantification With Inversion Recovery TrueFISP. MRM 45 (2001) 720. 9. Ghandi S, et al. Temperature dependence of relaxation times in bovine adipose tissue. Proceedings 6th ISMRM (1998) 701.