PhD Thesis booklet

Optimized measurement and reconstruction methods for phase-constrained parallel MRI

Ádám Ottó Kettinger

Supervisor: Dávid Légrády, PhD
Associate Professor
Department of Nuclear Techniques
Institute of Nuclear Techniques

Budapest University of Technology and Economics

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Introduction

In the last few decades magnetic resonance imaging (MRI) has become one of the most significant and most versatile imaging modality, with a wide range of applications from traditional anatomical tomography to functional neuroimaging and to the investigation of tissue microstructure.

Nevertheless, the inherently lengthy acquisition can still hinder its usage in several scenarios, and can have an adverse effect on the time resolution in dynamic measurements. To mitigate this problem, several techniques were proposed to accelerate the data acquisition. A large group of these techniques, called parallel imaging, aims to reconstruct the image from incomplete data by using the additional information provided by the multiple receiver coils used to measure the signal. However, such acceleration comes at a price of increased noise, a fact that ultimately gave rise to a specific set of image calculation algorithms, called phase-constrained reconstruction. These methods use a-priori phase information or take advantage of the symmetry properties of the measured data to decrease the noise amplification, and thus improve the signal-to-noise ratio of the final image.

A specific phase-constrained reconstruction technique called Virtual Conjugate Coil (VCC) concept [Blaimer et al., 2009] allows the implicit usage of data symmetry, therefore enables the mitigation of noise amplification without requiring a-priori phase information, and, interestingly, without any constraints imposed to the phase of the final image, evoking considerable research interest (e.g. [Bilgic et al., 2019; Deshmane et al., 2016; Haldar and Zhuo, 2016; Hamilton et al., 2017; Kim et al., 2019; Levine et al., 2018; Liao et al., 2019; Manhard et al., 2019]). Nevertheless, the fact that a symmetrical sampling of k-space data is necessary for this technique still forbids its application when methods employing asymmetrical sampling, e.g. partial Fourier imaging, are used.

It has been shown in the original work [Blaimer et al., 2009] that the phase of the underlying object being imaged has a great effect on the noise amplification if the VCC reconstruction is used. Furthermore, it was shown by simulation that an optimal object phase that minimizes the noise exists, however, in the in-vivo measurements it was only approximated by a simple one-dimensional linear phase ramp, revealing only parts of the potential of VCC.

Objectives

During my PhD work, I focused on the noise enhancement of phase-constrained accelerated MR imaging, aiming to address the Virtual Conjugate Coil reconstruction regarding both topics mentioned in the Introduction.

In the first part of the work I intended to prove that optimizing the object phase, and thus minimizing the noise amplification in a VCC reconstruction, is possible in vivo on a clinical scanner for both in-plane-accelerated and simultaneous multislice measurements. Besides this proof of concept, I also aimed to test the practical feasibility of this technique by examining whether a concurrent slice selection is possible together with the phase optimization.

My second goal was to combine the VCC reconstruction with partial Fourier imaging, to test whether some of the advantages of VCC can be retained in an asymmetrical k-space sampling. I also aimed to provide analytical noise computation formulae for this combined reconstruction depending on the partial Fourier algorithm and the extent of asymmetry, and to compare it with standalone VCC reconstruction without partial Fourier using the same net acceleration.

Furthermore, after realizing that the conventional noise computation is not valid for a magnitude VCC reconstruction, it became my intention to derive a new noise calculation method for this case as well, and to validate it numerically and experimentally.

Methods

To achieve the aforementioned goals, analytical calculations, numerical computations, and experiments were employed. Radiofrequency pulses were designed in the Low-Flip-Angle approximation using a regularized least-squares method, while phase optimization was performed with a derivative-free simplex search. All reconstruction and computation were performed offline using MATLAB (The MathWorks, Natick, MA, USA).

Phantom and in-vivo measurements were performed on a Siemens MAGNETOM Prisma 3T clinical scanner (Siemens Healthcare GmbH, Erlangen, Germany), using the vendor-provided 20-channel and 64-channel receiver coils. Product and prototype imaging pulse sequences were used for acquisition control, with the latter implemented in the vendor's development environment in C++. All volunteers gave written informed consent before their respective studies, in accordance with institutional and legal regulations.

New scientific results

The new scientific results are summarized in the following thesis points.

1. I have shown that using tailored radiofrequency excitation pulses designed specifically to the given patient and measurement parameters, the noise amplification in accelerated MRI reconstructed with Virtual Conjugate Coil algorithm can be decreased notably; in some cases, by more than a factor of 2. As proven with in-vivo measurements, this method works for both in-plane-accelerated and simultaneous multislice acquisitions, with the RF pulses using spiral or stack-of-spiral gradient waveforms, respectively. The designed pulses successfully introduce the optimized phase distribution previously computed using a prescan, while maintaining a reasonably homogeneous flip angle distribution. Furthermore, I have demonstrated the possibility of reconstructing the optimized accelerated measurement without additional calibration data, using only the prescan measured to compute the optimal phase, and the simulated excitation profile of the designed pulse. [T1, T2, T3]

2. I have shown by numerical simulation that incorporating slice selection to the phase optimization is possible using spokes pulses, by simultaneously optimizing the RF waveform and the excitation k-space trajectory. The simulations show that similar reduction of noise can be achieved as in the case of fixed-waveform spiral pulses, with unchanged pulse length and minimal degradation in flip angle homogeneity, while simultaneously performing slice selection. [T3]

3. I have derived a new analytical formula for the noise amplification of a real-valued or Sum-of-Squares-combined Virtual Conjugate Coil GRAPPA reconstruction, showing that the traditional GRAPPA g-factor formula is not valid in such a magnitude VCC reconstruction. Furthermore, I have validated the analytical result using numerical noise computations, and shown that the derived formula describes the noise amplification correctly. [T5]

4. I have developed a technique to combine the Virtual Conjugate Coil reconstruction with partial Fourier imaging, two phase-constrained techniques that were so far considered to be mutually exclusive. I have shown by noise computations and in-vivo measurements that using this combination method, some of the benefit of Virtual Conjugate Coil reconstruction can be retained in accelerated measurements employing partial Fourier acquisition, using either in-plane or simultaneous multislice acceleration. [T4, T5]

Utilization of the results

Realizing the full potential of the Virtual Conjugate Coil reconstruction by optimizing the object phase could be of particular interest in acquisitions where the measurement noise has a major contribution to image quality, like in fast high-resolution functional MRI. According to personal communications, the first experiments on using this technique for small-field-of-view layer-specific functional MRI are already ongoing at the Erwin L. Hahn Institute for Magnetic Resonance Imaging in Essen, Germany.

Furthermore, measurements with inherently poor signal-to-noise ratio where partial Fourier is commonly used can take advantage of the partial application of VCC reconstruction using the proposed combined method. Diffusion-weighted imaging is a promising candidate, as researchers from the Athinoula A. Martinos Center for Biomedical Imaging in Massachusetts, USA, with whom this second part of the work was performed in cooperation, have recently shown that VCC can indeed provide notable improvements for diffusion MRI in clinical settings [Liao et al., 2019].

Publications related to the thesis points

[T1] **Ádám Ottó Kettinger**, Stephan A. R. Kannengiesser, Felix A. Breuer, Zoltán Vidnyánszky, and Martin Blaimer, Tailored RF pulses for optimized phase-constrained parallel imaging: initial experience on a clinical system, in *Proc. Eur. Soc. Mag. Reson. Med.*, 33:661, 2016.

[T2] **Ádám Ottó Kettinger**, Stephan A. R. Kannengiesser, Felix A. Breuer, Zoltán Vidnyánszky, and Martin Blaimer, Tailored 3D RF pulses for g-factor reduction in phase-constrained simultaneous multislice imaging, in *Proc. Intl. Soc. Mag. Reson. Med.*, 25:1433, 2017.

[T3] **Ádám Ottó Kettinger**, Stephan A. R. Kannengiesser, Felix A. Breuer, Zoltán Vidnyánszky, and Martin Blaimer, Controlling the object phase for g-factor reduction in phase-constrained parallel MRI using spatially selective RF pulses, *Magn Reson Med*, 79(4):2113-2125, 2018.

[T4] **Ádám Ottó Kettinger**, Kawin Setsompop, Stephan A. R. Kannengiesser, Felix A. Breuer, Zoltán Vidnyánszky, and Martin Blaimer, Combining Virtual Conjugate Coil reconstruction with partial Fourier imaging for maximized utilization of k-space conjugate symmetry, in *Proc. Eur. Soc. Mag. Reson. Med*, 34:179, 2017.

[T5] **Ádám Ottó Kettinger**, Kawin Setsompop, Stephan A. R. Kannengiesser, Felix A. Breuer, Zoltán Vidnyánszky, and Martin Blaimer, Full utilization of conjugate symmetry: combining Virtual Conjugate Coil reconstruction with Partial Fourier imaging for g-factor reduction in accelerated MRI, *Magn Reson Med*, 2019.

Further publications

[F6] Balázs Játékos, Ádám Ottó Kettinger, Emőke Lőrincz, Ferenc Ujhelyi and Gábor Erdei, Evaluation of Light Extraction from PET Detector Modules Using Gamma Equivalent UV Excitation, in *Proceedings of the IEEE Nuclear Science Symposium, Medical Imaging Conference Anaheim, USA*, 2019.

[F7] Tamás Sarkadi, Ádám O. Kettinger and Pál Koppa, Spatial filters for complex wavefront modulation, *Applied Optics* 52(22):5449, 2013.

[F8] Ádám Ottó Kettinger, Christian Windischberger, Christopher Hill and Zoltan Nagy, Advanced combinations of dual-echo fMRI data provide no advantages over the simple average at group-level analyses, in *Proc. Intl. Soc. Mag. Reson. Med.*, 24:818, 2016.

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[F10] Ádám Ottó Kettinger, Petra Hermann, Pál Vakli, Martin Blaimer, Kawin Setsompop, Stephan A. R. Kannengiesser, Felix A. Breuer and Zoltán Vidnyánsyzky, Using Virtual Conjugate Coil reconstruction for statistical improvement in highly accelerated Simultaneous Multislice fMRI, in *Proc. Intl. Soc. Mag. Reson. Med.*, 26:261, 2018.

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M. K. Manhard, B. Bilgic, C. Liao, S. Han, T. Witzel, Y.-F. Yen, and K. Setsompop. Accelerated whole-brain perfusion imaging using a simultaneous multislice spin-echo and gradient-echo sequence with joint virtual coil reconstruction. *Magn Reson Med*, 2019.