Volumetric Brain Temperature Monitoring with the MASTER Sequence: Multiple Adjacent Slice Thermometry with Excitation Refocusing

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Purpose: MR-guided Focused Ultrasound (MRgFUS) has been used to treat brain disorders including essential tremor and neuropathic pain. The thermometry sequence currently supporting treatments is a single slice spoiled gradient echo. However, larger volume coverage is desired to detect undesired heating away from the target. High temporal resolution and temperature measurement accuracy are necessary to guide treatment, and difficult to achieve with traditional multi-slice SPGR. In particular, longer TE gives higher temperature accuracy, peaking at TE=T2*, while interleaving SPGR acquisitions in a given duration reduces the max TE. The purpose of this work was to develop a multi-slice SPGR thermometry sequence that allows for longer TEs by exciting multiple slices before performing readout, using offsets in k space to prevent interference similar to the MUSIC sequence[1]. This approach allows for multi-slice monitoring, possibly achieving full brain coverage, while maintaining clinically relevant temperature accuracy and sufficiently fast acquisition times.

Methods: The MASTER sequence was designed using Spinbench 1.3.1. and RTHawk (HeartVista) and implemented on a 3T Signa GE MR scanner. All simulation and image processing was performed in MATLAB. In MASTER, multiple slices are excited in adjacent k-space locations and are then sequentially refocused and recorded. An illustration of a single TR of a MASTER sequence and an interleaved SPGR sequence is shown in Fig 1, with colored arrows showing the TE for each slice. While the MUSIC sequence uses a constant TE for all slices, the MASTER sequence allows for variable TE across slices to improve sequence efficiency. In practice, slices will be ordered to obtain the highest accuracy where heating is expected.

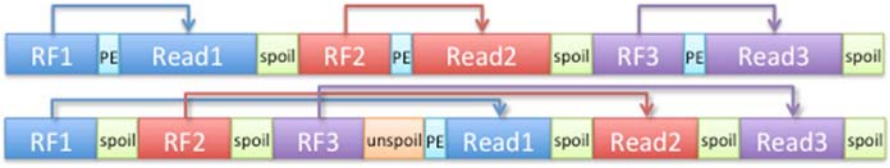

Figure 1: Sample TR for 3 slice interleaved SPGR (bottom) and MASTER (top). Not to scale. Arrows indicate TE, PE is phase encode

To investigate the design space of MASTER, sequences were simulated with varying bandwidths and numbers of slices. The tradeoff between collection time and temperature measurement uncertainty (standard deviation) for MASTER is compared with that of single slice SPGR in Fig 2. Each curve corresponds to the number of slices being collected, where the single slice MASTER reduces to SPGR. Predicted temperature uncertainties are based on measured treatment data. For validation, a 5 slice MASTER acquisition (orange box on Fig 2) was tested *in vivo* on a healthy volunteer.

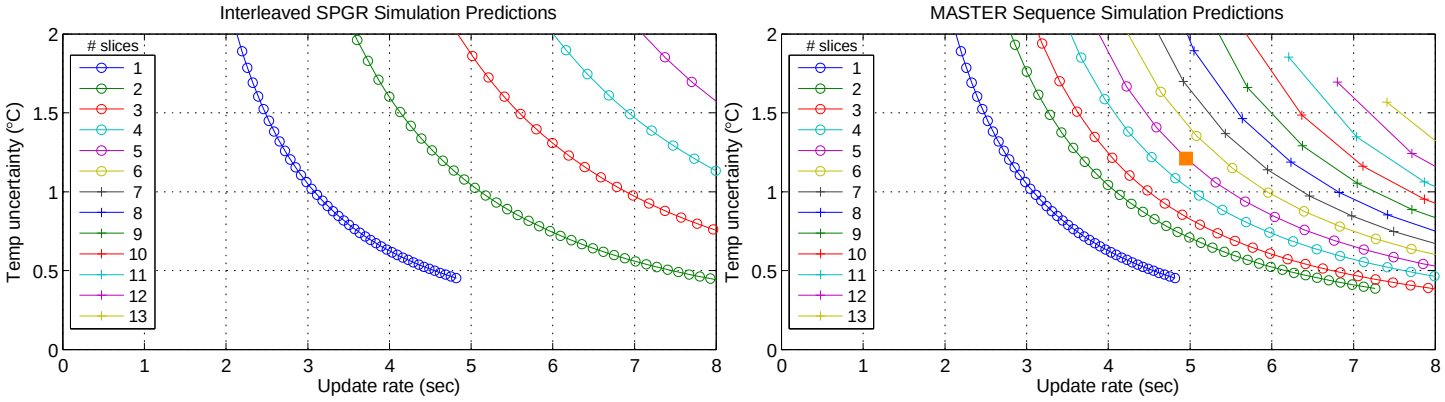

Figure 2: Predicted temperature uncertainty versus update rate (acquisition time) for interleaved SPGR (left) and MASTER (right)

Results: Initial *in vivo* measurements using the 5 slice MASTER sequence using the body coil yielded average temperature measurement uncertainty of 1.51˚C, with 1.22˚C in the region of highest SNR, as compared with 1.24˚C predicted SNR for a single slice SPGR sequence with the same parameters. Fig 3 shows the temperature uncertainty map from this collection, along with the average image intensity across the collection for reference. There was no measurable cross-slice interference signal when the RF was played only on one slice while the adjacent slice was read out.

Discussion: The curves in Fig 2 show that the MASTER sequence provides a better trade-off between update rates and accuracy than interleaved SPGR for multi-slice acquisitions. With the current configurations, up to five slices can be collected in ~5 seconds while maintaining adequate measurement accuracy. While validation measurement accuracy was up to 20% worse than predicted, the sequence implementation is still in development and expected to improve in uniformity. With improvements in SNR, such as from using a head coil instead of the body coil, all of the curves will shift down and improve measurement accuracy for every configuration. Applying acceleration techniques such as compressed sensing, parallel imaging, or multi-line readout would move the curves to the left, and allow even more slices to be collected with same accuracy and speed.

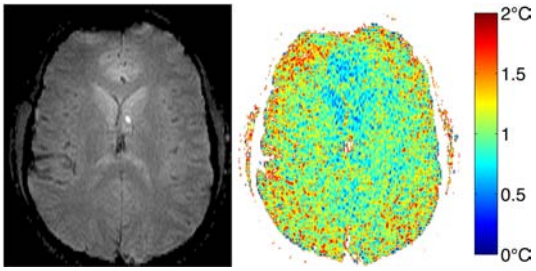

Figure 3: MASTER average intensity (left) and temperature uncertainty (right) *in vivo*

Conclusion: The MASTER sequence allows for the collection of multiple slices of SPGR data with significantly higher temperature measurement accuracy than a traditional interleaved SPGR sequence. This approach will allow for a much larger volume of the brain to be monitored for temperature rises during MRgFUS interventions, and may allow for whole brain coverage when combined with acceleration approaches and higher SNR coils. MASTER allows for researchers and clinicians to explore a large new design space to generate the best sequence for the needs of their particular application.

References: [1] Loenneker T, Hennel F, Hennig J. Magn Res Med 1996; 35: 870–874.
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