Accelerating 3D spiral MR thermometry with the Kalman filter

Samuel Fielden[1], Li Zhao[1], Wilson Miller[2], Xue Feng[1], Max Wintermark[2], Kim Butts Pauly[3], and Craig Meyer[1,2]

[1]Biomedical Engineering, University of Virginia, Charlottesville, VA, United States, [2]Radiology, University of Virginia, Charlottesville, VA, United States, [3]Radiology, Stanford University, Palo Alto, CA, United States

Introduction: MR-guided focused ultrasound (MRgFUS) is a promising non-invasive technique for cancer therapy, neural tissue ablation, and drug delivery across the blood brain barrier[1,2]. Real time MR thermometry of the heated volume, usually based on the proton-resonance frequency (PRF) shift[3], is a key aspect of these procedures. Early work in the field focused on 2D imaging, either of one slice or a small number of slices; however, the desire to monitor the entire sonicated volume has led the field towards the development of rapid, 3D methods[4]. Acquiring fully sampled 3D volumetric data to measure phase changes due to the PRF shift in response to heating is time consuming, however, and so accelerated methods must be developed in order to meet the spatial and temporal requirements for adequate monitoring of thermal therapy.

The data acquisition efficiency of spiral trajectories is higher than that of Cartesian scanning. Therefore, spiral trajectories are an attractive way in which to improve temporal resolution while maintaining spatial resolution in MR thermometry[5]. Additionally, spirals have good robustness in the presence of motion and, importantly for MRgFUS, off-resonance does not cause a shift in the position of the hot-spot as it does for EPI-based methods.

Further speed-ups can be gained by utilizing the large amount of static spatial information present in the series of thermal maps. The Kalman filter method uses a statistical model improve a series of temporal images and has been successful in acceleration of myocardial imaging[6], and has the potential to provide real time feedback in MRI thermometry[7]. Here, we present initial results of accelerated thermometry with a 3D spiral acquisition and Kalman filter reconstruction.

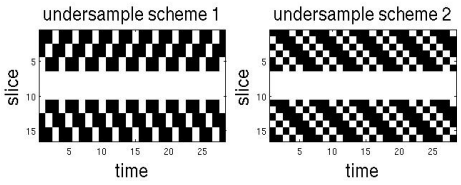

Fig. 1. Undersampling schemes in k_z-t space. White indicates acquired data.

Methods: The Kalman filter (KF) is a recursive and efficient method to estimate the state of a process described by a dynamic state-space model:

$$x_k = f(x_{k-1}) + w_k \qquad y_k = U_k F x_k + v_k$$

where, x_k is the target image at the k^{th} frame, y_k is the corresponding acquired data, and $f(x_{k-1})$ is the state transition function, which in the case of thermometry is simply x_{k-1}. F is a Fourier transform operator and U_k is the undersampling scheme at acquisition k. w and v are the system and measurement noise, assumed to have white Gaussian distributions with covariance matrices Q and R. Rapid imaging was achieved by a 3D interleaved stack-of-spirals spoiled gradient echo sequence. The center of k-space was fully sampled and provided low resolution images, which were used as initial values and training data for the noise covariance matrix. Two undersampling schemes were explored as shown in Fig. 1. For image reconstruction, KF with 1D Fourier transform was performed in k_z-t space for each acquired position along the spiral trajectory. Then, each partition image was reconstructed by 2D gridding, and temperature maps were calculated based on image phase differences from a reference frame.

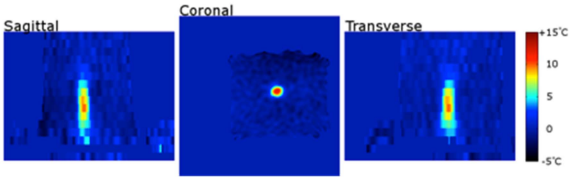

Fig. 2. 3D temperature map of phantom at t = 40 seconds calculated from fully sampled data. The FUS focal spot is an ellipsoid with the long-axis oriented in the through-plane direction.

The accelerated 3D spiral trajectory and reconstruction were tested experimentally in a gel phantom, using an MR-compatible FUS system (RK-100, FUS Instruments Inc., Toronto) in a 3T whole-body scanner (Siemens Trio). MRI parameters were: FA = 25°, TR/TE = 15/6 ms, readout length = 1 ms, interleaves = 16 over a FOV of 64 mm^2 for an in-plane resolution of 2.7 mm^2 (zero-padded in reconstruction to 0.25 mm^2), 3D phase encodes = 16 with through-plane resolution of 2 mm. Fully sampled data was acquired by collecting all 3D phase encoding partitions per volume, for a total acquisition time per volume of 4.1 seconds. Rate 2 undersampled data was acquired by skipping half of the 3D partitions per volume (Fig. 1), for a total acquisition time per volume of 2.05 seconds. The number of time points was increased for the undersampled acquisition in order to match the total scanning time of the fully sampled dataset. The in-plane (spiral) dimension was always fully sampled.

For each experiment, the MR pulse sequence was run for 20 seconds to establish steady-state, continued running during a 20-second continuous sonication at 5 W to measure the focal temperature rise, then continued running for an additional 20 seconds. After repeating this procedure for each of the fully sampled and under sampled acquisitions, the temperature of the focal spot was recorded and plotted for each by taking the mean of a 5 x 5 block of pixels centered on the focal spot in the slice with the maximum temperature response. To monitor a remote location and evaluate the noise of the measurements, the mean and standard deviation of a 15 x15 region was recorded in a location remote from the focal spot.

Results: Figure 2 shows sagittal, coronal (spiral plane), and transverse sections of the temperature map acquired from the fully-sampled data at the peak temperature time point. Background noise has been masked out of these images. In Fig. 3, the time-temperature plots of the FUS focal spots as well as a remote spot are shown. The measured temperatures follow predicted heating/cooling behavior for the experiment with small standard deviations (<0.5°C). The differences between the curves are at least partly explained by differing sonications. The first 3 time points of the undersampled data have been thrown out because the Kalman filter requires several time points of data before reliable results are obtained.

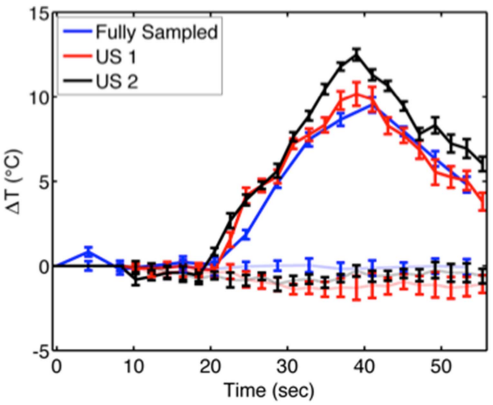

Fig. 3. Measured temperature at ultrasound focal position (solid) and background (dotted) for the fully sampled and two undersampled acquisitions.

Discussion: To our knowledge, this is the first report of 3D spiral-based thermometry. Theoretically, spiral trajectories will allow faster imaging than Cartesian scanning[5], although the small size of the phantom and the large susceptibility gradients generated by the large pool of deionized water used in the FUS system restricted the long readouts necessary to truly realize these advantages in this particular setup. Another advantage of spiral imaging is that while off-resonance can cause blurring, it does not shift the position of the focal spot, in contrast to EPI. With the short spiral readouts used in this study, blurring was not significant. The use of the Kalman filter facilitated a speed-up of 2X and has the potential to allow real-time feedback for accelerated MR thermometry.

References: [1] Kennedy, et al. Nat Rev Cancer. 2005;5:321-327. [2] Medel, et al. Neurosurgery. 2012;71:755-763. [3] Ishihara, et al. MRM. 1995;34:814-823. [4] Todd, et al. MRM. 2012;67:724-730. [5] Stafford, et al. MRM. 2000;43:909-912. [6] Feng, et al. MRM. 2012;69:1346. [7] de Senneville, et al. ISMRM. 2012;20:1558.

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