Magnetic Resonance Imaging

RLE Group
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MRI Group Overview
Our research area is magnetic resonance imaging (MRI) for medical imaging. We pursue research in four areas: (1) Radio-frequency (RF) excitation on multiple, simultaneous channels; (2) High-field spectroscopic magnetic resonance imaging (MRSI); (3) Arterial spin labeling (ASL); and (4) Magnetic nanoparticle properties and contrast manipulation in MRI. 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, (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, several 3 Tesla whole-body systems, and high-field animal scanners. In addition, the Martinos Center has presence on MIT campus with a whole-body, 3T human imager. 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 R01 EB007942, NIH R01 EB006847, NIH NCRR P41RR14075; Whitaker Foundation Fellowship, US Department of Defense NDSEG Fellowship F49620-02-C-0041, 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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[2] Siemens Medical Solutions, Erlangen, Germany.

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 R01 EB007942, NIH R01 EB00684, NIH NCRR P41RR14075, Siemens Medical Solutions.

Project Staff:
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In a collaboration with Prof. Wald at the Martinos Center, Dr. Schmitt at Siemens Medical Solutions, and Prof. V. Goyal, we have pursued a productive program in the development of multi-channel RF excitation 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 technology, which relies on single-channel excitation coils. Additionally, applications of pTx methods include flexibly tailored spatial excitation patterns that now become practical within reasonable excitation durations. The use of methods of more intricate excitation patterns that, for instance match a particular anatomical or vascular structure, are largely unexplored but may enable clinical and research applications in several new areas where such excitations have been impractical. However, for the present, the dominant goal of this work 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.

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 was installed at the 7T scanner at the Martinos Center in Charlestown Navy Yard where we have continued our developments and made substantial progress. In the following, we touch on selected examples of the impressive contributions made by graduate students Adam Zelinski (also advised by Prof. V. Goyal), Kawin Setsompop, and Borjan Gagoski, but refer to the complete publication list for a more detailed account of the various components of the research pTx methods.

Among graduate student Adam Zelinski's many contributions was a novel approach to pTx that determines the optimal subset of excitation modes for a given target of excitation. This approach yields a better match between the limited number of (expensive) RF power amplifiers and a larger number of excitation modes that can be obtained with (much less expensive) RF coil design. Hardware costs and complexity naturally limit the feasible number of excitation channels, but forming linear combinations of RF array elements can transform the spatial modes of the array into a different basis set, potentially capturing a majority of the pTx efficiency and acceleration capabilities in a subset of the channels. The available RF channels are then applied only to a subset of array modes, which are chosen based on their contribution to excitation efficiency and encoding. For pTx applications the desired excitation pattern is specified and an explicit incorporation of this knowledge into the selection of the mode subset proves to be useful. Here, Adam proposed a fast target-dependent

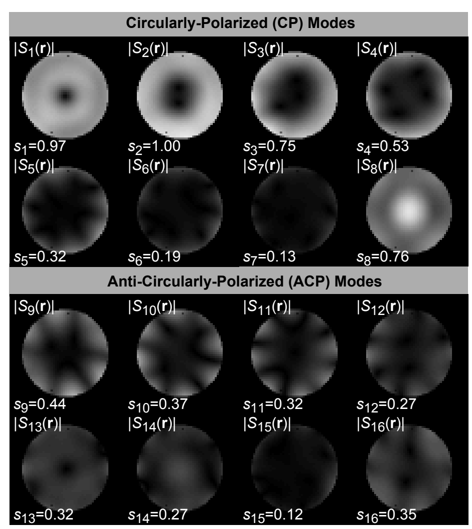

Figure 1 The 16 available channel modes in a water phantom at 7T. Only 8 RF amplifiers are available to implement pTx excitations with these modes.

sparsity-enforced subset selection (SESS) algorithm that explicitly accounts for the desired excitation pattern when choosing the mode subset, in contrast with principal component or covariance analysis methods that use only the spatial profiles and determine only a *single* subset for all excitations. For demonstration of the algorithm, he used SESS to determine 8 modes of a 16 mode array for use on an 8-channel pTx system at 7T when forming slice-selective spatially-tailored excitations with uniform and ring-shaped target patterns in a water phantom. Excitations using the SESS subsets were compared to those chosen from covariance analysis of the mode spatial maps. Brute-force analysis finds that SESS actually determines the best of all 12871 possible subsets for this coil for the former excitation, and a near-optimal subset for the latter.

Graduate student Kawin Setsompop demonstrated for the first time the mitigation, *in vivo*, of RF inhomogeneity at 7T in a recently accepted manuscript to *Magnetic Resonance in Medicine.* Slice-selective RF waveforms that mitigate severe B1+ inhomogeneity at 7 Tesla using parallel excitation were designed and validated in human studies on six subjects using a 16-element degenerate stripline array coil driven with a butler matrix to utilize the 8 most favorable birdcage modes. The parallel RF waveform design applied magnitude least squares criteria with an optimized k-space sampling to significantly improve profile uniformity compared to conventional least squares designs. Parallel excitation RF pulses designed to excite a uniform in-plane flip angle with slice selection in the z-direction were demonstrated and compared to conventional sinc-pulse excitation and RF shimming. In all cases, the parallel RF transmission significantly mitigated the effects of inhomogeneous B1+ on the excitation flip angle. The optimized parallel RF pulses for human B1+ mitigation were only 67% longer than a conventional single-channel sinc-based excitation, but significantly outperformed RF shimming. For example the standard deviations of the in-plane flip-angle (averaged over six human studies) were 16.7% for conventional birdcage excitation, 13.3% for RF shimming, and 7.6% for the parallel spatially tailored excitation. This work demonstrates that excitations with parallel RF systems can provide slice selection with spatially uniform flip angles at high field strengths with only a small pulse-duration penalty. (Fig 2).

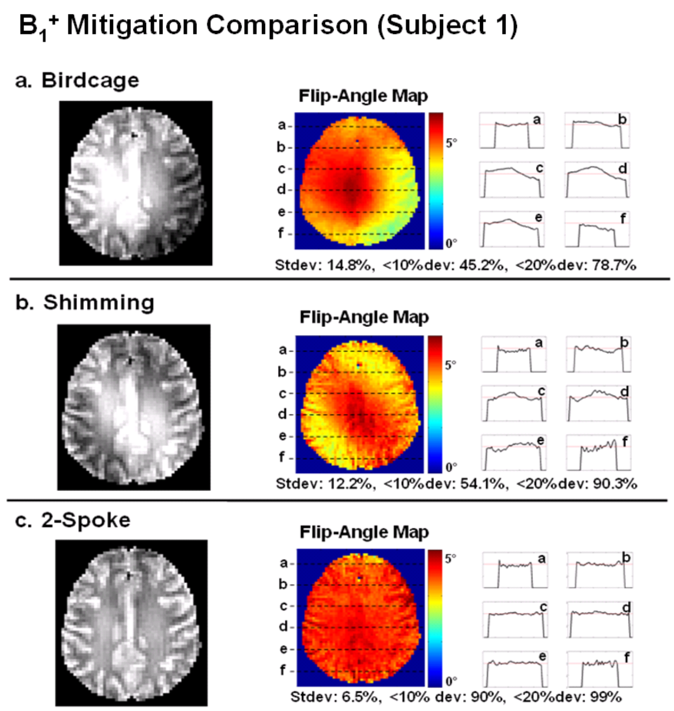

Figure 2 Comparison of B1+ mitigation for subject 1. The comparison includes slice selection based on conventional sinc excitation in birdcage mode (top row), RF shimming (center row), and two-spoke excitation pulses (bottom row). On the left of each row is the in-plane image of the excited slice after the removal of the received profile. On the right is the flip-angle map estimate, along with the line profile plots..

Future work in applications of pTx includes structural imaging, spectroscopic imaging, diffusion tensor imaging, functional imaging, as well as body imaging at 3T.

2. High-Field Magnetic Resonance Spectroscopic Imaging

Sponsors:
HST, EECS, NIH NCRR P41RR14075, The Korean Foundation for Advanced Studies, A*STAR, NIH Grant Number 5P01NS 3561. Robert J. Shillman career development award. NIH R01 EB007942, NIH R01 EB00684, NIH NCRR P41RR14075, Siemens Medical Solutions.

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The benefits of 7T chemical shift imaging (CSI) include increased SNR and chemical shift dispersion compared to lower-field CSI. However, high field imaging suffers from severe B1 inhomogeneities that manifest as SNR loss, which is a serious burden in CSI applications. In addition, for volumetric CSI, phase-encoded (PE) CSI suffers from intrinsically long acquisition times. CSI using spiral readout gradients samples (kx, ky, kf) space efficiently without SNR tradeoffs and addresses the encoding-time constraint of PE CSI at the cost of high-fidelity gradient hardware and non-trivial trajectory design and reconstruction algorithms. Prior work on in vivo 7T Spiral CSI demonstrated the encoding efficiency of spiral CSI, but also illustrated the expected and significant signal variation across the FOV.

Graduate students Borjan Gagoski and Kawin Setsompop combined spiral CSI readouts with parallel RF transmission (pTx) to mitigate B1+ inhomogeneities. This initial demonstration was limited to the low flip-angle domain where excitation k-space analysis holds, and spokes-based slice selective RF design to an eight channel transmit system at 7T. The 8 transmit channels enable reduced-duration, slice-selective RF pulses that implement excellent on-resonance B1+ mitigation and can be optimized to yield B1+ mitigation over a 600 Hz bandwidth. The goal of this work is to demonstrate efficient spiral CSI encoding with B1+ mitigated spatial-spectral excitation over a spatial FOV and frequencies of interest for 1H brain spectroscopic imaging by spiral CSI acquisitions of the high-SNR water signal shifted to 5 different off-resonance frequencies.

Constant-density spiral readout was used in a gradient-echo (TE=5ms) 8-channel pTx pulse on a 7T scanner with whole-body gradients (40mT/m, 180 mT/m/ms). Eight orthogonal birdcage (BC) modes were driven via a Butler matrix transformation of a 16 channel stripline array. After quantitative B1+ mapping, the pTx pulses were designed and optimized to provide B1+ mitigation for uniform spatial-spectral excitation over a 5-cm slab in z and 600Hz spectral bandwidth. In addition, a B0-correction optimization using a separately acquired B0 map improved reliability of the spectral excitation. The pTx duration was 1.76 ms. The spiral readout encoded the (x,y,z,f) space for Cartesian grid of 32x32x8x512 points (x,y,z,f) with a 1600Hz bandwidth. The encoding used a 24-cm in-plane FOV and 8cm in z, for an overall voxel size of 0.56 cc. The maximum slew rate and amplitude were limited to a conservative 100T/m/s and 10mT/m, respectively, yielding imaging time of 1.75 minutes (TR=1s). The acquisition was repeated, in the absence of water suppression, for a series of off-resonance shift of the water peak, ranging from -300 to 300Hz. The spiral CSI data were received with 16 Rx channels, 2X-gridded with a Kaiser-Bessel kernel, and combined using complex weights from the spectroscopy data themselves.

In addition to spiral CSI, we collected gradient-recalled echo 2DFT images using the wide-band excitation. After dividing out the receive profile, the transmit profile demonstrated excellent uniformity of signal in both space and frequency. Due to the low-flip-angle domain of the pTx, and in order to yield high SNR for evaluation of the spectral and spatial evaluation of the pulse with spiral CSI we performed five spiral CSI scans on a single peak water phantom, in four of which we manually shifted the central frequency of the transmitter in order to get the off-resonance water at -300Hz, -150Hz, 100Hz and 200Hz. The resulting spectra in voxels at several different locations, the peak amplitude as a function of frequency was only slowly varying.

We successfully demonstrated the feasibility of pTx with spiral CSI encoding using 8 transmit channels and 16 receive channels. These results provide strong motivation for extending the low-flip-angle developments to large-flip-angle pTx designs with the demonstrated wide-band pTx properties, a prerequisite for detection of low-concentration brain metabolites. I RF excitation schemes for uniform excitation.

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