Magnetic Resonance Imaging

RLE Group
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Technical and Support Staff
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MRI Group Overview
Our research area is magnetic resonance imaging (MRI) for medical imaging, focusing on methods for acquisition, reconstruction, and processing with applications to human disease. Currently, we pursue research in three areas: (1) Radio-frequency (RF) excitation on multiple, simultaneous channels; (2) High-field spectroscopic magnetic resonance imaging (MRSI); and (3) Magnetic nanoparticle contrast manipulation in MRI. The group consists of EECS and HST graduate and MD students, along with 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, (or briefly, the Martinos Center.)

We are members of the Martinos Center, directed by Dr. Bruce Rosen and Dr. Greg Sorensen. The Martinos Center is unique in its scope and variety of imaging resources, including a 7 Tesla human MRI scanner, two 3 Tesla whole-body systems with insert gradients, and three high-field animal scanners. In addition, the Martinos Center has presence on MIT campus with a whole-body, 3T human imager that mirrors the comparable software and hardware platforms in Charlestown. 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; NIH NCRR (P41RR14075); the MIND Institute. Collaborators on ferrofluid research received support from the Thomas and Gerd Perkins Chair held by Professor Mark Zahn; and generous alumnus Thomas F. Peterson. Prof. Adalsteinsson receives generous support through the Robert J. Shillman career development award.

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1. Parallel RF Excitation Design for Magnetic Resonance Imaging

Sponsors:
HST, EECS, National Defense Science and Engineering Graduate Fellowship, Robert J. Shillman career development award, NIH NCRR P41RR14075. Siemens Medical Solutions.

Project Staff:
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In a collaboration with Prof. V. Goyal, Prof. Wald at the Martinos Center, and Dr. Schmitt at Siemens Medical Solutions, we have pursued a productive program in the development of multi-channel RF excitation for MRI, also termed parallel RF excitation. A strong motivation for this work is the drive to mitigate the severe RF excitation field inhomogeneity present at 7T for brain imaging with conventional single-channel excitation coils. Additionally, flexibly tailored spatial excitation patterns become practical within reasonable excitation durations, and such methods may enable clinical and research applications in several areas. A goal of this work is to produce robust and reliable RF excitation for high-field imaging, a necessary condition for routine use of this emerging research imaging platform to the research and clinical communities.

Initial demonstrations of the proposed designs took place on an 8-channel prototype system configured by Siemens Medical Solutions in Erlangen, Germany, where we successfully demonstrated 8-channel parallel excitations at 3T. As of June 2007, an equivalent 8-channel system is being configures at the Martinos Center, where we will carry out future development. In the following, we touch on selected examples of the impressive contributions made by graduate students Adam Zelinski (also advised by Prof. V. Goyal) and Kawin Setsompop, but refer to the publication list for a more detailed account of each component of the work.

Among graduate student Adam Zelinski's many contributions was a novel RF pulse design algorithm that yielded fast slice-selective excitation pulses for mitigation of B_1 inhomogeneity at high field strength. This work is important in that it demonstrates *in vivo* that by optimally designing the placement of RF deposition, it is possible to mitigate B1 inhomogeneity at 7T within feasible pulse duration. The method is based on sparse approximation theory, and under the low-flip-angle domain approximation, was capable of significant B_1 mitigation is shown at 7T in a human head for the critical class of slice-selective excitations, even in the presence of extremely severe B1 inhomogeneity. While the design method was developed and tested for conventional single-channel excitation systems, it extends nicely to multi-channel excitation systems where even further time reductions and excitation flexibility are available.

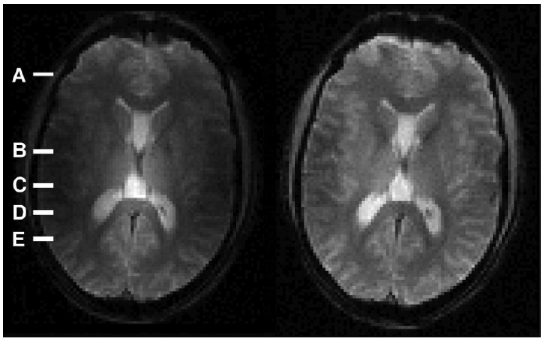

Figure 1 Demonstration of sparsity-enforced B1 mitigation at 7T. The image on the left is acquired with a conventional RF pulse, while the right-side image shows the effect of incorporating both the transmit and receive coil profiles into the RF design to produce essentially a uniform profile for improved conspicuity of anatomical features. The labels A-E indicate locations of segments that were used for quantification of the performance of the design.

Parallel RF design methods have relied on the small-flip-angle approximation to the Bloch equation. Such methods have been used for demonstration of B1 mitigation and to produce highly uniform slice selective excitation with relatively short excitation durations. However, at larger flip angles this low-flip-angle design method fails, and several important RF pulses for conventional MRI rely critically on accurate production large flip angles. Among his contributions,

graduate student Kawin Setsompop proposed a method that incorporates the full non-linear Bloch equation into the RF design of pulses with arbitrary flip angle. A Powell-based non-linear optimization with local cost function based on partial Bloch simulations was used to improve the speed and convergence of the design by an order of magnitude. The method was then used in the design of 90º and 180º spin-echo excitation on our 8-channel prototype system at 3T, equipped with an 8-channel transmit array (Fig. 2).

Additional work in parallel excitation included the design of magnitude-least-squares for improved profile homogeneity with a tradeoff of less important phase profiles; the formulation, analysis, and evaluation of specific absorption ratio (SAR) in parallel excitation, a critical constraining parameter to *in vivo* application of any RF pulse; reduced artifact burden and improved power characteristics of RF design with LSQR and CGLS algorithms; quantitative B1 mapping; and the incorporation of unavoidable residual main field inhomogeneities into the RF design.

We look forward to a productive upcoming phase in this research with the 7T parallel excitation system at the Martinos Center where we pursue these and other ideas, and to extend them further to applications such as spectroscopic imaging, functional imaging, diffusion tensor imaging, and large-volume structural imaging.

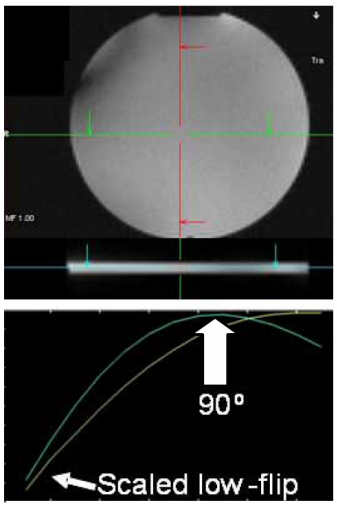

Figure 2 Phantom demonstration of a 90º degree excitation, showing excellent in-plane homogeneity (top) as well as slice selection (middle profile). At the bottom is shown a measured validation of the 90º excitation by comparison with anticipated signal behavior as a function of excitation voltage. Excellent agreement is shown with Bloch simulation prediction of the two designs, scaled low-flip vs. a 90º high-flip. The 10 o'clock in-plane artifact is due to a component failure during the experiment.

2. High-Field Magnetic Resonance Spectroscopic Imaging

Sponsors:
HST, EECS, NIH NCRR P41RR14075, The Korean Foundation for Advanced Studies, National Defense Science and Engineering Graduate Fellowship, NIH Grant Number 5P01NS 3561. Robert J. Shillman career development award.

Project Staff:
Mr. Borjan Gagoski, Mr. Joonsung Lee, Mr. Joseph Y. Cheng, Mr. Joonsung Lee, Ms. Trina Kok, Ms. Eva Ratai, PhD, Prof. Florian Eichler, MD, Prof. Larry L. Wald, Prof. Elfar Adalsteinsson

Within this project, we pursue the efficient and fast encoding of volumetric spectroscopic imaging, the detection and quantification of low-SNR brain metabolites, and the development of techniques that optimally encode for coupled or overlapping spins in the proton spectrum. Related work is the characterization and design of gradient waveforms necessary to implement fast MRSI. Here, we describe an important milestone in this area, where graduate student Borjan Gagoski has implemented and validated 7T spiral-based MRSI.

Among the challenges in MRSI are the intrinsically low signal-to-noise ratio (SNR) of the metabolites of interest as well as main field (B0) and RF excitation field (B1) inhomogeneities. In addition, in phase-encoded (PE) CSI, field-of-view (FOV), spatial resolution and imaging time are not independent parameters, imposing imaging time constraints. CSI with time-varying readout gradients offers significantly improved acquisition efficiency without SNR tradeoffs, but at the cost

of high-fidelity gradient hardware, high-capacity receiver pipeline, and non-trivial trajectory designs and reconstruction algorithms. With emerging 7T human scanners, SNR and chemical shift dispersion are improved over 1.5T and 3T platforms, but at the cost of more severe B0 and B1 inhomogeneities. For brain imaging at 7T, these inhomogeneities are very pronounced and responsible for a significant signal variation within the volume of interest (VOI). In this work we present in vivo PRESS box excitation for spiral MRSI with results and demonstrate the equivalence of spectra with the conventional phase-encoded technique. We also present in vivo spiral MRSI at 7T. The feasibility of efficient spatial encoding for CSI without SNR tradeoffs is demonstrated and compared to phase encoded acquisitions.

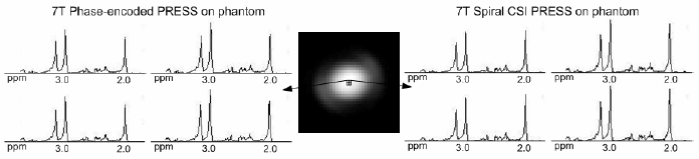

Figure 3 Comparison of spectra acquired with phase encoded (left) and spiral readout (right). With matched voxel size and imaging time, the two acquisitions yield equivalent data.

The single-slice spiral CSI was compared with PE CSI in a phantom study for validation. Fig. 3 shows spectra from four spatial locations in the middle of the uniform spherical phantom with physiological concentrations of the major brain metabolites acquired by 1) PE CSI (16x16 grid, TR = 2s) and 2) Spiral CSI (7 averages) with spirals matching the PE voxel size. We show that for fixed voxel size and acquisition time, the PE and spiral readouts yield equivalent results. Fig. 4 shows spectra from the single slice excitation on a healthy volunteer. As expected, peripheral lipid signals are strong, but the Hanning apodization aids in limiting the extent of contamination.

In this work we have demonstrated in vivo 7T 3D spiral CSI acquisition with variable-density sampling. As is the case for conventional imaging, means of providing uniform excitation flip angle across the volume of interest are critical to the success of largevolume CSI at 7T, and future work will combine the efficient encoding presented with adiabatic or parallel RF excitation schemes for uniform excitation.

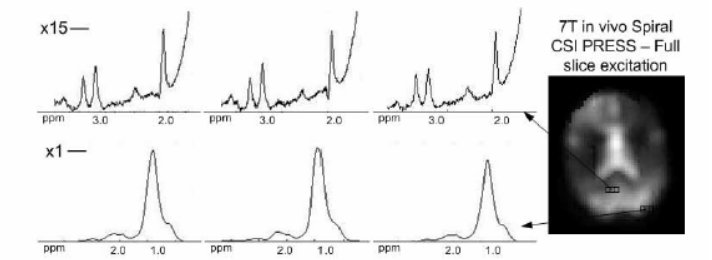

Figure 4 In vivo spiral MRSI at 7T with full-FOV excitation, including subcutaneous lipid signals.

3. Manipulation of Magnetic Nanoparticles for Application in Magnetic Resonance Imaging

Sponsors:
HST, EECS, The Thomas and Gerd Perkins Chair, Robert J. Shillman career development award.

Project Staff:
Mr. Pádraig Cantillon-Murphy, Prof. Mark Zahn, Prof. Larry L. Wald, Prof. Elfar Adalsteinsson

In magnetic resonance imaging, contrast agents are classified as either ‘positive’ or ‘negative’ agents based on their effect of increasing or decreasing the detected signal relative to a

background region. Compounds in both categories are well studied, including commercially available and widely used gadolinium-based agents for signal enhancement, (e.g. in MR angiography), and iron-oxide based agents for cell labeling in animal models, also known as super-paramagnetic iron oxides (SPIO), that reduce local signal intensities in regions that contain contrast material.

In this project we seek to establish experimental verification of recent novel observations based on theoretical derivations and numerical simulations, which suggest that the complex susceptibility of magnetic nanoparticles can be modulated in the presence of either a rotating magnetic field or via a rotating flow component. Such variation in nanoparticle-induced susceptibility could be used to modulate relaxation effects on hydrogen nuclei in water, the signal source in MRI.

In order to demonstrate an effect on MRI signal intensity, we are exploring a model of concentric cylinders, shown in Figure 5, by simulation with *Comsol Multiphysics*. A large DC field, B_0, along the z axis, is orthogonal to a second rotating field, B_{rot} in the *xy* plane such that the two excitations are uncoupled by Shliomis' Relaxation Equation and the problem is reduced to a 2D simulation of two sub-domains consisting of ferrofluid and water. Due to the differing susceptibilities between the ferrofluid and the water, the applied rotating field results in a changing dipolar field in the water, dependent on the frequency of excitation of B_{rot}. This change in the local B field in the water can be used to impact the MRI image signal intensity under careful selection of MRI excitation techniques.

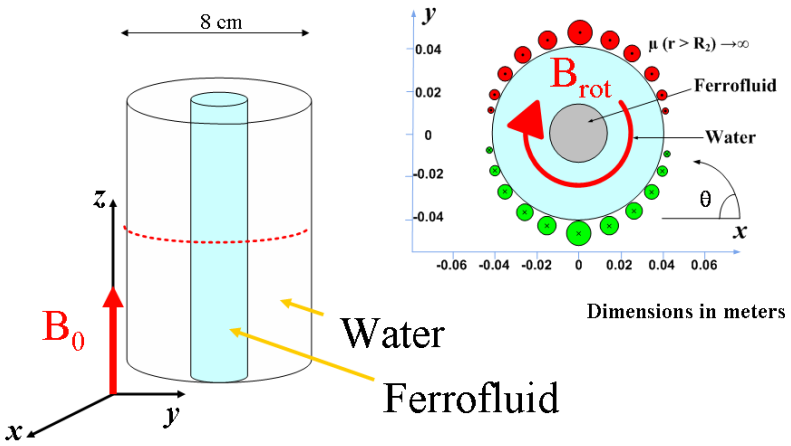

Figure 5 Schematic illustration of the model of susceptibility modulation with magnetic nanoparticles under the influence of an external, transverse rotating field and a static, longitudinal main field that corresponds to the main field in conventional MRI.

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