Magnetic Resonance Imaging

RLE Group
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MRI Group Overview
Our research in magnetic resonance imaging (MRI) for medical imaging can be grouped under three themes: (1) Radio-frequency (RF) excitation on multiple, simultaneous channels; (2) High-field spectroscopic magnetic resonance imaging (MRSI); and (3) Quantitative imaging of brain oxygenation parameters. The group consists of EECS and HST Ph.D. and MD students, and several collaborating faculty and students who are associated with MIT and with the HST Athinoula A. Martinos Center for Biomedical Imaging at Massachusetts General Hospital.

As members of the Martinos Center, directed by Dr. Bruce Rosen and Dr. Greg Sorensen, our students have access to a unique array of imaging resources, including a 7 Tesla human MRI scanner equipped with the first parallel transmit system of its kind, several 3 Tesla whole-body systems, a combined MRI/PET imager, and several high-field animal scanners. In addition, the Martinos Center has presence on MIT campus with a whole-body, 3T human imager with state-of-the art hardware, software, facilities and support. This center is under the direction of Professor John Gabrieli, HST and Brain and Cognitive Sciences.

Support for our work includes startup funds from HST and EECS; equipment, engineering expertise, and software training from Siemens Medical Solutions; equipment support from the Athinoula A. Martinos Center for Biomedical Imaging; HST Martinos Catalyst Fund; NIH R01 EB007942, NIH R01 EB006847, NIH NCRR P41RR14075.

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1. Parallel RF Excitation Design for Magnetic Resonance Imaging

Sponsors:
HST, EECS, NIH R01 EB007942, NIH R01 EB00684, NIH NCRR P41RR14075, Siemens Medical Solutions, HST Martinos Catalyst Fund.

Project Staff:
Mr. Lohith Kini, B.S. Kawin Setsompop, Ph.D., Mr. Borjan Gagoski M.S., Mr. Joonsung Lee, M.S., Prof. Vivek Goyal, Prof. Larry Wald, Prof. Elfar Adalsteinsson

In collaboration with Prof. Wald at the Martinos Center, and Dr. Schmitt at Siemens Medical Solutions, we are developing an emerging multi-channel RF excitation platform for MRI, also termed parallel RF transmission (pTx). Our primary motivation for this development is the mitigation of the severe RF excitation field inhomogeneity present at 7T for brain imaging with conventional single-channel RF excitation. Beyond the inhomogeneity mitigation application, other uses of pTx methods include flexibly tailored spatial excitation patterns of magnitude and phase that now become practical within reasonable excitation durations. Such methods are largely unexplored in MRI, but may enable clinical and research applications in several new areas where such excitations have been impractical. At present, our dominant goal is to produce robust and reliable RF excitation for high-field imaging, a necessary component to routine use of the emerging high-field imaging platform to the research and clinical communities.

A critical constraint on RF excitation in high-field human MRI is specific absorption rate (SAR). With recent demonstrations of highly-fidelity RF excitations with pTx systems, SAR has become a topic of significant interest as both local (1 g and 10 g) and whole-volume average SAR are critical parameters of interest. An ideal pTx system would deliver a real-time estimate of local SAR for each subject. With current computational simulation tools, such as FDTD on conventional processors, real-time estimates of electric fields and subsequent local SAR is a lengthy procedure (~10 hours for whole-head, sub-cm resolution).

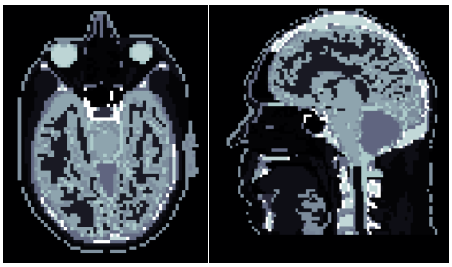

Figure 1 Axial and sagittal slices through the 3D segmented head model used in FDTD simulations for the pTx system.

In this work, Master of Engineering student Lohith Kini takes advantage of the advance in computational capabilities of graphics cards (GPU) for game developers, which have enabled dramatic speedups for computer graphics, and he applied some of this functionality to faster numerical electric field and SAR simulation compared to general CPUs. Mr. Kini used the Compute Unified Device Architecture (CUDA) enabled graphics cards in Finite Difference Time Domain (FDTD) simulations for SAR computation. He showed that using this framework, he can speed up computation by at least an order of magnitude compared to regular CPU computation. This will allow us to estimate SAR, B1, and E1 fields quickly for instances where SAR estimation for parallel transmission imaging of individual subjects (if head models are reshaped to fit the subject) is necessary, or for optimizing coil designs based on these estimates.

FDTD with Uniaxial Perfect Matching Layer (UPML) boundary conditions was coded on a NVIDIA GeForce 9800 GX2 (2 GPUs with 512 MB configurable memory on each GPU, approximate retail cost $200-$300) using the NVIDIA CUDA framework. FDTD equations were CUDA optimized by use of two kernel functions, one for the E field update equations and another for the B field update equations. FDTD simulations were run on a high-resolution (1x1x3 mm3) multi-tissue human head model, which is obtained via segmentation of anatomical MRI data. Each of the segmented tissues in the model are assigned both a density, ρ (kg/m3) and electrical conductivity, σ (S/m). Figure 1 shows an axial slice of the human head model. A parallel transmit coil was modeled by placing P = 8 copper loop elements at 45^{o} increments along a 20-cm-

diameter cylindrical surface centered on the head. Each loop element had an edge length of 10 cm with no input resistance, for computational simplicity and more accurate simulation results. The spatial resolution (256x256x128 cells) was 1 mm in-plane, 3 mm in z, and the time step resolution was 1.67ps. To obtain each individual transmit channel field profile, each channel was driven with a 1-ampere peak-to-peak 300-MHz sinusoid, while leaving all other channels without current to obtain steady-state electric and magnetic fields per ampere of input current per coil. The absorbing boundary conditions (UPML) were 10 cells deep and a perfect electrical conductor covered the outside of the entire grid. The UPML had a polynomial grading of order 4 and maximum reflection error of E fields obtained from FDTD simulation were then input into optimized SAR calculation algorithms. SAR for parallel transmission with current pulses played on channel p computed at any vector location r can be solved by numerical integration.

Computation of electric and magnetic fields via FDTD involves the time step update of E and H fields to be sequential in a leap-frog manner. Each update for each cell in a grid can be run a parallel since each field component being updated in a grid cell depends on neighboring cell field components, and thus makes ideal use of the capabilities of the GPU. Optimization of memory handling and GPU architecture allows for fast computation of each update with only overhead cost of storing maximum 6 field arrays (256x256x128 floats). UPML material properties can be broken up for each of the different edge regions of the grid (8 corner elements, 8 non-corner edge PML layers, and 6 faces). With multiple GPUs (Tesla or more advanced architecture), it is possible to run different channels simultaneously for FDTD simulation. Current card model allows only 2 channels to be excited separately but computed simultaneously.

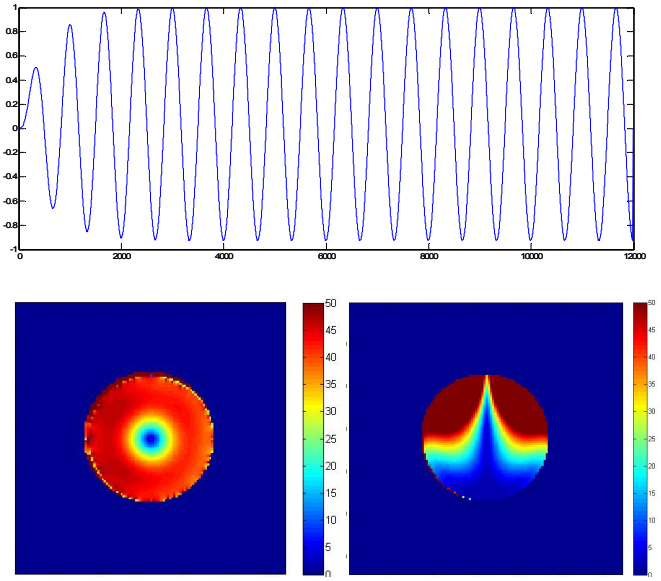

Figure 2 On the top is a plot of the input current waveform, a 300 MHz. 1-Ampere current source injected into the FDTD grid. On the bottom are two slices (axial and transverse) of the magnitude of the steady state electric **E** field (units V/m) in a spherical phantom with parameters that simulate muscle.

Figure 2 (top) shows the current waveform, driven as a 1A 300-MHz current over multiple cycles of the sinusoid as a function of the number of time steps simulated. Figure 2 (bottom) shows the steady state magnitude of the electric field throughout a spherical muscle phantom caused by driving the waveform in a current loop above the sphere. The runtime for 8,000 time steps (~12 cycles at 300 MHz) is 15 minutes (an order of magnitude faster than most CPU processing run times) on the present graphics card model (9800 GX2) and the runtime increases linearly with number of time steps used to update the field equations. The presented data support the idea that using CUDA for parallel implementation of FDTD can help alleviate time constraints on SAR computation and iterative coil optimization.

Current work is focused on quantitative validation of field and SAR estimates, and the integration of these computation modules into prototype SAR estimation for the Siemens pTx excitation system.

2. High-Field Magnetic Resonance Spectroscopic Imaging

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Project Staff:
Mr. Borjan Gagoski, Mr. Joonsung Lee, Ms. Trina Kok, Ms. Eva Ratai, PhD, Prof. Florian Eichler, MD, Kawin Setsompop, Ph.D., Prof. Larry L. Wald, Prof. Elfar Adalsteinsson

Imaging at 7T suffers from severe B_1 inhomogeneities that manifest as signal to noise ratio (SNR) loss, which is a particularly serious burden in chemical shift imaging (CSI). Parallel RF transmission (pTx) is an emerging technology to mitigate B_1^+ inhomogeneity during RF excitation, where, typically, 8 RF amplifiers play 8 independent RF waveforms, enabling more complicated RF excitation patterns using shorter RF waveforms compared to single-channel systems. Previous work in this field includes successful 7T in-vivo B_1^+ mitigation. For CSI related applications however, the B_1^+ mitigation constraint extends over the frequency bandwidth of the metabolites of interest and presents a more challenging RF design problem.

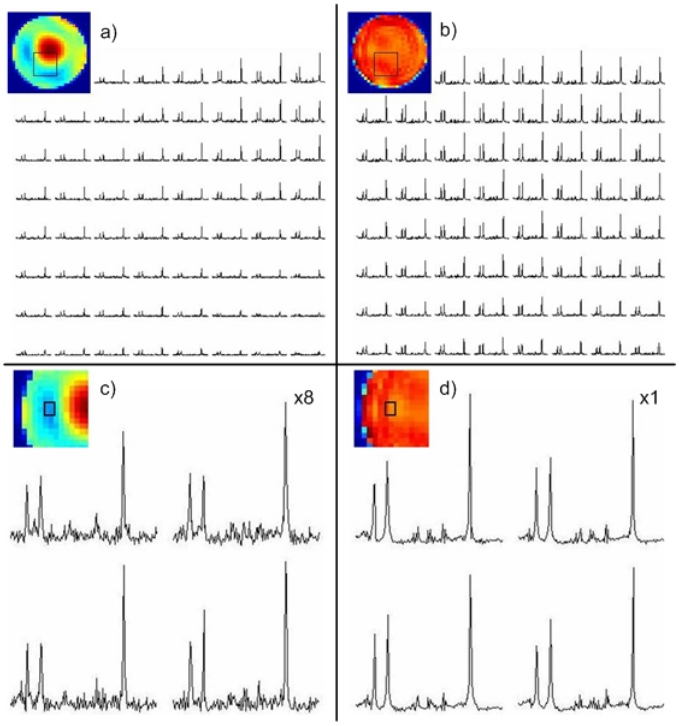

Figure 3 Magnitude spectra acquired using phased-encoded CSI readout (TR=1s, TE = 5ms, voxel size = 0.78cc) from particular spatial locations of the spectroscopy phantom containing physiological concentrations of the major brain metabolites. Spectra from the spokes-based design shown in b) demonstrate spatially uniform excitation compared to the sinc BC excitation shown in a). The most dramatic benefit is shown on the bottom two images where the glutamate signals are easily detectable for the spokes-based excitation as shown in d) but are at the noise level for the BC sinc excitation as shown in c).

In this work, graduate student Borjan Gagoski demonstrated the feasibility of spectroscopic imaging combined with parallel RF transmission for wideband RF mitigation. His proof-of-concept implementation included a phase-encoded (PE) CSI readout with a pTx mitigation excitation over a 600Hz spectral bandwidth and an excitation with a 3 cm thick slab. Due to current hardware constraints, he limited this demonstration to the low flip-angle domain where excitation k-space analysis holds, and applied spokes-based slice selective RF design due to Dr. Kawin Setsompop to our eight channel 7T pTx system at the Martinos Center. He used a spectroscopy phantom containing physiological concentrations to mimic the major brain metabolites of interest in vivo. pTx water suppression was achieved with a Gaussian-shaped pulse preceding the excitation. The goal of this work is to demonstrate that compared to the regular birdcage (BC) mode excitation, the proposed pTx wideband excitation provides spatial uniformity of metabolite signals in a phantom with physiological brain metabolite concentrations.

As he demonstrates quite dramatically with the data in Figure 3, the 4-spoke design yields greatly improved spatial-spectral uniformity across the entire excited slice, and performs significantly better than the standard BC-sinc excitation. Furthermore, the excellent water suppression was achieved by 3-spectrally-selective pulses in a RF-shim, pTx version of CHESS for 8 channels.

Future work includes the extension of the current pTx design to large flip angles and estimation and monitoring of SAR for human imaging.

Publications

Journal Articles, Published

Zelinski AC, LL Wald, K Setsompop, V Goyal, and E Adalsteinsson, "Sparsity-Enforced Slice-Selective MRI RF Excitation Pulse Design," IEEE Transactions Medical Imaging, 27, 1213-29, September 2008.

Zelinski AC, LM Angelone, VK Goyal, G Bonmassar, E Adalsteinsson, and LL Wald, "Specific absorption rate studies of the parallel transmission of inner-volume excitations at 7T," Journal of Magnetic Resonance Imaging. 28 1005-18, October 2008.

Setsompop K, V Alagappan, AC Zelinski, A Potthast, U Fontius, F Hebrank, F Schmitt, LL Wald, and E Adalsteinsson, "High-flip-angle slice-selective parallel RF transmission with 8 channels at 7 T," Journal of Magnetic Resonance, 195, 76-84, November 2008.

Ratai E, T Kok, C Wiggins, G Wiggins, E Grant, B Gagoski, G O'Neill, E Adalsteinsson, and F Eichler, " Seven-Tesla proton magnetic resonance spectroscopic imaging in adult X-linked adrenoleukodystrophy," Archives of Neurology, 65, 1488-94, November 2008.

Setsompop K, V Alagappan, BA Gagoski, T Witzel, J Polimeni, A Potthast, F Hebrank, U Fontius, F Schmitt, LL Wald, and E Adalsteinsson, "Slice-selective RF pulses for in vivo B1+ inhomogeneity mitigation at 7 Tesla using parallel RF excitation with a 16-element coil," Magnetic Resonance in Medicine, 60, 1422-32, December 2008.

Setsompop K, V Alagappan, BA Gagoski, A Potthast, F Hebrank, U Fontius, F Schmitt, LL Wald, and E Adalsteinsson, "Broadband slab selection with B1+ mitigation at 7T via parallel spectral-spatial excitation," Magnetic Resonance in Medicine 61, 493-500, February 2009.

Pfefferbaum A, E. Adalsteinsson, T. Rohlfing, EV Sullivan, "MRI estimates of brain iron concentration in normal aging: comparison of field-dependent (FDRI) and phase (SWI) methods.," NeuroImage. 47(2), 493-500, August 15, 2009.

Journal Articles, Accepted for Publication

Cantillon-Murphy P, LL Wald, M Zahn, and E. Adalsteinsson, "Measuring SPIO and Gd contrast agent magnetization using 3 T MRI." NMR Biomed. Forthcoming.

Meeting Papers, Published

Gagoski, BA, K Setsompop, J Lee, V Alagappan, M Hamm, A. vom Endt, LL Wald, and E. Adalsteinsson, "Spectroscopic imaging using wideband parallel RF excitation at 7T," Proceedings of the International Society for Magnetic Resonance in Medicine, Honolulu, Hawaii, (1 page), April 2009.

Bolar DS, BR Rosen, AG Sorensen, and E Adalsteinsson, “QUantitative Imaging of eXtraction of Oxygen and TIssue Consumption (QUIXOTIC) using velocity selective spin labeling,” Proceedings of the International Society for Magnetic Resonance in Medicine, Honolulu, Hawaii, (1 page), April 2009.

Bolar DS, AG Sorensen, BR Rosen, and E Adalsteinsson, “Feasibility of QUantitative Imaging of eXtraction of Oxygen and TIssue Consumption (QUIXOTIC) to assess functional changes in venous oxygen saturation during visual stimulus,” Proceedings of the International Society for Magnetic Resonance in Medicine, Honolulu, Hawaii, (1 page), April 2009.

Pfefferbaum A, E. Adalsteinsson, T. Rohlfing, and EV Sullivan, “In vivo estimates of regional iron deposition in young and elderly human brains,” Proceedings of the International Society for Magnetic Resonance in Medicine, Honolulu, Hawaii, (1 page), April 2009.

Lee J, B. Gagoski, M. Hamm, and E. Adalsteinsson, "Subcutaneous lipid suppression via variable-density spiral sampling for full cortical coverage in chemical shift imaging," Proceedings of the International Society for Magnetic Resonance in Medicine, Honolulu, Hawaii, (1 page), April 2009.

Kini L, LL Wald, and E. Adalsteinsson, "Fast E1, B1 and SAR simulation with the use of graphics processors," Proceedings of the International Society for Magnetic Resonance in Medicine, Honolulu, Hawaii, (1 page), April 2009.

Theses

K. Setsompop, *Design Algorithms for Parallel Transmission in Magnetic Resonance Imaging,* Ph.D. Thesis, Department of Electrical Engineering and Computer Science, MIT, 2008.

P. Cantillon-Murphy, *On the Dynamics of Magnetic Fluids in Magnetic Resonance Imaging,* Ph.D. Thesis, Department of Electrical Engineering and Computer Science, MIT, 2008.

A.C. Zelinski, *Improvements in Magnetic Resonance Imaging Excitation Pulse Design,* Ph.D. Thesis, Department of Electrical Engineering and Computer Science, MIT, 2008.

T. Kok, *Detection of Brain Metabolites in Magnetic Resonance Spectroscopy,* M.S. Thesis, Department of Electrical Engineering and Computer Science, MIT, 2008.