Improved Temperature Reconstruction for Multiple-Echo SPGR

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Target Audience: Engineers and clinicians working with HIFU (high-intensity focused ultrasound) brain ablation.

Purpose: Currently, PRF (proton resonance frequency) shift thermometry using a 2DFT SPGR sequence is used to guide HIFU ablation of targets in the brain. To obtain sufficient SNR with fast update rates, very low sampling bandwidths are used (~11kHz), which can lead to shift artifacts from off-resonance. By forming multiple images at a train of echo times, using high sampling bandwidth, shift artifacts can be minimized while temperature SNR is maintained. Prior publications have used linear fits to estimate B_0 at each time point, and calculated temperature differences from the frequency changes. The purpose of this work was to demonstrate that temperature uncertainty can be decreased by processing the temperature differences for each echo and taking a weighted average of the estimates.

Methods: Two SPGR sequences were implemented and tested on a 3T GE scanner using developmental builds of SpinBench and RTHawk (HeartVista, Inc. Menlo Park, CA USA). The first was single echo SPGR ('SPGR'), meant to mimic the sequence currently used to monitor clinical treatments. The second was multiple-echo SPGR ('ME_SPGR') without flyback. Each sequence used the following parameters: FOV = 28 cm, matrix = 256x128, flip angle = 30°, slice thickness = 3 mm, TBW = 6. SPGR used TE/TR = 14.3/28.8 ms with ADBW=11.36 kHz, while ME_SPGR used TR = 27.5 ms and 9 echos with TEs ranging from 4.8 to 22.8 ms, and ADBW = 125 kHz. A healthy volunteer was scanned under IRB approval using the body coil, with instructions to remain motionless during the scan. 23 frames of each sequence were collected.

The first three frames of each dataset were discarded to ensure steady state had been reached. The next three frames were averaged, to produce a higher SNR baseline image. Single-echo temperature measurements were computed from the phase difference between the baseline and the remaining images. Temperature uncertainty was calculated as the voxel-wise standard deviation through time of the temperature estimates. Multiple-echo temperature was estimated using three approaches. In the first two approaches, B_0 was estimated for each frame using least squares fits of the phase against time. Least squares was used for a linear fit in the first case ('ME_lin'), and weighted least squares was used in the second case ('ME_het') to correct for heteroskedacity. The heteroskedasticity approach used the magnitude values of the baseline as an estimate of each echo's relative SNR on a voxel-wise basis. To avoid phase wrapping, the frequencies calculated from the baseline were used to demodulate the remaining frames, and phase unwrapping was performed across echoes before least squares fits were calculated.

For the third approach to temperature estimation ('ME_new'), each echo at each time point was used to calculate temperature based on its phase difference with that echo of the baseline. Relative temperature SNR of each echo was estimated on a voxel-wise basis as the product of the baseline magnitude and the TE of that echo (because phase accrues linearly with TE.) A weighted average across echoes for each frame was computed using the square of the relative temperature SNRs of each echo for each voxel as weights. Temperature uncertainty was then calculated as the standard deviation through time. To estimate the lower bound for multi-echo temperature uncertainty ('ME_bound'), the temperature uncertainties of each echo were combined using 1./norm(1./Uncertainty) where Uncertainty is a vector of temperature uncertainties across echoes.

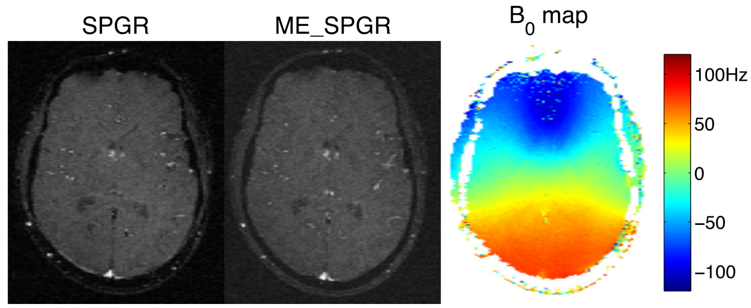

Figure 1: Magnitude of single acquisition for each sequence, (sum-of-squares for ME_SPGR echoes,) and B0 map from ME_SPGR

Results: Magnitude images of the SPGR and ME_SPGR (sum-of-squares across echoes) are shown in Fig 1, along with a B_0 map estimated from ME_SPGR. Temperature uncertainties are shown in Fig 2 for each approach. Above each image are average temperature uncertainties from an ROI encompassing the majority of the brain.

Discussion: As can be seen in the B_0 map, there is frequency variation across the brain of approximately -100Hz to +80Hz. This variation causes geometric distortion that is visible in the single-echo magnitude and not in the multi-echo magnitude. Comparing the temperature uncertainty obtained from the different multi-echo reconstructions, it is clear that the new approach yields significantly better uncertainty than performing a linear fit to the phase data. The new approach performs nearly as well as the lower bound calculated from individual echo uncertainties. With the multiple-echo approach, susceptibility to shift artifacts has been reduced by a factor of 11, while uncertainty has only increased 9.8% as compared to the single echo approach, which matches the expected change in SNR from reduced sampling time.

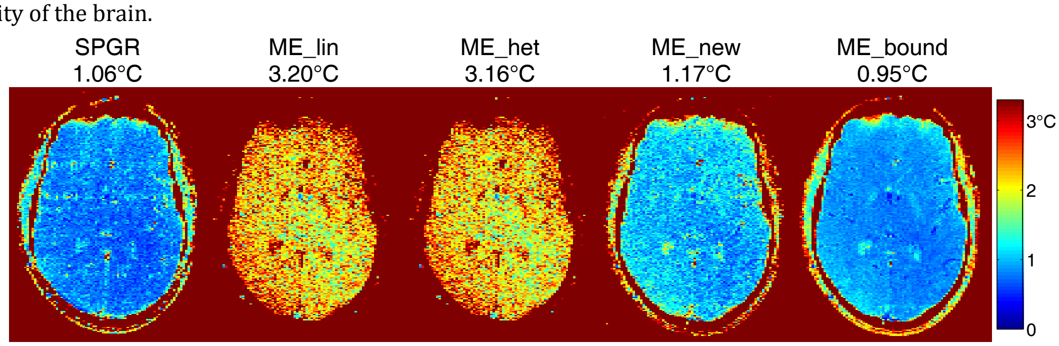

Figure 2: Temperature uncertainty for each sequence and reconstruction approach

Conclusion: Using a new approach to multiple echo combination, thermometry was performed with multiple high bandwidth echoes to remove frequency shift artifacts while maintaining the SNR performance of a single echo sequence. In future clinical treatments, use of multi-echo images will improve targeting accuracy by minimizing shift artifacts. By treating each echo independently and performing an optimal combination of the individual temperature estimates, temperature estimates are more precise than those obtained through linear phase fitting.

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