GARSE: Generalized Autocalibrating Reconstruction for Sensitivity Encoded MRI

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Introduction: Parallel MRI (P-MRI) [1,2] has been widely used to improve spatial/temporal resolution and to reduce scan time and SAR [1,2]. All P-MRI methods require coil sensitivity calibration information. In many practical situations, such information is not available a priori or not reliable due to the patient motion between coil calibration and imaging scans. For such cases, autocalibration is preferable [3,4]. In this study, we have proposed a novel approach for autocalibrated P-MRI that takes into account specifics of coil sensitivity representation in k-space domain to achieve an improved reconstruction. We demonstrated that GRAPPA [4] is a limited case of the proposed method that gives optimal results only for special coil geometry and low reduction factors.

Theory and Methods: Image $s_i(r)$ acquired by i–th coil can be described by $s_i(r) = c_i(r)\, f(r)$, where $f(r)$ is the imaged object, $c_i(r)$ is the i-th coil sensitivity (i=1:Nc, Nc – the number of coils), or in k-space $S_i(k) = C_i(k) \otimes F(k)$. Assuming discrete k-space sampling, the equation can be expressed in matrix form $\mathbf{S}_i = \mathbf{C}_i\mathbf{F}$. Combining all coil equations, the matrix equation for P-MRI in k-space can be written as $\mathbf{S} = \mathbf{CF}$ [5,6].

In case of P-MRI, vector $\mathbf{S}$ and sensitivity matrix $\mathbf{C}$ can be presented as $\mathbf{S} = \left[\mathbf{S}'\ \hat{\mathbf{S}}\right]^{\mathbf{T}}$ and $\mathbf{C} = \left[\mathbf{C}'\ \hat{\mathbf{C}}\right]^{\mathbf{T}}$, where $\mathbf{S}'$ denotes a vector of the acquired k-space data, $\hat{\mathbf{S}}$ - a vector of the missing k-space data, $\mathbf{C}'$ and $\hat{\mathbf{C}}$ are the corresponding sub-blocks of the coil sensitivity matrix $\mathbf{C}$. A system of two matrix equations with unknown $\mathbf{F}$ and $\hat{\mathbf{S}}$ can be constructed as $\mathbf{S}' = \mathbf{C}'\mathbf{F}$ and $\hat{\mathbf{S}} = \hat{\mathbf{C}}\mathbf{F}$. The solutions to the system can be found as $\mathbf{F} = (\mathbf{C}'^{H}\boldsymbol{\Psi}^{-1}\mathbf{C}')^{-1}\mathbf{C}'^{H}\boldsymbol{\Psi}^{-1}\mathbf{S}'$ and $\hat{\mathbf{S}} = \mathbf{A}\mathbf{S}'$, where $\mathbf{A} = \hat{\mathbf{C}}(\mathbf{C}'^{\mathbf{H}}\boldsymbol{\Psi}^{-1}\mathbf{C}')^{-1}\mathbf{C}'^{\mathbf{H}}\boldsymbol{\Psi}^{-1}$. The first equation is the standard P-MRI equation for image reconstruction from the undersampled multicoil data. The second equation shows that missing k-space data in individual coil datasets can be found by linearly combining the acquired k-space data:

$S_i(\hat{k}) = \sum_{j=1}^{Nc} \sum_{k'} a(i,\, j,\, k')S_j(k')$, where k' ($\hat{k}$) denotes the k-space positions of the acquired (missing) k-space samples.

Slowly varying coil sensitivities $c_i(r)$ can be adequately described by small number of Fourier terms. Consequently, only samples $S_j(k')$ (j=1:Nc) in k-space locations inside a limited neighborhood of $\hat{k}$ should be used to estimate $S_i(\hat{k})$:

$$S_i(\hat{k}) = \sum_{j=1}^{Nc} \sum_{k' \in \Omega_k} a(i,\, j,\, k')S_j(k')\text{, where } \Omega_k \text{ is a neighborhood of } \hat{k}.$$

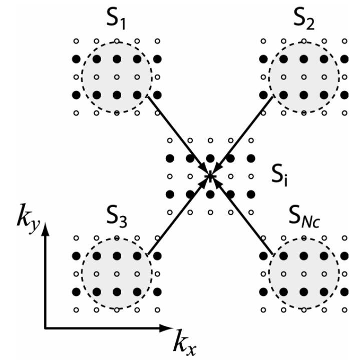

Figure 1. Illustration of GARSE reconstruction for 2D imaging. Filled circles denote the acquired data, open circle – missing data, Ω_k is the k-space region restricted by the dashed line.

In case of P-MRI with sampling on the regular Cartesian grid, the reconstruction coefficients $a(i,\, j,\, k')$ should be the same for all $\hat{k}$ and can be easily evaluated from reference (autocalibrating) k-space lines. Ω_k should be defined taking into account the geometry of coil elements and their orientation relatively to imaging axis. For the cases, when coil sensitivity profiles can be described by slow varying functions of y coordinate (phase-encoding direction) and independent from x and z coordinates ($c_i(r)=c_i(y)$), Ω_k is limited to several neighbors in the k_y direction. In this case, our reconstruction (GARSE) is equivalent to GRAPPA method.

To test the proposed technique, brain MRI studies were performed on a 3T Trio MR system (Siemens Medical Solutions, Erlangen, Germany) using a dual contrast 2D turbo spin echo pulse sequence. Imaging parameters: FOV=240x240 mm, in-plane matrix = 256x261, 2 mm slice thickness, TR=4 sec, TE1/TE2=10/90 ms, ETL=18, 100 Hz/pixel bandwidth. The eight-channel head coil (MRI Devices, Waukesha, WI) was used for the imaging studies. The reduced data were created by undersampling full datasets. The method was tested for different reduction factors, numbers of reference lines and size of Ω_k.

Results: Typical results of GARSE reconstruction and comparison with GRAPPA are shown in Fig. 2. GARSE gave better image quality and low RMS errors than GRAPPA, especially for high reduction factors. The results demonstrate that GRAPPA is much more restrictive in reduction factor values than GARSE.

Discussion: Our new image reconstruction method for P-MRI is an autocalibrating technique based on the fact that coil sensitivity profiles have limited support in k-space domain. GARSE exploits all data dimensions to calculated reconstruction coefficients. In this way, a more robust and feasible reconstruction than with GRAPPA may be achieved. The new technique is applicable for reconstruction of highly undersampled data acquired by receiver arrays with arbitrary coil configurations.

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[4] Griswold MA, et al, MRM 2002;47:1202-10. [5] Wang Y. MRM 2000;44:495-9. [6] Bydder M, et al, MRM 2002;47:160-70. [7] Yeh EN, el al, ISMRM 2002, p.2390.

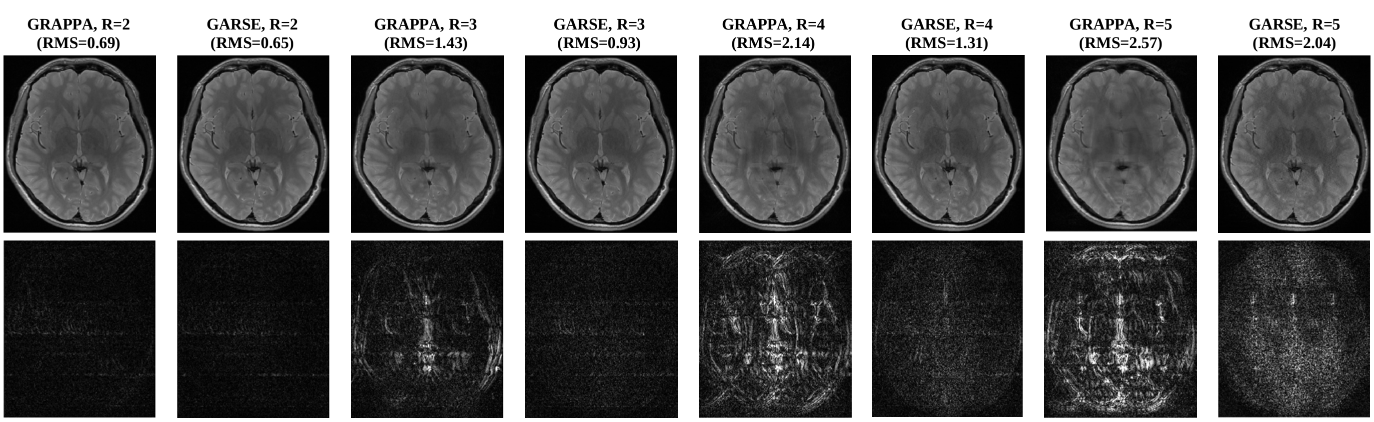

Figure 2. Comparison between GRAPPA and GARSE reconstruction on the brain data. The number of reference lines was equal to 24 for R=2-4, and 30 for R=5.