FAT-REFERENCED MR THERMOMETRY USING 3-ECHO PHASE-BASED FAT WATER SEPARATION METHOD

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Introduction: Accurate and stable MR thermometry is critical for interventional procedures such as RF hyperthermia and MR guided focused ultrasound therapy. Fat-referenced techniques [1-5] can minimize thermal mapping errors caused by time-varying B_0 field changes. Methods described in [3-5] use IDEAL [6], a phase-based fat/water separation technique [7], to generate complex valued fat and water images from which temperature maps are made. This work elucidates the underpinnings of how these 3-echo fat-referenced MR thermometry techniques work. In doing so, we present a new fat-referenced approach that uses conventional phase-based separation techniques for the fat and water imaging. This method reduces computational complexity, when compared with IDEAL based fat-referenced thermometry methods.

Methods: We use a positive polarity 3-echo spoiled gradient echo (SPGR) imaging sequence (Fig. 1) to acquire images $\{S_{-1}, S_0, S_1\}$ with echo times $\{\tau_0-\Delta\tau, \tau_0, \tau_0+\Delta\tau\}$ respectively. The echo time increment, $\Delta\tau$, is defined by $\Delta\tau = \pi / \hat{\omega}_{fw}$ where $\hat{\omega}_{fw} = 2\pi \cdot (210/s)$ (at 1.5T) is the assumed chemical shift of fat referenced against water at 37ºC. Introducing a temperature dependent proton resonance frequency shift (PRFS) term, ω_T, into Glover's fat/water signal model [8], the signal intensity of a voxel (S_n) with echo time τ_n (where n = -1, 0, 1 to denote different TEs) can be modeled according to:

$$S_n = \left(\rho_w e^{i\omega_T \tau_n} + \rho_f e^{i\omega_{fw}\tau_n}\right) \cdot e^{i(\omega_0 \tau_n + \phi_0)} \qquad \textbf{(Eq. 1)}$$

where ρ_w is the water signal intensity in given voxel (real quantity), ρ_f is the fat signal intensity in given voxel (real quantity), ω_{fw} is the actual chemical shift of fat referenced against water at 37ºC, ω_0 is the magnetic resonance offset, and ϕ_0 is the phase offset that is independent of echo time. Quantities ω_T and ω_0 are time-varying, whereas ω_{fw} is not. Using techniques described in [6], the magnetic resonance offset term, ω_0, is measured when the imaged object is at a known reference temperature T_{ref}. This static measurement of ω_0 is denoted by $\hat{\omega}_0$. At each measurement time-point, images $\{S_{-1}, S_0, S_1\}$ are acquired and complex valued water (W) and fat (F) images are generated according to Eqs. 2 and 3:

$$W = (\hat{S}_{-1} + \hat{S}_1)/2 + \hat{S}_0 \qquad \textbf{(Eq. 2)} \qquad\qquad F = (\hat{S}_{-1} + \hat{S}_1)/2 - \hat{S}_0 \qquad \textbf{(Eq. 3)}$$

where $\hat{S}_n$ is defined by $\hat{S}_n = S_n e^{-i\hat{\omega}_0\tau_n}$. We choose the echo time of image S_0 to satisfy $\tau_0 = \pi(2k+1)/\hat{\omega}_{fw}$ where k is a positive integer. In general k can be any positive real number, but integer values of k allow Eqs. 2 and 3 to be written in a more revealing form. If time-varying changes in ω_0 are small and $\tau_0 >> \Delta\tau$, it can be shown that:

$$W \approx 2\rho_w e^{i[(\omega_T+\omega_d)\tau_o+\phi_o]} \qquad \textbf{(Eq. 4)} \qquad\qquad F \approx 2\rho_f e^{i[(\omega_d+\omega_f)\tau_o+\phi_o]} \qquad \textbf{(Eq. 5)}$$

where $\omega_d = \omega_0 - \hat{\omega}_0$ captures any time-varying phase disturbances, and $\omega_f = \omega_{fw} - \hat{\omega}_{fw}$ captures any discrepancy between the actual and assumed (210 Hz) frequency shift of fat relative to water at 37ºC. Since the quantity ω_f does not depend on time, the phase difference between two fat images ($\Delta\phi_f$) acquired at different time points provides a measure for the time-varying B_0 field changes where $\Delta\phi_f = \Delta\omega_d \tau_0$. Similarly the phase difference between two water images ($\Delta\phi_w$) acquired at the same two time points is shown as follows: $\Delta\phi_w = (\Delta\omega_T + \Delta\omega_d)\tau_0$. Using these equations, change in the temperature dependent frequency shift term ($\Delta\omega_T$) can be isolated and the phase-corrected temperature measurement is computed according to Eq. 6:

$$T = \frac{\Delta\phi_w - \Delta\phi_f}{\gamma\alpha B_0 \tau_0} + T_{ref} \qquad \textbf{(Eq. 6)}$$

where γ is the gyromagnetic ratio, α = -0.00909ppm/ºC [9] is the PRFS temperature coefficient, and B_0 is the field strength.

The thermometry method outlined by Eq. 6 was validated using a 1.5T GE scanner (GEHC, Waukesha, WI). A 1L bottle of cream (36% fat) was heated to 45.2ºC and allowed to cool to 36.8ºC. A fiber-optic temperature probe (Neoptix, Quebec, Canada) provided ground truth measurements. MRI with a standard head coil was performed as the sample cooled. For each of 18 measurements, three SPGR images at echo times τ = {14.3ms, 16.7ms, 19.1ms} were acquired using the following scan parameters: TR=26ms, flip angle=15°, FOV=30cm, matrix 128x128, axial slice 10mm, BW 125kHz. All three echoes were acquired in one excitation per line of k-space (~3.3 seconds/image). The resonance offset map $\hat{\omega}_0$ was acquired when the cream sample was at 45.2ºC. Temperature measurements were computed using Eq. 6 with T_{ref} = 45.2ºC.

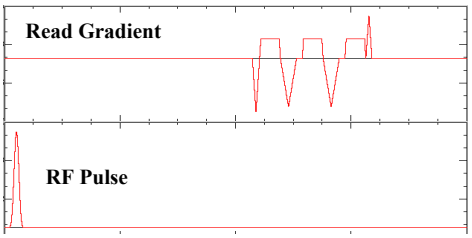

Fig 1. Sequence diagram showing read gradient and RF pulse of multi-echo SPGR acquisition. Three echos are acquired in a single excitation.

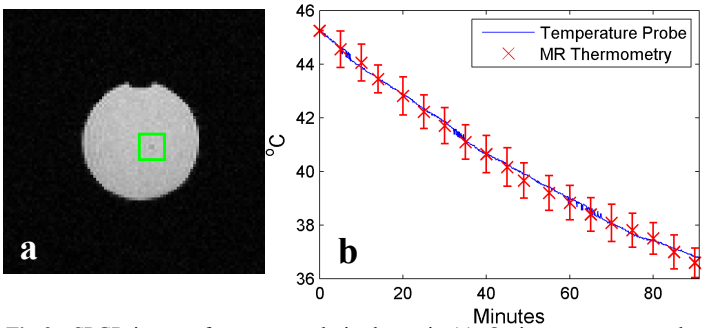

Fig 2. SPGR image of cream sample is shown in (a). Optic temperature probe readings (black dot in center of green ROI) and the mean MR thermometry readings in ROI (green box) are plotted in (b). Error bar depicts ±1 standard deviation from average within the ROI. Source of noise in probe measurement (blue line) is likely a result of the electronics.

Results and Discussion: Fig. 2 depicts the results from the cream cooling experiment. Temperature values over the 100 pixel ROI (shown in Fig. 2a) were averaged and compared with the temperature probe measurement (Fig. 2b). The maximum deviation between the MR thermometry measurement and the temperature probe was 0.28°C.

Conclusions: We presented a generalized theory for a 3-echo fat-referenced thermometry technique that uses standard phase-based fat/water image reconstruction methods. This thermometry technique was validated in a cream cool-down experiment, where the mean MR and ground truth fiber-optic probe measurements coincided within 0.28°C over the entire 90-minute cool-down experiment.

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