Real-time online reconstruction of 3D MR thermometry data for MRgFUS applications

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INTRODUCTION

Focused ultrasound (FUS) is a totally non-invasive thermal treatment modality that holds great promise for a wide variety of disorders, and treatments are commonly done under MR guidance utilizing MR temperature imaging (MRTI). One of the main challenges in MRTI is achieving high spatio-temporal resolution to accurately monitor the focal spot heating, while simultaneously monitoring a large field-of-view to detect unwanted near- and far-field power depositions. In current clinical applications only a few 2D slices are monitored with MRTI to allow real-time availability of the data. With 2D slices there is an increased risk of not detecting the peak of the focal spot and off-focal heating due to the placement of the slices. 3D MRTI can acquire temperature images over a large FOV with good spatial resolution but poor temporal resolution. To guide the FUS procedure, the MR temperature maps should be available in real-time during the treatment. To speed up 3D MRTI, k-space subsampling in conjunction with dedicated reconstruction methods can be utilized, and model-based and iterative compressed-sensing-like algorithms have been described [1,2]. Model-based methods, such as Model Predictive Filtering (MPF) [1] require less computation and are better suited for rapid real-time reconstruction. While these methods have been shown to work well, they have never been tested in a real-time environment. In this work we demonstrate for the first time the integration of the MPF algorithm into the reconstruction pipeline on a commercial MRI scanner. The integration allows for online real-time availability of 3D high-resolution full FOV temperature maps at the scanner console during an MRgFUS experiment. A skull phantom is used to demonstrate that real-time availability of 3D temperature measurements over a full human sized skull can be achieved.

$$\rho C \frac{\delta T}{\delta t} = k\nabla^2 T - WC(T - T_{blood}) + Q \quad \textbf{(1)}$$

$$\phi_{n+1} = \phi_n + \gamma B_0 \alpha TE(T_{n+1} - T_n) \quad \textbf{(2)}$$

Equation 1. PBTE: ρ=tissue density, *C*=specific heat, *T*=temperature, *k*=thermal conductivity, *W*=perfusion parameter, and *Q*=power density. **Equation 2.** PRF shift: ϕ=phase, *Y*=gyromagnetic ratio, B_0=field strength, α=PRF coefficient, *TE*=echo time.

Table 1. Times for the individual tasks of the real-time reconstruction.

Task	Time (s)	% of time
Transmit/Receive data	0.81	34.9
MPF Recon	1.25	53.9
Logging	0.06	2.6
Misc.	0.20	8.6
Total:	2.32	100

METHODS

MPF: Temperature maps for time-frame (*n+1*) are calculated by combining subsampled k-space data with a forward-prediction of the temperature from time-frame (*n*) using the Pennes Bioheat Transfer equation [3] (PBTE), **(Equation 1)**. After combination and projection into image space, temperatures are calculated from the image phase with the proton resonance frequency (PRF) shift method, **(Equation 2)**. In **Equation 1** *k* and *Q* are obtained from low-power heatings using recently published methods [4,5], and tabular values are used for ρ (1000 kg /m^3) and *C* (3635 J/kg/°C).

MRTI and FUS: All data was acquired on a 3T MRI scanner (Tim Trio, Siemens Medical Solutions, Erlangen, Germany) with a 3D Segmented Echo Planar Imaging (EPI) pulse sequence with gradient recalled echo readout (TR/TE = 22/11 ms, FOV = 256x192x135 mm, Voxel size = 2.0x2.0x2.5 mm, ETL = 7, BW = 752 Hz/px, flip angle = 15°, Tacq = 2.398s). k-space was subsampled with a reduction factor of R=7, utilizing a recently described variable density sampling scheme that samples the k-space center more frequently [6]. FUS heatings were performed with a MR-compatible phased array US transducer (256 elements, 1 MHz frequency, 13 cm radius of curvature, 2x2x8 mm focal spot FWHM, Imasonic, Besançon, France, and Image Guided Therapy, Pessac, France) in a phantom consisting of a human sized PVC plastic skull (model A20, 3B Scientific, Tucker, GA, USA) embedded in gelatin gel at 112 acoustic watts for 29 s.

Online reconstruction: A custom image reconstruction pipeline was developed connecting the Siemens Image Calculation Environment (ICE) with a networked compute server (2.4GHz Intel Xeon, Redhat CentOS, 95G RAM, 1G Ethernet) and the FUS controller computer. The ICE pipeline diverts partial k-space updates to the compute server and receives MPF-updated fully sampled k-space in return. The MPF algorithm was implemented in Python along with networking and graphical user modules. Once the MPF reconstructed data reaches the end of the modified ICE pipeline, it is transferred to a FUS controller computer where the MR temperature maps are calculated. The different tasks of the reconstruction were timed to evaluate the performance.

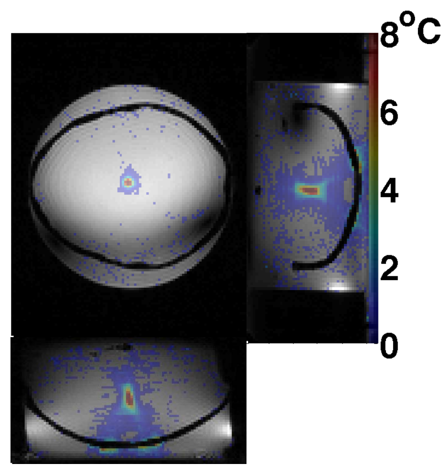

Figure 1. Three orthogonal views of the MR temperature maps through the focal spot as reconstructed in real-time on the FUS controller computer.

RESULTS

The total reconstruction time from end of data acquisition until the reconstructed data was sent to the FUS controller was 2.33 s per complex 3D dataset, where the time for each task is shown in **Table 1**. It can be noted that the majority of the Misc. time involves waiting for the pipeline to process the reconstructed images before proceeding to the next update. Three orthogonal views of the heating in the phantom as calculated in the FUS controller computer, superimposed on the magnitude image, are shown in **Figure 1**. Near-field heating in tissue-bone interfaces can be observed, highlighting the need for the large FOV MRTI.

DISCUSSION AND CONCLUSION

This work has for the first time combined the acquisition of high spatio-temporal resolution, large FOV MR thermometry data with online and real-time reconstruction at the scanner console. It demonstrates that it is feasible to acquire and reconstruct in real-time large FOV MR temperature maps monitoring the fully insonified FOV of a human sized skull. For applications where motion is a concern, such as liver and kidney, both acquisition and reconstruction times can be decreased by sampling a smaller FOV while maintaining the high spatial resolution. Future work will aim at decreasing the total reconstruction time by employing GPUs as well as reducing the networking load by running the MPF and the FUS controller on the same computer. A previously described adaptive model-predictive treatment planning controller [7] will also be implemented in conjunction with the MPF and the FUS controller to allow dynamic treatment planning during FUS experiments.

REFERENCES

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