Rapid fetal HASTE imaging using variable flip angles and simultaneous multislice wave-LORAKS

Yamin Arefeen1, Tae Hyung Kim2, Justin Haldar3, Ellen Grant4,5, Borjan Gago6,7, Berkin Bilgic2,9, and Elfar Adalsteinsson1,8,9
1Massachusetts Institute of Technology, Cambridge, MA, United States, 2AthenaHealth A. Martinos Center for Biomedical Imaging, Charlestown, MA, United States, 3Department of Electrical Engineering, University of Southern California, Los Angeles, CA, United States, 4Boston Children’s Hospital, Boston, MA, United States, 5Harvard Medical School, Boston, MA, United States, 6Fetal-Neonatal Neuroimaging and Developmental Science Center, Boston Children’s Hospital, Boston, MA, United States, 7Department of Radiology, Harvard Medical School, Cambridge, MA, United States, 8Harvard-MIT Health Sciences and Technology, Cambridge, MA, United States, 9Institute for Medical Engineering and Science, Cambridge, MA, United States

Synopsis
Fetal MRI utilizes Half-Fourier-acquisition-single-shot-turbo-spin-echo (HASTE) for rapid T2-weighted imaging to mitigate motion. However, specific-absorption-rate (SAR) constraints from the refocusing pulse train reduce acquisition efficiency. Variable refocusing flip angle (VFA) acquisitions can improve efficiency, but may suffer from low signal-to-noise ratios (SNR). Here, we propose a VFA scheme and incorporate a rapid, low-SAR calibration scan. We simulate and prospectively evaluate the SNR and SAR properties of the VFA scheme and utilize the calibration scan for LORAKS parallel imaging and retrospective evaluation of wave-encoded simultaneous-multislice (SMS). VFA prospectively reduces acquisition time by ~2.3-2.5x and incorporating SMS could further improve efficiency.

Introduction
Fetal MRI utilizes Half-Fourier-acquisition-single-shot-turbo-spin-echo (HASTE) for motion robust, rapid T2-weighted imaging. Typically, HASTE encodes a slice in ~0.5 seconds (Rplane=2) but specific-absorption-rate (SAR) constraints from the train of high flip angle refocusing pulses necessitate ~1.5 seconds between slices, a 3x loss in efficiency.

Variable refocusing flip angles (VFA) reduce SAR while maintaining image quality. VFA has been employed in a fetal setting, but suffered from low signal-to-noise ratios (SNR).

We propose an alternative VFA scheme and incorporate a low-SAR external calibration scan to improve acquisition efficiency in fetal MRI. Simulations evaluate SAR and SNR of the proposed VFA scheme, prospective phantom and in-vivo experiments compare standard HASTE to our proposed scheme reconstructed using an external calibration scan, and retrospective experiments illustrate the potential of SMS-wave encoded acquisitions with LORAKS reconstruction. VFA prospectively reduces acquisition time by ~2.3x and incorporating SMS could further improve efficiency.

Methods
Standard clinical HASTE acquires 92 \( \frac{1}{2} \) lines (511ms readout duration) with 63% partial Fourier, TE = 122 ms, 24 auto-calibration lines, Rplane = 2, and 160 degree refocusing pulses. VFA sets 4 control angles to specify the train and acquires 91 lines (505ms readout duration) with 71% partial Fourier, TE = 155 ms, no calibration region and Rplane = 2. Figure 1 visually compares the described HASTE and VFA acquisitions. A rapid, low-SAR GRE calibration scan obviates the need for integrated ACS data, and the proposed regime achieves 2.94x lower SAR and 1.36x reduction in voxel blurring.

Figure 2a compares the refocusing profile of the 160° pulse scaled to different VFA's and the profile generated from the scaled VFA HASTE pulse using RF-Tools. For angles greater than 90°, VFA refocusing profiles match the scaled 160° profile up to 5%. Smaller angles later in the train match between 10 - 30%, but potential effects are minimal due to signal decay.

Figure 2b and 2c compares HASTE and VFA signal simulation using an isochromat-based Bloch, Carr-Purcell-Meiboom-Gill simulation for T1 values expected in the fetal brain and T1 = 1 s, with and without slice profile effects. Assuming SNR is proportional to signal strength at the TE, VFA yields between 82.90% SNR relative to HASTE in both cases.

Experiments
We acquired data using the standard HASTE and VFA schemes with 350x350 mm FOV and 1.36x1.36x3 mm voxels on both an anthropomorphic fetal phantom and a pregnant mother who signed an informed consent form approved by our institution’s IRB. In both cases, a rapid GRE calibration scan was also acquired immediately before the HASTE readouts.

We compare GRAPPA reconstructions on the standard HASTE acquisition using integrated calibration lines and the proposed acquisition using external references and compute SNR by dividing averaged regions inside and outside the object.

We also compare GRAPPA with projection-onto-convex-sets (POCS) partial Fourier on the HASTE acquisition to SENSE-LORAKS reconstructions on the proposed VFA acquisition. To illustrate constrained reconstructions with external references, we chose LORAKS to take advantage of phase smoothness to estimate missing portions of k-space.

For some pregnant mothers, including the one that participated in our study, our prescribed minimum TR of 600 ms operates at 70-75% of the SAR limit. In cases with remaining SAR budget, SMS encoding could further improve sequence efficiency between 1.25-1.75x. To evaluate proof-of-concept SMS, we perform retrospective multiband=2, Rplane=2, wave-encoded SMS experiments on the proposed in-vivo VFA data.

We generate wave-encoded SMS data by applying the wave point-spread-function to the acquired multi-channel data and then collapsing the FOV-shifted data across slices. We reconstruct with and without LORAKS regularization using the generalized SENSE-forward model that uses Fourier encoding, coil sensitivities, and wave point spread functions to map multislice images to k-space. We modeled wave-encoded SMS data with maximum gradient amplitudes of 10.2 mT/m, 4 cycles, maximum slew rate of 180 mT/m/ms, FOV shift of 3.7 and 51 mm slice distance. Coil sensitivity maps and slice-GRAPPA kernels are calibrated from the external calibration scans.
Acknowledgements

This work was supported in part by research grants NIH R01 EB017337, U01 HD087211, R01HD100009, R01 EB028797, U01 EB025162, P41 EB030006, U01 EB026996 and the NVidia Corporation for computing support. In addition, this material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 1122374. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.
Figures

Figure 1: (a) Comparison between the flip angle train and sampling raster of (c) standard HASTE and (d) the proposed VFA scheme. c) HASTE acquires data with constant 160° refocusing pulses and a sampling raster with integrated calibration lines and 63% partial Fourier. b) VFA achieves 1.36x reduction in voxel blurring with extended k-space coverage by employing a rapid reference GRE for calibration. In addition, the variable flip angles reduce SAR by 2.94x, potentially enabling a ~3x improvement in acquisition efficiency.

Figure 2: (a) Refocusing profile of the 160° refocusing pulse scaled to different VFA's and the profile generated from the scaled VFA HASTE pulse for three different flip angles. (b) HASTE and VFA signal evolution without and (c) with slice profile effects. VFA yields refocusing profiles that maintain the shape of the original 160° pulse profile and retains between 82-90% relative SNR to the standard HASTE both when considering and not considering slice profile effects.

Figure 3: (a) GRAPPA reconstructions of standard HASTE and the proposed VFA regime in the fetal phantom for two different slices. VFA visually reduces voxel blurring and retains ~75% SNR in comparison to HASTE. (b) HASTE reconstructed with GRAPPA and POCS partial fourier and the proposed VFA reconstructed with SENSE-LORAKS. The external calibration scan enables more advanced reconstruction techniques for the proposed VFA acquisition even without a calibration region.
Figure 4: Prospectively acquired in-vivo data comparing (a) GRAPPA reconstructions of standard HASTE and the proposed VFA scheme. VFA reduces blurring and retains 83% SNR in comparison to standard HASTE. (b) HASTE reconstructed with GRAPPA and POCS partial Fourier, and the proposed VFA reconstructed with SENSE-LORAKS using the external calibration scan. The reference scan allows prospective calibration of SENSE-LORAKS, and the proposed VFA regime acquired the entire stack of slices 2.3x faster than the standard HASTE.

Figure 5: Comparison between slice-by-slice GRAPPA, retrospective GRAPPA SMS, wave-encoded SMS and wave-LORAKS SMS. While slice-GRAPPA incurs some noise amplification, wave-LORAKS SMS produces cleaner images. Accounting for SAR associated with multi-band pulses in a prospective implementation, combining the proposed VFA technique with SMS could yield between 3-5x reduction in total scan time.