Research Funding Agreement Between
The Focused Ultrasound Surgery Foundation
and
Vanderbilt University
MR Temperature Imaging Toolbox for Focused Ultrasound Neurosurgery
Progress Report: 14th February, 2015

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Aim 1: Develop an accelerated 3D EPI sequence and reconstruction for preclinical whole-brain temperature imaging.

This Aim targets a 25x-accelerated 3D EPI sequence with whole-brain coverage. We have implemented this sequence on our Philips 3T scanner. While the basic acceleration was achieved simply by reducing the FOV by 5x in the two phase-encoded dimensions of the vendor's 3D EPI sequence, we have added additional phase encoding blips in those dimensions that are incremented so that the entire k-space sampling pattern shifts each dynamic, which enables a) fully-sampled baseline acquisition, which is required for the k-space hybrid reconstruction we will apply to estimate temperature maps from the data; and b) undersampling artifact "blinking" between dynamics during sonications, which enables aliasing to be further filtered out with temporally-regularized reconstruction to improve temperature accuracy (as in the Utah group's TCR method; our k-space hybrid reconstruction can also easily incorporate temporal regularization). This segmented acquisition scheme differs from the vendor's conventional EPI scan which would acquire all lines in a single plane of 3D k-space before moving to the next plane. An example phantom image reconstructed from this sequence is shown in Figure 1.

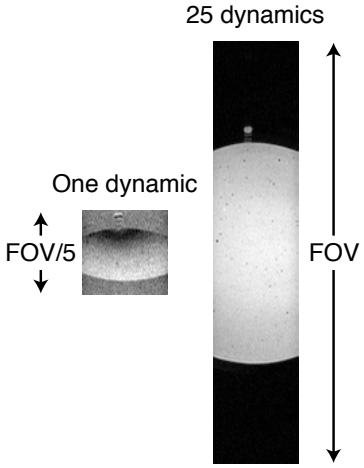

Figure 1. A *phantom image acquired using our segmented 3D EPI sequence. Left: An aliased image can be reconstructed from a single 25x/uniformly-undersampled dynamic. Right: A fully-sampled image can be reconstructed from 25 consecutive dynamics, due to the developed segmented acquisition scheme.*

This Aim also proposed an optional chemical shift compensation step, to alleviate temperature map errors due to phase accrual across k-space due to temperature-induced heating (i.e., the hot spot distorts itself). We completed development of that method, with results shown for 2DFT and EPI temperature mapping in Figure 2. One unanticipated finding was that the accuracy of the reconstructions is considerably improved when we estimate both the change in chemical shift of the protons due to heating and the image attenuation due to changing T1/T2* with heat, jointly. This finding was described in conference abstract [4] listed below. A manuscript describing the overall chemical shift compensation method will be submitted to Magnetic Resonance in Medicine in Q1 2015. We have also developed a fast chemical shift reconstruction (outlined in Figure 3) that applies to Cartesian EPI and 2DFT data and is compatible with online use (< 0.1 s computation time for a 2D image, implemented in MATLAB without parallelization; further acceleration will be achieved with parallelized C-based implementation). We are currently implementing that fast method in Python so that it can be

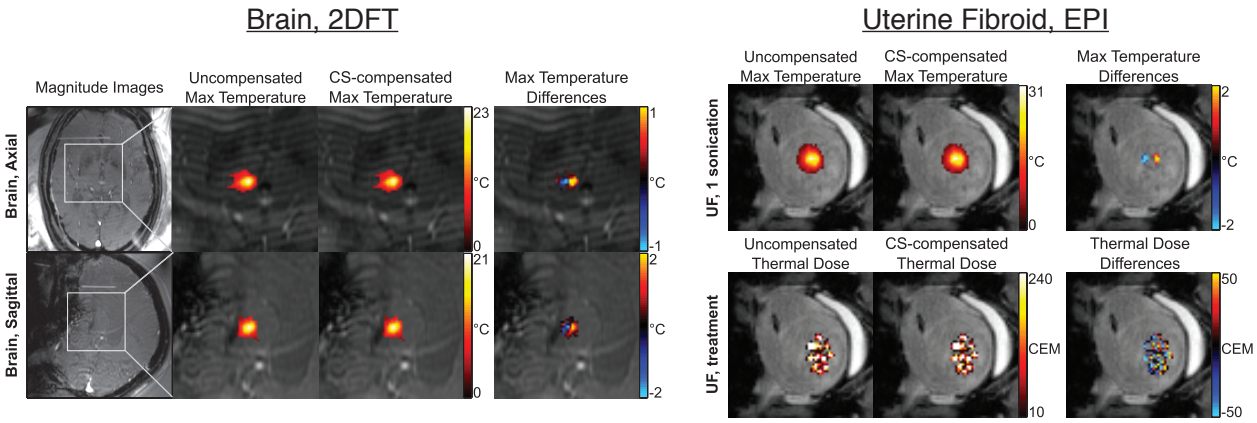

Figure 2. *Chemical shift-compensated temperature reconstruction in brain 2DFT (left) and uterine fibroid EPI MR-guided focused ultrasound procedures. In both cases, the algorithm primarily corrects a spatial shift of the hot spot and predicted necrotic regions along the chemical shift direction (left-right in both cases).*

used seamlessly in the Philips SonAlleve HIFU temperature reconstruction pipeline, and easily distributed to other sites. Once RTHawk 2.0 is installed and validated at UVA/FUS Center, we will make a trip to implement the method there (anticipated March/April 2015). It will improve the accuracy of any 2DFT or EPI temperature map acquisition, and is compatible with any temperature map estimation algorithm (e.g., baseline subtraction, referenceless, or hybrid).

Once the chemical shift compensation work is completed, we will turn our attention back to the accelerated temperature map reconstruction. The basic extension of our k-space hybrid algorithm (Gaur P and Grissom WA, MRM Early View) to this acquisition will be straightforward, but in the original project proposal we anticipated two problems: 1) Estimating baseline images from the undersampled data without corruption by respiratory or cardiac phase and motion effects, and 2) The presence of the water bath, the signal from which is constantly changing in a random way, and cannot be modeled using baseline images. We believe we have identified a solution to the first problem, which will be to treat the baseline images as additional unknowns in the temperature reconstruction, and estimate them jointly with the temperature map by enforcing a low-rank matrix constraint on the matrix of baseline images (whose rows index spatial

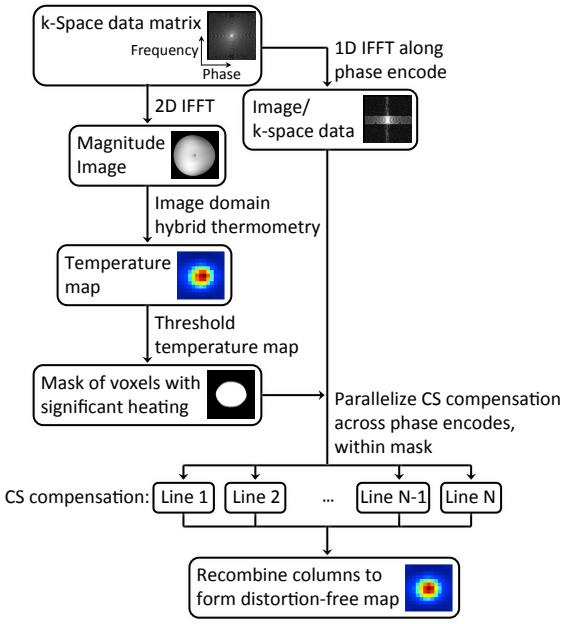

Figure 3. *Flowchart for the fast chemical shift-compensation algorithm for 2DFT and EPI scans. The algorithm is implemented as a post-correction step that applies to a previously-computed temperature map. It works by iteratively correcting the temperature map to maximize consistency with the acquired k-space data. Since chemical shift blurs only in one dimension in 2DFT and EPI scans, the algorithm can be parallelized across the other dimension.*

locations and columns index temporal dynamics). We still anticipate that we can solve the second problem by not enforcing the hybrid image model in the water bath, but instead treating those voxels as unknowns subject to spatial smoothness constraints.

Aim 2: Develop an accelerated reduced-FOV 3D EPI sequence and reconstruction for test shot localization.

We have made less progress on this Aim. The primary effort required to complete this Aim is the development of the reduced-FOV pulse sequence. The reconstruction will be a straightforward adaption of the reconstruction from Aim 1.

Aim 3: Develop a high-resolution 3D slab-selective EPI protocol and fast chemical shift-deblurring temperature reconstruction for ablation monitoring.

As described in Aim 1, we have developed the fast chemical shift-deblurring temperature reconstruction for this Aim. Our next steps will be to implement this in the Philips SonAlleve temperature map reconstruction pipeline, so that it can be easily distributed to other sites, and to implement it in RTHawk using the temperature mapping scan provided with RTHawk 2.0.

Presentations/Publications The following conference abstracts have been presented or accepted for presentation on the work resulting from this project:

1. Gaur P and Grissom W A. Temperature map reconstruction directly from k-space with compensation for heating-induced geometric distortions. In: Proceedings 22nd ISMRM, 2014, p. 2362.
2. Gaur P and Grissom W A. Comparison of single and multi-echo PRF-shift thermometry and method for penalized-likelihood multi-echo temperature reconstruct. In: Proceedings 22nd ISMRM, 2014, p. 2351.
3. Gaur P and Grissom W A. Temperature map reconstruction directly from k-space with compensation for heating-induced geometric distortions. In: Proceedings ISTU 2014.
4. Gaur P and Grissom W A. Improved k-space-based MR thermometry by joint PRF phase shift and T1/T2* attenuation estimation. In: Proceedings 4th Intl Symp Foc Ultras 2014.
5. Gaur P, Werner B, Ghanouni P, Bitton R, Pauly K B, and Grissom W A. Chemical shift-compensated MR thermometry applied to brain and soft tissue tumor MR-guided focused ultrasound. Accepted for presentation at ISTU 2015.
6. Gaur P, Werner B, Ghanouni P, Bitton R, Pauly K B, and Grissom W A. In vivo chemical shift-compensated MR thermometry. Accepted for presentation at 23rd ISMRM.

Follow-on Funding The work done under this project formed part of the preliminary data for the following grant proposal:

Title: “Curing Epilepsy With a Needle”
PI: E Barth
Grissom Role: Co-Investigator
Description: Epilepsy affects one in every 100 to 200 people globally with 50% undertreatment for surgical candidates, sudden unexplained death (SUDEP) risk of 1% per patient per year, and ineffective drug therapy for 20 to 40% of patients. This project focuses on providing access to epileptic seizure foci in the brain with a 3D-printed needle steering robot guiding a needle beneath the cheek skin and through the skull base under MRI guidance. We hypothesize that thermal therapy delivered with this needle will be less invasive and enable a greater number of

patients to receive a permanent cure for epilepsy than provided by current surgical and drug therapy methods.
Sponsor: NIH/NINDS, R21
Total Award Amount (Direct + Indirect): $426,000
Dates: (NoGA not yet received; scored 10th percentile with funding level of 14th)