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); (3) Quantitative imaging of brain oxygenation parameters; and (4) Image reconstruction from substantially undersampled data. The group consists primarily of EECS graduate students, with several collaborating faculty, postdocs, and students who are associated with MIT and with the HST Athinoula A. Martinos Center for Biomedical Imaging at Massachusetts General Hospital. Two projects are highlighted in this report as examples of ongoing work in the group.

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; research funding through the Siemens-MIT Alliance; 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. Phase-based Regional Oxygen Metabolism (PROM) at 3T and feasibility at 7T

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Project Staff:
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In collaboration with Prof. Rosen, Director of the Martinos Center, we are developing methods for non-invasive imaging of fundamental brain oxygenation parameters with MRI. We have pursued two separate paths towards this goal, one developed by Dr. Bolar and termed QUIXOTIC for with QUantitative Imaging of eXtraction of Oxygen and TIssue Consumption, and the other PROM, for Phase-based Regional Oxygen Metabolism by Audrey Fan as presented in her masters thesis. The two methods are motivated by the same goal, i.e. the quantitative measurement of cerebral metabolic rate of oxygen (CMRO2) with MRI, but make use of different physics, require different acquisition designs, and yield different degree of spatial localization of oxygenation quantification. Here we outline recent work on PROM, the subject of a recent conference paper and a paper manuscript.

$CMRO_2$ is an important indicator for brain function and disease, including stroke and tumor. $CMRO_2$ can be quantified from measurements of venous oxygen saturation (Y_v) and cerebral blood flow (CBF) in cerebral veins. Bulk susceptibility measurements based on gradient-echo phase maps has been used to estimate Y_v *in vivo* at 3T. Challenges of this technique include partial volume effects, phase wrapping, and background susceptibility gradients. Here we quantify $CMRO_2$ by independently measuring Y_v and CBF at 3T using MR susceptometry and arterial spin labeling (ASL). We also demonstrate feasibility of quantifying Y_v at 7T, which offers higher-resolution analysis of vessels of interest.

A flow-compensated, 2D GRE sequence was used to acquire axial magnitude and phase images at 3T (0.5-mm resolution in-plane, 2.0-mm thick, FOV 224 x 224 mm^2). Data were collected for TEs of 10, 15, 20, and 25 ms. Local regions of interest (32 x 32 pixels) containing veins perpendicular to the slice were manually identified. The phase of the ROI was high-pass filtered.

The average phase difference ($\Delta\varphi$) between the inside of the vein and the surrounding tissue was measured for each TE. The corresponding field difference, $\Delta B = B_{vein} - B_{tissue}$, was calculated by a linear fit of the measured $\Delta\varphi$ vs. TE. The oxygen saturation Y_v was then determined from ΔB through Eq 1, where $\Delta\chi_{do}$ = 0.18ppm (cgs) is the susceptibility difference between fully deoxygenated and fully oxygenated blood, and *Hct* = 0.4 is the assumed hematocrit value.

$$\Delta B = \frac{1}{3} 4\pi \Delta\chi_{do} Hct \cdot (1 - Y_v) B_0 \qquad (Eq.1)$$

$$CMRO_2 = \frac{Y_a - Y_v}{Y_a} \frac{Hct}{3.0 \cdot 1.6125} \cdot CBF \cdot Y_a \qquad (Eq.2)$$

To measure CBF, a PICORE-Q2TIPS pulsed ASL acquisition was used with 3.5-mm in-plane resolution and 4.0-mm slice thickness. To calibrate the CBF measurement, the fully relaxed longitudinal magnetization of arterial blood (M_{0B}) was estimated from the local tissue equilibrium magnetization. $CMRO_2$ (μmol/g/min) was determined for five vessels from one healthy subject using Eq 2, where the arterial oxygen saturation was assumed to be Y_a = 1.

At 7T, a 3D GRE sequence was used to acquire axial images with 0.33 mm in-plane resolution, 1.0 mm slice thickness and FOV of 192 x 168 mm^2, for TE's of 10, 14, and 20 ms. The phase images were unwrapped using FSL *prelude* and high-pass filtered with a Gaussian kernel. Y_v was quantified for ten vessels from one healthy subject at rest using Eq 1.

Through-plane vessels from various slices were identified from magnitude images at 3T and 7T. After filtering the phase ROI, the average $\Delta\varphi$ between the vein and the surrounding tissue was determined for each TE. A sagittal view of the vessel (magnitude) was used to confirm that the vessel was perpendicular to the slice. For each vessel, the linear fit of $\Delta\varphi$ versus TE was robust, yielding R^2 values >0.95. Y_v measurements were consistent across several adjacent slices to which the vessel was approximately perpendicular. The Y_v was determined for ten veins at 7T, yielding a mean oxygenation value $\overline{Y}$ = 0.61±0.04, which lies in the expected physiological range.

Y_v and CBF were determined for five vessels in a healthy subject at 3T. The CBF for each vein was measured by averaging values from a 7 mm^2 region that included the vessel of interest. The mean CBF was 49.1 ml/100g/min, which is consistent with the normal physiological range. $CMRO_2$ was then determined for each vein using Eq 2 as described above. The mean $CMRO_2$ across the five vessels was 1.66 ± 0.22 μmol/g/min, which lies in the range reported for $CMRO_2$ by PET.

We have combined phase-based measurements of venous oxygen saturation (Y_v) with ASL measurements of cerebral blood flow (CBF) to quantify the cerebral metabolic rate of oxygen ($CMRO_2$) in cerebral vessels at 3T. Further, we extended estimates of Y_v to 7T achieving a 1/5 reduction in voxel size. The improved spatial resolution allows examination of smaller vessels expected to be more indicative of regional brain function.

Current work is focused on extension of the susceptibility inversion to general vessel geometry and improved ASL measurements at 7T for PROM measurements at high field with high resolution. Future quantitative CMRO2 measurements have the potential to become valuable for the study of diseases where oxygenation quantification can be a critical factor in diagnosis or management decisions.

2. Multi-contrast Reconstruction with Bayesian Compressed Sensing

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Project Staff:
Mr. Berkin Bilgic, S.M., Prof. Vivek Goyal, Prof. Elfar Adalsteinsson

In this work, graduate student Berkin Bilgic demonstrated that joint Bayesian MRI reconstruction of multiple different undersampled observation of the same object under different contrast preparations yields important gains in image fidelity when compared to independent undersampled reconstructions or competing joint reconstructions.

The motivation for this work arises from clinical imaging with structural MRI, which routinely relies on multiple acquisitions of the same region of interest under several different contrast preparations. A reconstruction algorithm based on Bayesian compressed sensing was used to jointly reconstruct a set of images from undersampled k-space with higher fidelity than when the images are reconstructed either individually or jointly by a previously proposed algorithm, M-FOCUSS. The joint inference problem is formulated in a Bayesian setting, wherein solving each of the inverse problems corresponds to finding the parameters (here, image gradient coefficients) associated with each of the images. A shared hyperprior for the image gradient variances is separable spatially but not separable across contrasts. All of the images from the same anatomical region, but with different contrast properties, contribute to the estimation of the hyperparameters, and once they are found, the *k*-space data belonging to each image is utilized independently to infer the image gradients. Thus, commonality of image spatial structure across contrasts is exploited without the problematic assumption of correlation across contrasts. Examples demonstrate improved reconstruction quality (up to a factor of 4 in root-mean-square

error) compared to previous CS algorithms and show the benefit of joint inversion under a hierarchical Bayesian model.

Apart from making use of the joint Bayesian CS machinery to improve the image reconstruction quality, the proposed method presents several novelties. First, we reduce the Bayesian algorithm to practice on MRI data sampled in *k*-space with both simulated and *in vivo* acquisitions. In the elegant work by Ji *et al*. (Ji, S.H., D. Dunson, and L. Carin, Multitask Compressive Sensing. IEEE Transactions on Signal Processing, 2009. 57(1): p. 92-106), their method was demonstrated on CS measurements made directly in the sparse transform domain as opposed to in the *k*-space domain that is the natural source of raw MRI data. The observations $\boldsymbol{y}_i$ were obtained via $\boldsymbol{y}_i = \boldsymbol{\Phi}_i \boldsymbol{\theta}_i$ where $\boldsymbol{\theta}_i$ are the wavelet coefficients belonging to the i^{th} test image. But in all practical settings of MRI data acquisition, the observations are carried out in the *k*-space corresponding to the reconstructed images themselves, i.e. we do not acquire the *k*-space data belonging to the wavelet transform of the image. In our method as presented here, we obtain the measurements belonging to the image gradients by modifying the *k*-space data and thus overcome this problem. After solving for the gradient coefficients with the Bayesian algorithm, we recover the images that are consistent with these gradients in a least-squares setting. Secondly, our version accelerates the computationally-demanding joint reconstruction algorithm by making use of the Fast Fourier Transform (FFT) to replace some of the demanding matrix operations in the original implementation by Ji *et al*. This makes it possible to use the algorithm with higher resolution data than with the original implementation, which has large memory requirements. Also, we exploit partially overlapping undersampling patterns to increase our collective *k*-space coverage when all images are considered; we report that this flexibility in the sampling pattern design improves the joint CS inversion quality. Finally, we compare our findings with the popular method by Lustig et al. (Lustig, M., D. Donoho, and J.M. Pauly, Sparse MRI: The application of compressed sensing for rapid MR imaging. Magn Reson Med, 2007. 58(6): p. 1182-95) and with the M-FOCUSS joint reconstruction scheme (Cotter, S.F., et al., Sparse solutions to linear inverse problems with multiple measurement vectors. IEEE Transactions on Signal Processing, 2005. 53(7): p. 2477-2488). In addition to yielding smaller reconstruction errors relative to either method, the proposed algorithm contains no parameters that need tuning.

In addition to the demonstration of the joint CS reconstruction of multiple different image contrasts, other applications lend themselves to the same formalism for joint Bayesian image reconstruction. These include, for instance, (*i*) Quantitative Susceptibility Mapping (QSM). In this setting, we again aim to solve an inverse problem of estimating a susceptibility map related to the phase of a complex image via an ill-posed inverse kernel. Since the magnitude image is expected to share common image boundaries with the susceptibility map, it might be possible to use it as a prior to guide the inversion task; *(ii)* Magnetic Resonance Spectroscopic Imaging (MRSI). Combining spectroscopic data with high resolution structural scans might help reducing the lipid contamination due to the subcutaneous fat or enhance resolution of brain metabolite maps; and *(iii)* Multi-modal imaging techniques. Simultaneous PET/MRI acquisitions with different modalities (e.g. PET-MRI) may benefit from joint reconstruction with this Bayesian formulation.

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Theses

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Patent Applications Filed

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