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Opinion

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Implementation of Building Information Modeling

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Introduction

Magnetic Resonance (MR) data acquisition routinely involves image acquisition at multiple echoes or phase-cycles to obtain complementary information. Multi-echo acquisition finds important applications in T2 and T2 relaxation time mapping, water/fat imaging, and reduction of field inhomogeneity related distortion. Although enabling numerous applications, achieving whole-brain coverage with high-resolution multi-echo imaging is encoding intensive, leading to excessive scan times. Another application where multiple images are acquired and combined is Balanced Steady State Free Precession (BSSFP). Despite being an SNR efficient sequence with unique T2/T1 contrast, BSSFP suffers from image banding artifacts due its sensitivity to B0 field inhomogeneity. To mitigate these artifacts, multiple images with different RF phase-cycling can be acquired. This scheme shifts the location of the banding artifacts in each acquisition, so that the phase-cycled images can be combined through Maximum Intensity Projection (MIP) to eliminate the artifacts. However, collecting multiple phase-cycles increases the scan time and counteracts the inherent efficiency of BSSFP.

Faster acquisitions are possible using receiver encoding, e.g. with sensitivity encoding or Generalized Auto-Calibrating Partially Parallel Acquisitions (GRAPPA). While parallel imaging allows acceleration along one phase encoding direction in 2D acquisitions, under sampling can be flexibly distributed between two axes phase encoding and partition/slice direction in 3D and SMS imaging to achieve higher accelerations. Parallel imaging can be combined with compressed sensing to exploit sparsity/low-rank properties, and can be augmented with the Virtual Coil (VC) concept to provide additional spatial encoding using image phase prior information. On the other hand, LORAKS has been introduced as a novel method that can harness image phase smoothness and limited spatial support, and relies on local low rank properties of k-space to estimate missing data. Its extension to parallel imaging also allows utilization of coil sensitivity encoding. Earlier applications of low rank prior in k or image space have also permitted calibration less parallel imaging.

Parallel Imaging

These approaches have been designed to utilize coil sensitivity encoding and prior information to reconstruct a single contrast, without exploiting potential differences across multiple images.

Within the sense framework, joint reconstruction across contrasts can be performed by exploiting joint sparse in this context; we use “joint reconstruction” to refer to approaches that couple the reconstruction of multiple images of the same anatomy. However, compared to regularized sense per single image, exploiting similarities at the regularization level was seen to provide a small improvement. Joint reconstruction at the receiver encoding level could serve as a better alternative to coupling the images at the regularization stage. Such approaches include k-t GRAPPA, joint reconstruction of multiple shots in echo-planar diffusion imaging, k-space interpolation across all echoes in a Gradient and Spin Echo (GRASE) acquisition, or across multiple gradient echoes for temperature mapping. Moreover, transmit inhomogeneity at ultra-high field can be mitigated by acquiring multiple images with different excitation modes, which are then jointly reconstructed in the TIAMO approach.

Recent advances in multi-shot diffusion imaging also perform joint reconstruction. These techniques aim to reconstruct a single, high-resolution k-space by merging data from multiple acquisitions while avoiding motion artifacts use of self-navigated trajectories to estimate motion-induced shot-to-shot phase variations. Inverse reconstruction instead solves for the complex-valued diffusion images in each shot separately. The phase information of each shot is then used as additional coil sensitivity variation to jointly reconstruct a combined, real-valued diffusion image with data from all shots. Similarly, Muse estimates the phase variation of each shot using regularization, and then solves a general model incorporating data from all shots and the calculated phase information. GRAPPA based realigned kernel techniques embed these phase variations into GRAPPA kernels estimated from additional navigators, which are then used for jointly reconstructing multi-shot data. The goal of such joint GRAPPA DWI techniques is to reduce the sensitivity to mismatches between navigator and image echoes.

Mussels are a new approach for phase-calibration-free multi-shot DWI reconstruction. This considers the multi-shot images to have the same contrast, but allow for slowly varying phase across the shots. These constraints are modeled with an annihilating k-space filter, which is learned during the structured low-rank recovery of the missing data. While multi-shot DW images have the same contrast except for phase discrepancies, we instead focus on joint reconstruction to treat a broader class of applications, where the acquisitions are made with multiple contrasts/echoes/cycles. Rather than improved combination of multiple shots, we are targeting higher acceleration rates. For this, we propose a general framework for joint reconstruction. We reformulate the joint reconstruction problem as an extension of parallel imaging, and employ existing components such as GRAPPA, LORAKS, and virtual coils as our building blocks. We also extend the scope, performance and application space of these techniques. In designing our joint parallel imaging approaches, our hypothesis was that joint reconstruction would allow us to accelerate multi-contrast acquisitions further than currently possible with conventional parallel imaging.

Virtual Coil

To this end, we introduce the Joint Virtual Coil (JVC) technique wherein multiple echoes/cycles are reconstructed jointly under the GRAPPA framework. This combines and extends k-t, realigned GRAPPA and TIAMO approaches with the VC concept to permit highly accelerated 2D, 3D and SMS acquisitions. JVC-GRAPPA allows all channels from all image contrasts to contribute to the reconstruction of a particular channel, and employs VC to convert image phase information into additional spatial encoding. Data were under sampled with shifts in the k-space sampling pattern across echoes/cycles to provide complementary k-space coverage and improve reconstruction.

We further extend the joint parallel imaging concept to exploit limited support and smooth phase constraints through Joint (J) LORAKS formulation. J-LORAKS achieves a more parsimonious low rank representation of local k-space by considering multi-contrast images as additional coils, and allows reconstruction from limited ACS region. J-LORAKS seamlessly incorporates partial Fourier sampling into joint parallel imaging and permits improved calibration less parallel imaging through joint reconstruction.

Here in, we demonstrate our joint parallel imaging concept in 2D phase-cycled BSSFP, 3D ME-MPRAGE Multi-Echo Gradient-Echo (ME-GRE), and SMS multi-echo spin-echo imaging. We have reported initial versions of this work as abstracts, where we have shown the application of joint GRAPPA and Spirit in reconstructing phase-cycled BSSFP with 2D and SMS encoding. Herein, we have extended this initial version with the addition of VC concept, J- LORAKS formalism that admits arbitrary sampling patterns including partial Fourier and CAIPI, calibration less reconstruction, and application to multi-echo acquisitions. We also note the elegant profile-encoding by that independently developed joint parallel imaging reconstruction for phase-cycled BSSFP, which was also extended to multi-echo acquisition in a recent abstract.