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)[1]. These long TEs allow for low receiver bandwidths, which increase the readout duration but have high SNR[2]. Recent studies have reported bandwidths per pixel (BW_{pp}) of 14 Hz and 29 Hz for uterine fibroid[3] and neurosurgical[4] 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[2]. 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[5]. We also introduce a penalized-likelihood algorithm for estimating temperature changes from multiecho data, and compare the method to conventional linear fitting[2].

Methods ***Algorithm.*** We fit a hybrid multibaseline and referenceless frequency shift model to multiecho data to estimate temperature change. The data are modeled as $\tilde{y}_j = \left(\sum_{l=1}^{N_b} b_{j,l} w_l\right) e^{i(\{\boldsymbol{Ac}\}_j + \boldsymbol{f}_j)\boldsymbol{T_E}} + \varepsilon_j$ for each spatial location j, where N_b is the number of baseline images $\boldsymbol{b}$ with weights $\boldsymbol{w}$, $\boldsymbol{A}$ is a polynomial matrix with coefficient vector $\boldsymbol{c}$, $\boldsymbol{f}$ are temperature-induced frequency shifts, $\boldsymbol{T_E}$ is a vector of echo times, and $\boldsymbol{\varepsilon}$ is Gaussian noise[6]. 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), 0^{th} order polynomial background phase, and 8 receive coils with sensitivities modeled using a finite difference time domain method[7]. 9 echoes were spaced 3.3 ms apart with the first echo occuring at 1.8 ms. A T_2^* of 50 ms was used to model signal decay over the echoes, corresponding to values in brain tissue at 3T[8]. The SNR of the first echo was 40 in the Monte Carlo tests. Frequency change maps were reconstructed using a linear fit[2] and the penalized-likelihood method using one baseline image and a 0^{th} order polynomial model. Frequency changes were converted to temperature maps using the relation $\Delta f = \gamma B_0 \alpha \Delta T$, where Δf is the frequency change, γ is the proton gyromagnetic ratio, B_0 is the magnetic field strength, α is the temperature dependence of the PRF shift, and ΔT 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 BW_{pp} 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 BW_{pp}. 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[6]. Standard deviation of temperature maps were calculated over the timecourse of the experiment in a region away from the heating area after removal of background phase variations using a 5^{th} order polynomial fit.

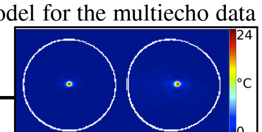

Figure 1: Temperature maps from multiecho (left) and 44 Hz BW_{pp} single echo (right) scans. Outlines of outer phantom boundaries are overlayed in white.

RMSE (°C)	Penalized-Likelihood	Linear Fit
Inside hotspot	0.110	0.182
Outside hotspot	0.159	0.276

Table 1: Root-mean-square error (RMSE) of penalized-likelihood and linear fit estimates within and outside the simulated hotspot.

Results Root-mean-square error (Table 1) and standard deviation (σ) averaged over the Monte Carlo tests were lower for temperature maps of the simulated data reconstructed using the penalized-likelihood method (σ: 0.070°C) compared to the linear fit (σ: 0.170°C). Figures 1 and 2 shows temperature maps reconstructed from the single echo and multiecho experiments. Outlines of the phantom overlayed on temperature maps illustrate geometric distortions at lower BW_{pp} (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 BW_{pp}.

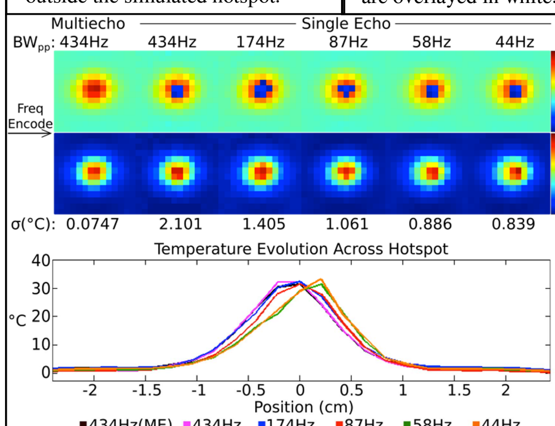

Figure 2: Temperature maps for multiecho (ME) and single echo scans for each BW_{pp}. Single echo scans required phase unwrapping (first row: wrapped; second row: unwrapped). Standard deviations (σ) outside the hotspot are reported below each map. Profile along frequency-encode direction shows distortion of peak heat location as BW_{pp} increases (bottom).

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[2], 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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