B_0-Correction in Parallel Imaging with Arbitrary k-Space Trajectories

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Introduction

Non-Cartesian trajectories, such as spirals, allow highly efficient sampling of k-space. The acquisition time can be further reduced by combining arbitrary k-space sampling with parallel imaging [1]. To model the physical encoding, the coil sensitivities as well as the k-space sampling has to be included in one encoding matrix, which has to be inverted for reconstruction. A conjugate-gradient (CG) reconstruction has been proposed [1], because this matrix is typically too large for a direct inversion. The unfolding problem is solved iteratively without directly expressing the large encoding matrix. Each iteration step includes a gridding and inverse-gridding reconstruction of all separate coil channels.

Another challenge in MRI is to avoid or correct for artefacts due to B_0 inhomogeneities. The local magnetic field distribution $B_0(r)$ can be measured and included in the reconstruction. A simple and mathematically correct way to compensate for $B_0(r)$ variations is the conjugate-phase (CP) reconstruction [2,3]. This is a direct Fourier transformation, where each k-space point is multiplied with the Fourier kernel and corrected for the additional phase from $B_0(r)$. Another way is multi-frequency interpolation (MFI) [4], which reconstructs the data to several frequencies to form a set of base images. These are then added together with spatially varying linear coefficients derived from $B_0(r)$. Advantageous is the ability to use the numerically efficient gridding reconstruction, however the whole reconstruction is algorithmically considerably more complex than regular CP.

Combining both sensitivity encoding and B_0 inhomogeneity correction was proposed for MFI in [5], which is also based on the iterative CG reconstruction, only that during each iteration the number of channels times the off-resonance frequencies have to be reconstructed and then recombined. In this work, we propose to combine conjugate-gradient (CG) unfolding with conjugate-phase (CP) reconstruction [2,3] for a direct B_0 inhomogeneity correction. Also, we show the first results for B_0 corrected parallel imaging for the spiral k-space trajectory.

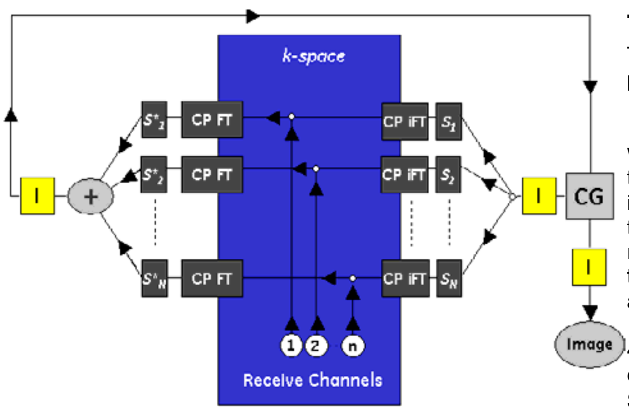

Fig. 1. Principle functioning of the conjugate-phase (CP) conjugate-gradient (CG) arbitrary k-space parallel imaging reconstruction. Each iteration implies a CP and inverse CP Fourier transformation of all individual coils, which are then recombined. The individual coil sensitivities are denoted by s. Intensity correction [I] is performed on the combined images to speed up convergence.

Theory and Methods

The CP reconstruction of an image ν is given by Fourier kernel plus the additional phase term

$$\nu_\rho = \sum_\kappa m_\kappa d_\kappa \exp\left(ik_\kappa r_\rho + i\omega_\rho t_\kappa\right)$$

where m_κ denotes the acquired data at the κ-sampling position along the arbitrary trajectory k_κ, d_κ the k-space density, r_ρ the ρ^{th} pixel position, and $\omega_\rho=\gamma B_0$ the $B_0(r)$ induced frequency offset. The gridding and inverse-gridding reconstruction steps in the CG arbitrary-k-space parallel-imaging reconstruction [1] are replaced by this CP reconstruction (Fig. 1). That is, the B_0 inhomogeneity is directly compensated during the Fourier transformation (FT). During the inverse FT, the $B_0(r)$ induced phase terms are again added.

The spiral sequence was used for demonstration purposes (six arms with each 4096 points; TR=1s; BW=250 kHz; flip angle=90°). For the simulations (Fig. 2), an exponential B_0 inhomogeneity with 100 Hz off-resonance was added to the modified Shepp-Logan phantom data (96×96). For the human brain, a slice through the frontal cavities was selected (Fig. 2). B_0 and sensitivity maps were acquired with a spoiled gradient echo sequence (TE=4ms and 4.5ms; TR=300ms; 160×256; flip angle=30°). Three arms were discarded from the *in vivo* data for generating sufficient under-sampling. All experiments were performed on 1.5T Signa Excite 2 scanner equipped with an 8-channel receive-only birdcage head coil.

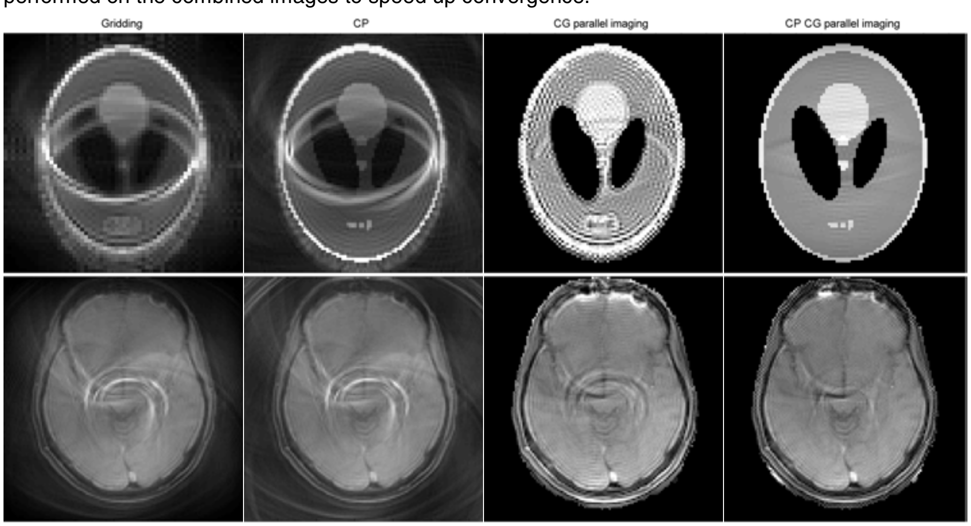

Fig. 2. Shepp-Logan simulation phantom (top) and human brain image (bottom). Distortions due to B_0 inhomogeneities are visible in the simulation (lower end), and *in vivo* around the cavities (upper end). Under-sampling artefacts are showing up as bright ellipsoids inside. Gridding reconstruction (left) suffers from both B_0 and under-sampling artefacts, CP reduces B_0, CG under-sampling and only CP-CG reconstruction tackles both artefacts.

Results and Discussion

The B_0 induced artefacts, mainly geometric distortions and blurring, can be considerably reduced (Fig. 2). This will be particularly beneficial for sequences with long read-out times. The suggested reconstruction is easier to implement as MFI combined with CG [5]. However, it is computationally more expensive, particularly for large matrices. The reconstruction of the *in vivo* dataset (3×4096) to a 128×128 image took 7 s (gridding), 3 min (CP), 88 s (CG with 15 iterations) and 73 min (CP CG with 15 iterations) (MATLAB running on a CPU with 3.2 GHz).

References

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