COMPARISON OF SINGLE- AND MULTI-ECHO PRF-SHIFT THERMOMETRY AND METHOD FOR PENALIZED-LIKELIHOOD MULTI-ECHO TEMPERATURE RECONSTRUCTION

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Target Audience: Scientists and clinicians interested in proton resonance frequency (PRF)-shift MR thermometry.

Purpose: Relatively long echo times (TEs) in gradient echo-based PRF-shift MR thermometry are typically used to produce good phase contrast signal-to-noise ratio (SNR). These long TEs allow for low receiver bandwidths, which increase the readout duration but have high SNR. Recent studies have reported bandwidths per pixel (BWpp) of 14 Hz and 29 Hz for uterine fibroid and neurosurgical interventions, respectively. However, collecting multiple gradient echoes at higher bandwidths rather than one low bandwidth echo offers advantages without a substantial cost in SNR, including the elimination of phase wrapping errors with large temperature rises. In this work, we evaluate the advantage of multiecho acquisitions for reducing chemical shift distortions, which manifest as pixel shifts in the frequency-encoding direction. We also introduce a penalized-likelihood algorithm for estimating temperature changes from multiecho data, and compare the method to conventional linear fitting.

Methods. We fit a hybrid multibaseline and referenceless frequency shift model to multiecho data to estimate temperature change. The data are modeled as \( \tilde{y}_j = \sum_{i=1}^{N_b} b_j i w_t e^{i \left( \Delta f \left( \alpha T_x + \epsilon \right) \right)} + \epsilon_j \) for each spatial location \( j \), where \( N_b \) is the number of baseline images \( b \) with weights \( w \), \( A \) is a polynomial matrix with coefficient vector \( c \), \( f \) are temperature-induced frequency shifts, \( T_x \) is a vector of echo times, and \( \epsilon \) is Gaussian noise.

The model is fit using a sparsity penalized-likelihood method.

Simulation. Monte Carlo simulations were performed to evaluate positive temperature errors from the penalized-likelihood and linear fit methods. Multiecho data of a simulated phantom with a Gaussian-shaped phase shift corresponding to a 30°C temperature rise were generated for a 2DFT trajectory, 96 x 96 image matrix, 20 cm field of view (FOV), 0th order polynomial background phase, and 8 receive coils with sensitivities modeled using a finite difference time domain method. 9 echoes were spaced 3.3 ms apart with the first echo occurring at 1.8 ms. A T2* of 50 ms was used to model signal decay over the echoes, corresponding to values in brain tissue at 3T. The SNR of the first echo was 40 in the Monte Carlo tests. Frequency change maps were reconstructed using a linear fit and the penalized-likelihood method using one baseline image and a 0th order polynomial model. Frequency changes were converted to temperature maps using the relation \( \Delta T = \gamma B_0 \Delta \omega \), where \( \Delta \omega \) is the frequency change, \( \gamma \) is the proton gyromagnetic ratio, \( B_0 \) is the magnetic field strength, \( \alpha \) is the temperature dependence of the PRF shift, and \( \Delta T \) is the temperature change.

Phantom heating experiment. 2DFT data of a heated gel phantom were acquired at 3T (Philips Achieva, Philips Healthcare, Best, Netherlands) with 5 receive coils and TR/TE/FOV/matrix/slice thickness/scan duration = 32 ms/16 ms/200 x 200 mm 2/96 x 96/7 mm/6 min and BWpp of 434, 174, 87, 58, and 44 Hz. A 9 echo scan with the first echo time at 1.8 ms and subsequent echoes spaced at 3.3 ms intervals was also collected with a 434 Hz BWpp. The phantom was heated for 41 s using a Philips Sonalleve HIFU system with a 4 mm treatment cell size, 110 W power, and 1.2 MHz frequency. Temperature maps were reconstructed relative to 1 baseline image using the penalized-likelihood frequency model for the multiecho data and a previously reported penalized-likelihood phase model for single echo data. Standard deviation of temperature maps was calculated over the timecourse of the experiment in a region away from the heating area after removal of background phase variations using a 5th order polynomial fit.

Results. Root-mean-square error (Table 1) and standard deviation (\( \sigma \)) averaged over the Monte Carlo tests were lower for temperature maps of the simulated data reconstructed using the penalized-likelihood method (\( \sigma \) = 0.070°C) compared to the linear fit (\( \sigma \) = 0.170°C). Figures 1 and 2 show temperature maps reconstructed from the single echo and multiecho experiments. Outlines of the phantom overlaid on temperature maps illustrate geometric distortions at lower BWpp (Figure 1). Single echo maps required phase unwrapping to produce usable temperature maps (Figure 2). The temperature profile was plotted across the center of the hotspot along the frequency-encode direction. A spatial shift in the estimated peak temperature is observed for the single echo acquisitions, with a larger shift at lower BWpp.

Discussion and Conclusion. We have introduced a penalized-likelihood temperature reconstruction method that produces lower error and standard deviation in multiecho PRF-shift temperature measurements compared to a linear fit. We investigated heating-induced off-resonance effects in temperature measurements of a gel phantom by varying readout bandwidth. In addition to eliminating phase wrap errors, the use of multiple echoes avoids geometric and chemical shift distortions seen in low bandwidth single echo data while also producing temperature maps with low standard deviation. Penalized-likelihood temperature estimates from multiecho data offer the potential for reduced distortion with acceptable SNR as compared to linear fit or single echo data.

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