Fat Referenced Volumetric MR Thermometry Using 2 point Dixon and Alternating EPI Read Out Directions

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Introduction
MRI guided High Intensity Focused Ultrasound (MRgHIFU) has the potential of non-invasive thermal treatments for e.g. tissue ablation and targeted drug activation in the breast. Accurate and stable temperature mapping of a three dimensional (3D) region of interest covering the HIFU hotspot is fundamental to accurately monitor tumour ablation and surrounding tissue heating. The current gold standard for MR Thermometry (MRT) neautrophic tissue is the proton resonance frequency shift (PRF) method [1]. Since PRF is a phase-based method, field disturbances can be misinterpreted as temperature changes. However, fat protons experience the same field disturbances but do not have a temperature dependent phase component, so they have been used to correct the PRF maps in 2D [2-4]. In this work we propose the use of a 3D Segmented Echo Planar Imaging (EPI) pulse sequence with alternating Read Out (RO) directions and 2 point Dixon to measure phase disturbances and correct PRF temperature measurements.

Methods
Alternate Read Out Direction EPI sequences that use positive and negative RO polarities in the same acquisition suffer from N/2 ghosting artifacts due to phase errors that can be corrected by post-processing phase correction, and due to off-resonant signals (fat/water) that cannot be corrected easily. To avoid such artifacts, a standard segmented EPI sequence was modified to alternate the polarity of the whole RO train from measurement to measurement, see Figure 1. If measurement \( n \) starts with a positive RO lobe (+RO), measurement \( n+1 \) will start with a negative RO lobe (-RO). The k-space data from each measurement can then be divided into a +RO and a -RO bin, each containing k-space lines only acquired with either +RO or -RO polarity. Since the polarity of the RO lobes alternate from measurement to measurement the positive/negative bin will contain alternating only odd/even segments from measurements \( n/n+1 \). Each bin can be reconstructed with the Temporally Constrained Reconstruction method previously applied to MRT PRF data [5], to achieve ghost free images.

Dixon separation and Phase Correction Two MR images with the water and fat components in and out of phase can be acquired by choosing two echo times (TE) that differ according to equation (1), where \( \Delta f_p \) = frequency difference between fat and water, \( \sigma \) = chemical shift, \( \gamma \) = gyromagnetic ratio, and \( B_0 \) = field strength. The two images can then be written in the form of equations (2) and (3), where \( f_{\text{w}} \) and \( f_{\text{h}} \) are real non-negative numbers representing magnetization magnitudes, \( \Phi \) is the phase increment during \( \Delta T E \) (due to field inhomogeneities and temperature), and \( \Phi_0 \) is the phase due to field inhomogeneity, temperature, and system imperfections. Water and fat only images can then be acquired according to equations (4) and (5), where \( \Phi \) is estimated and corrected for using equations (6), where \( \Phi_0(x) \) is the phase angle, and \( x^* \) is the complex conjugate [6].

Experiment A fat/water phantom consisting of 2 round 1.5 cm diameter plastic vials filled with water, surrounded by a 13x13 cm square container filled with vegetable oil (100% Soybean) was used. One of the water vials was heated to about 70 °C and allowed to cool down for about 4 minutes of data acquisition. The data was acquired by changing the TE between every measurement to facilitate fat/water separation, and changing the EPI RO train polarity every other measurement, so TE/RO for the measurements permuted as follows: (TE1/+RO), (TE2/+RO), (TE3/-RO), (TE4/-RO), (TE5/+RO), (TE6/+RO) … etc. K-space data from measurements 1,3,5… and 2,4,6…, respectively, the measurements permuted as follows: (TE1/+RO), (TE2/+RO), (TE3/-RO), (TE4/-RO), (TE5/+RO), (TE6/+RO) … etc. K-space data from measurements 1,3,5… and 2,4,6…, respectively, were first reconstructed using the TCR algorithm to create complex images for all 2D TE/RO combinations. Equations (4)-(6) were then applied to create water only images, corrected by a spatially varying, weight least square second order fit of the fat phase, from which 3D temperature maps could be calculated using the PRF method. The scan parameters used included Field of View = 192x138x24 mm, Voxel size = 1.5x1.5x3 mm, TR = 18 ms, TE1 = 9.3/10.5 ms, EPI factor = 7, \( \tau_{\text{acq}} \) = 2.5 s/measurement. All scans were performed on a 3T MRI System (TIM Trio, Siemens Medical Solutions, Erlangen, Germany), and all post-processing was performed using Matlab (MathWorks Inc., Natick, MA, USA). True temperatures during the experiment were obtained using a fiber-optic sensor (OpSens, Quebec, Canada). True temperatures during the experiment were obtained using a fiber-optic sensor (OpSens, Quebec, Canada).

Results and Conclusion
Figure 2 shows fat only and water only images of the phantom acquired using 2 point Dixon. Red box shows ROI shown in figure 3. Figure 3 shows temperature maps of 3 orthogonal views. In figure 4 the temperatures from the fiber-optic sensor (blue), and temperatures as measured over a 4x4 voxel region with regular PRF method (red) and PRF corrected using fat phase (black) are shown. The noise in the PRF measurements is a result of relatively low SNR due to a long TI of the water. The RMS error of the temperature over 265 seconds of cooling from 70 °C to 45 °C decreased from 4.0 °C to 2.5 °C when using the described fat reference method. A 3D MRT method using alternating EPI ROI and TCR, to avoid N/2 ghosting, and phase referenced PRF temperature measurements is demonstrated. An RMS error improvement of 1.5 °C was shown compared to non-corrected PRF measurements.


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