A New Spectrum-Based Model for MR Thermometry

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Introduction The conventional PRF method for MR thermometry suffers from the disturbances caused by the presence of lipid protons, motion-induced error, and field drift. Some successful results have been demonstrated with our previous IDEAL-based model (1) which tackles the aforementioned problems. However, in the previous model, the T_2^* effect is not considered when TE is long, and only relative temperature is obtained since a baseline image is still required. In this work, a spectrum-based model is proposed to consider all the effects mentioned above. The new model describes the signal under temperature change more accurately and can be solved by using a modern spectrum analysis algorithm – the extended Prony method. With this model, the absolute temperature map can be obtained without being contaminated by fat, motion and field drift. Experimental results demonstrate the feasibility of the proposed model.

Method While the imaging object consists of two species, water and fat, the signal of a specific voxel obtained at echo time TE_n is given by $s(TE_n) = \sum_{i=1,2} \rho_i e^{j\phi_i} e^{(-1/T_{2,i}^* + j2\pi f_i)TE_n}$, where ρ_i, ϕ_i, $T_{2,i}^*$ are the magnitude, initial phase and T_2^* of water and fat, respectively. The resonance frequencies of water and fat protons are $f_1 = \alpha\gamma\!\!\!/ B_0(T - T_{ref}) + \psi$, $f_2 = \gamma\!\!\!/ B_0 \Delta_{f-w} + \psi$ respectively, where T and ψ represent the absolute temperature and field inhomogeneity, Δ_{f-w} is the chemical shift in ppm between fat and water at the reference temperature T_{ref}. Based on such signal model, MR PRF thermometry is converted to a frequency estimation problem. After f_1 and f_2 are calculated, the chemical shift between water and fat $\delta_{H_2O-CH_2}$ ($|f_1 - f_2|/(\gamma\!\!\!/ B_0)$, in ppm) is determined and the field drift influence is removed. The chemical shift is then plugged into a linear equation and the absolute temperature can be calculated: $\delta_{H_2O-CH_2} = aT + b$, where coefficients *a* and *b* are calibrated by temperature measurements. In our work, a multi-echo GRE sequence is used with echo time $TE_n = TE_0 + n\Delta TE$, and the signal is expressed as $s(n) = \sum_{i=1,2} \rho_i e^{-TE_0/T_{2,i}^*} e^{j(\phi_i + 2\pi f_i TE_0)} e^{(-\Delta TE/T_{2,i}^* + j2\pi f_i \Delta TE)n}$, where TE_0 is the first echo time and ΔTE the echo spacing, n = 0, 1, 2 … N-1 and N is the number of echoes used. The signal model now meets the assumption of the extended Prony method (2), which solves the nonlinear least squares problem by linearization and a non-iterative process. In our algorithm, the amplitude, phase, frequency and T_2^* ($\rho_i, \phi_i, f_i, T_{2,i}^*$) can be estimated simultaneously. During the experiment, a whipping cream phantom (1) was scanned on a Siemens Trio 3T MR scanner using a single-channel wrist coil. A copper-constantan thermocouple probe (Physitemp Instruments, Inc., New Jersey) was used to record the temperature for calibration and verification of our model. An 8-echo GRE sequence with $TE_0 = 4.15ms$ and $\Delta TE = 3.59ms$ was used for our continuous measurements. Other imaging parameters were TR/BW/Flip/FOV/Slice Thickness/data matrix = 50ms/ $\pm 16.64kHz$ /25°/100 x 200 mm/5mm/128 x 128.

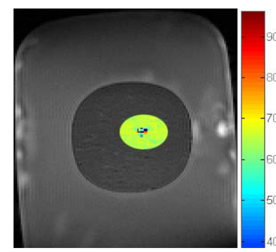

Fig.1: Phantom image and temperature map of the 56th measurement around the probe.

Results There were 70 temperature points measured. The phantom image and temperature map of the 56th measurement are shown in Figure 1. The first 25 points were used for calibration (3x3 averaged) with the calculated chemical shift $\delta_{H_2O-CH_2}$ (Figure 2). The regression line for the water-lipid difference is $\delta_{H_2O-CH_2} = -0.01021T + 3.80284$, and the correlation coefficient r is 0.998. Figure 3 shows the temperature evolution curves measured by thermocouple and calculated from our algorithm, respectively. The maximum temperature estimation error and standard deviation are 0.614°C and 0.06°C, which indicate a high correlation of our method to the thermocouple measurements. For comparison, the spectrum is also analyzed by using the conventional FFT method (3) where 8 echo signals collected are zero-padded to 1024 points. As shown in Figure 4, the peak frequencies of the model are explicitly displayed for both our method and the FFT method, but in FFT spectrum the peaks are much widened and its frequency resolution is limited. As calculated, the spectral resolution from our method can be improved by nearly 50 folds, which is about 0.6Hz/point.

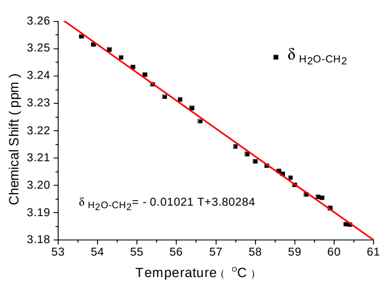

Fig.2: Relationship between temperature and the chemical shift.

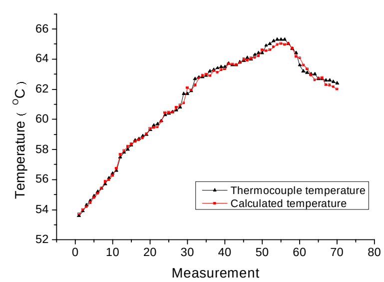

Fig.3: Temperature measured by thermocouple and calculated by our new algorithm.

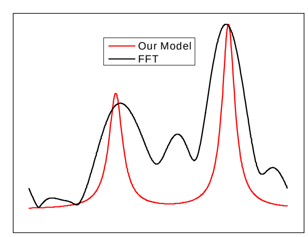

Fig.4: Spectrums of our model and conventional FFT method.

Conclusion / Discussion Due to its intrinsic characteristics, the newly proposed frequency spectrum model for MR thermometry is robust to the disturbances caused by the fat component, inter-view motion and field drift. Thus, a more accurate absolute temperature map can be obtained. In the future work, how the percentage of fat to water in each voxel and the number of echoes affect the effectiveness of new model should be studied. Since the robustness of frequency estimation, fast imaging techniques like parallel imaging and dynamic imaging techniques like k-t BLAST can be integrated into our method to accelerate signal acquisition process, especially for catching the fast temperature changes during the initial heating phase of thermotherapy.

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