In vivo chemical shift-compensated MR thermometry

Pooja Gaur[1,2], Beat Werner[3], Pejman Ghanouni[4], Rachelle Bitton[4], Kim Butts Pauly[4], and William A Grissom[2,5]

[1]*Chemical and Physical Biology, Vanderbilt University, Nashville, TN, United States,* [2]*Institute of Imaging Science, Vanderbilt University, Nashville, TN, United States,* [3]*Center for MR-Research, University Children's Hospital, Zurich, Switzerland,* [4]*Radiology, Stanford University, Stanford, CA, United States,* [5]*Biomedical Engineering, Vanderbilt University, Nashville, TN, United States*

Purpose It has been demonstrated that the PRF shift caused by tissue heating causes geometric distortions in MR images and temperature maps [1]. A method to correct this chemical shift (CS) effect by accounting for heat-induced phase accrual and signal magnitude decay during the MR signal readout has been developed and validated in simulations and phantom experiments [2, 3]. In this work that method is demonstrated in patient heating data from brain and soft tissue tumor MR-guided focused ultrasound ablations. Such data are typically sensitive to CS distortions because of the low readout bandwidths used to maximize SNR during treatment, or when EPI readouts are used to increase scan efficiency.

Methods ***Chemical Shift Compensation Algorithm.*** Temperature change maps were first reconstructed using the algorithm in Ref. [4]. CS compensation was then performed by fitting a k-space signal model to the maps (following 1DFT of the k-space data in the phase-encode dimension), given by [2]: $\tilde{y}_i = \sum_{j=1}^{N_s} e^{i\vec{k}_i\cdot\vec{x}_j}\left(\sum_{l=1}^{N_b} b_{l,j}w_l\right)e^{i\{\boldsymbol{Ac}\}_j}e^{i\theta_{R,j}(1+t_i/T_E)-\theta_{I,j}} + \varepsilon_i$, where $\vec{k}_i$ is the k-space location of sample i acquired at time t_i, N_s is the number of spatial locations $\vec{x}_j$, N_b is the number of baseline images $\boldsymbol{b}$ with weights $\boldsymbol{w}$, $\boldsymbol{A}$ is a polynomial matrix with coefficient vector $\boldsymbol{c}$, θ_R are temperature-induced phase shifts at the echo time T_E, θ_I are exponential signal decay terms, and $\boldsymbol{\varepsilon}$ is complex Gaussian noise [3].

Patient treatment data. 2DFT GRE data were acquired during clinical brain and leg sonications at 3T (GE Signa, GE Healthcare, Milwaukee, WI, USA; Insightec ExAblate, Insightec Ltd., Haifa, Israel) with 8 receive coils/body coil reception for brain/leg, 28/25 ms TR for brain/leg, 12 ms TE, 280 x 280 mm^2 FOV, 256 x 256 matrix, 3/5 mm slice thickness for brain/leg, and 44 Hz readout BW per pixel. Temperature maps were reconstructed using 1 baseline image and a 0th order B_0 drift-compensating polynomial for 2 brain sonications (axial and sagittal image orientations; 14 image frames each) targeting the same focal region, and 94 sonications of a soft tissue tumor in the leg (10 image frames each) over many adjacent focal targets. Absolute and maximum thermal rise and thermal dose (ranging from 0 to ≥240 CEM) from maps created before and after CS compensation were compared.

Results Uncompensated and CS-compensated temperature maps had similar temperature amplitudes but the uncompensated hot spots were shifted to the right by about 1 mm along the frequency-encode dimension in both brain (Fig 1) and leg tumor (Fig 2) as shown in temperature difference maps. Differences in maximum temperature between uncompensated and CS-compensated maps in heated voxels ranged from: -0.4°C to 1.3°C (brain, axial); -1.6°C to 2.7°C (brain, sagittal); -4.4°C to 5.6°C (leg, one sonication); and -8.5°C to 7.4°C (leg, entire treatment). Both methods identified a common core of heat with differences along the hotspot boundaries, similar to difference patterns observed in the temperature maps.

Discussion and Conclusion We have shown that CS distortions resulting from transient heating can be compensated in MR temperature maps from patient sonications. Without CS compensation, temperature measurements were systematically shifted along the readout direction, resulting in temperature estimation errors that persisted across multiple sonicated areas. The impact of CS distortions on thermometry will increase as lower bandwidth EPI strategies are used to increase spatio-temporal resolution and volumetric coverage [5]. Spatially-accurate temperature maps are critical for neurological applications, where crucial structures are within millimeters of the sonicated targets [6]. Overall, correcting for CS errors will improve dosimetry, particularly when narrow treatment margins and small sonication volumes are targeted. Calculation times were small (0.6 s for one soft tissue tumor sonication map at peak heat) so the method is compatible with online use.

Acknowledgments This work was supported by NCI R25CA136440, NIBIB T32EB014841, the Focused Ultrasound Foundation, the HHMI-VUMC Certificate Program in Molecular Medicine, and PO1 CA159992.

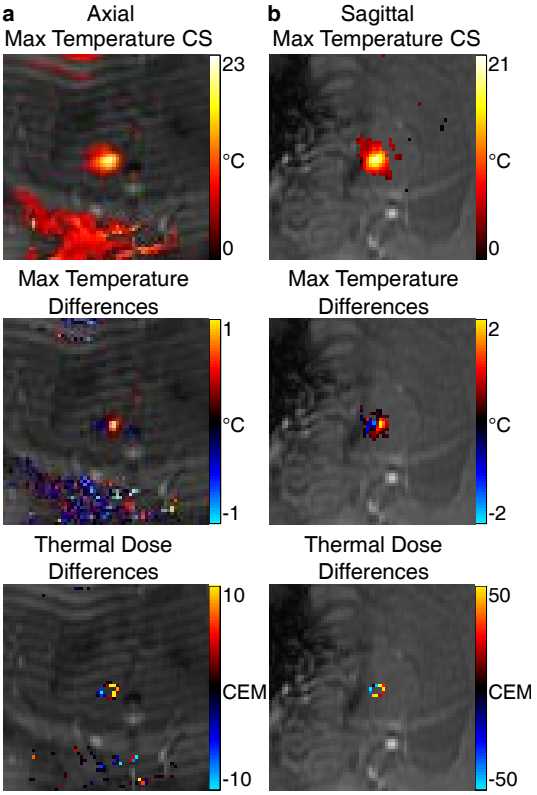

Fig 1. Results from brain sonications in (a) axial and (b) sagittal imaging orientations showing: maximum temperature maps after CS compensation (top row); differences of 0.1°C and greater from uncompensated maps in heated voxels (middle row); and thermal dose differences greater than 0.5 (axial) and 5 (sagittal) CEM (bottom row).

References [1] Josan S et al. Proc Intl Soc Mag Reson Med 18. 2010:1802. [2] Gaur P and Grissom WA. Proc Intl Soc Mag Reson Med 22. 2014:2362. [3] Gaur P and Grissom WA. 4th Int'l Symp Focused Ultrasound, 2014. [4] Grissom WA et al. Med Phys. 2010;37(9):5014-26. [5] Todd N et al. Magn Reson Med. 2012;67(3):724-30. [6] Jeanmonod D et al. Neurosurg Focus. 2012;32(1):E1.

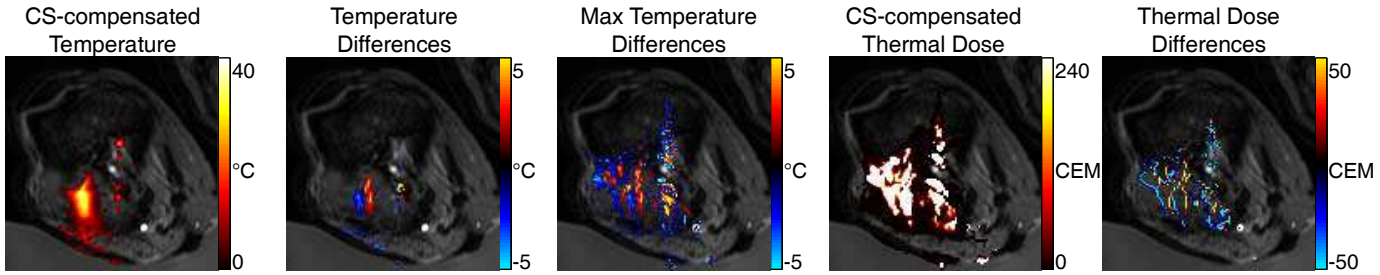

Fig 2. Results from leg tumor sonications showing: CS-compensated temperature map and differences of 1°C and greater from uncompensated temperature map in heated voxels for one sonication (left 2 plots; pulsation artefacts appear to right of hot spot); differences in maximum temperature of 1°C and greater in heated voxels over the entire treatment (3rd plot); and thermal dose for CS-compensated maps and differences greater than 2 CEM (right 2 plots).