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Superresolution parallel magnetic resonance imaging: Application to functional and spectroscopic imaging

Ricardo Otazo [a,b,*], Fa-Hsuan Lin [c,d], Graham Wiggins [c], Ramiro Jordan [a], Daniel Sodickson [b], Stefan Posse [a,e,f]

[a] Electrical and Computer Engineering Department, University of New Mexico, Albuquerque, NM, USA
[b] Center for Biomedical Imaging, Department of Radiology, New York University Langone Medical Center, New York, NY, USA
[c] MGH-HMS-MIT Athinoula A. Martinos Center for Biomedical Imaging, Charlestown, MA, USA
[d] Institute of Biomedical Engineering, National Taiwan University, Taipei, Taiwan
[e] Department of Neurology, University of New Mexico School of Medicine, Albuquerque, NM, USA
[f] Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA

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A B S T R A C T

Standard parallel magnetic resonance imaging (MRI) techniques suffer from residual aliasing artifacts when the coil sensitivities vary within the image voxel. In this work, a parallel MRI approach known as Superresolution SENSE (SURE-SENSE) is presented in which acceleration is performed by acquiring only the central region of k-space instead of increasing the sampling distance over the complete k-space matrix and reconstruction is explicitly based on intra-voxel coil sensitivity variation. In SURE-SENSE, parallel MRI reconstruction is formulated as a superresolution imaging problem where a collection of low resolution images acquired with multiple receiver coils are combined into a single image with higher spatial resolution using coil sensitivities acquired with high spatial resolution. The effective acceleration of conventional gradient encoding is given by the gain in spatial resolution, which is dictated by the degree of variation of the different coil sensitivity profiles within the low resolution image voxel. Since SURE-SENSE is an ill-posed inverse problem, Tikhonov regularization is employed to control noise amplification. Unlike standard SENSE, for which acceleration is constrained to the phase-encoding dimension/s, SURE-SENSE allows acceleration along all encoding directions — for example, two-dimensional acceleration of a 2D echo-planar acquisition. SURE-SENSE is particularly suitable for low spatial resolution imaging modalities such as spectroscopic imaging and functional imaging with high temporal resolution. Application to echo-planar functional and spectroscopic imaging in human brain is presented using two-dimensional acceleration with a 32-channel receiver coil.

Introduction

Magnetic resonance imaging (MRI) methods involve imaging objects with high spatial frequency content in a limited amount of time. However, information over only a limited k-space range is usually acquired in practice due to SNR and time constraints. For example, in functional MRI (fMRI) (Belliveau et al., 1991) k-space coverage is traded off for increased temporal resolution. In MR spectroscopic imaging (MRSI) (Brown et al., 1982), which is constrained by relatively low SNR, k-space coverage is sacrificed to achieve an adequate SNR within a feasible acquisition time. The lack of high k-space information leads to limited spatial resolution and Gibbs ringing when the Fourier transform is directly applied to reconstruct the image. Constrained image reconstruction techniques using prior information (Liang et al., 1992) have been proposed to achieve superresolution image reconstruction, i.e. to estimate high k-space values without actually measuring them. For example, the finite spatial support of an image can be used to perform extrapolation of k-space at expense of SNR loss. However, this method performs well only at positions close to the periphery of the object being imaged (Plevritis and Macovski, 1995). For experiments with temporal repetitions such as fMRI and MRSI; k-space substitution (Jones et al., 1993), also known as the key-hole method, was proposed to fill the missing high k-space values of the series of low resolution acquisitions using a high resolution reference. However, this method is vulnerable to artifacts due to inconsistencies between the reference and the actual acquisition. An improvement of this approach, known as generalized series reconstruction (Liang and Lauterbur, 1991), forms a parametric model using the high resolution reference to fit the series of low resolution acquisitions and thus reduce the effect of data replacement inconsistencies. Alternatively, superresolution reconstruction can be performed by combination of several low resolution images acquired with sub-pixel differences (Elad and Feuer, 1997).

* Corresponding author. Center for Biomedical Imaging, Department of Radiology, New York University Langone Medical Center, 660 First Ave, 4th Floor, New York, NY, USA. Fax: +1 212 263 7541.
E-mail address: ricardo.otazo@nyumc.org (R. Otazo).

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This method is well developed for picture and video applications and was employed before in MRI by applying a sub-pixel spatial shift to each of the low resolution acquisitions (Peled and Yeshurun, 2001). However, its application is very limited since a spatial shift is equivalent to a linear phase modulation in k-space, which does not represent new information to increase the k-space coverage of the acquisition.

Parallel MRI (Sodickson and Manning, 1997; Pruessmann et al., 1999) has been introduced as a method to accelerate the sequential gradient-encoding process by reconstructing an image from fewer acquired k-space points using multiple receiver coils with different spatially varying sensitivities. The standard strategy for acceleration is to reduce the density of k-space sampling beyond the Nyquist limit while maintaining the k-space extension in order to preserve the spatial resolution of the fully-sampled acquisition. The rationale for this sub-sampling scheme is that the coil sensitivities are spatially smooth and retrieve k-space information only from the neighborhood of the actual gradient-encoding point. However, any arbitrary k-space sub-sampling pattern can in principle be employed at the expense of increasing the computational cost and decreasing the stability of the inverse reconstruction, i.e. increasing the nominal noise amplification in the reconstruction (g-factor) (Pruessmann et al., 1999; Sodickson and McKenzie, 2001). On the other hand, standard parallel MRI performed at a spatial resolution that presents intra-voxel coil sensitivity variation suffers from residual aliasing artifacts which are depicted as spurious side lobes around the aliasing positions in the reconstructed point spread function (PSF) (Zhao et al., 2005). The minimum-norm SENSE (MN-SENSE) technique was proposed to remove the residual aliasing artifact by performing an intra-voxel reconstruction of the PSF using coil sensitivities acquired with higher spatial resolution (Sanchez-Gonzalez et al., 2006). However, while this method improves the spatial distinctiveness of image voxels, it does not increase the number of voxels and hence the underlying spatial resolution.

Receiver arrays with a large number of small coils tend to have rapidly varying coil sensitivity profiles, and therefore offer the promise of high accelerations for parallel imaging. However, standard Sensitivity Encoding (SENSE) reconstruction with many-element arrays is exposed to residual aliasing artifacts due to potential intra-voxel coil sensitivity variations. On the other hand, many-element arrays open the door for other k-space sub-sampling patterns that might not be feasible with few-element arrays. For example, highly accelerated parallel imaging using only one gradient-encoding step was proposed in the Single Echo Acquisition (SEA) technique with a 64-channel planar array (McDougall and Wright, 2005) and in the Inverse Imaging (InI) technique with a 90-channel helmet array for human brain fMRI (Lin et al., 2006, 2008). However, the price to pay for these extreme levels of acceleration is reconstruction with low spatial resolution as dictated by the degree of variation of the coil sensitivity maps.

The current work presents a novel method for parallel MRI in which acceleration is performed by acquiring only the central region of k-space instead of increasing the sampling distance over the complete k-space matrix. The proposed method, termed Super-resolution SENSE (SURE-SENSE), increases the spatial resolution of the fully-sampled low resolution acquisition using coil sensitivities acquired with higher resolution. Regularization of the ill-conditioned inverse reconstruction is performed to control noise amplification due to the relatively large weights required to reconstruct high k-space values from low resolution data. The attainable increase in spatial resolution is determined by the degree of variation of the coil sensitivities within the acquired image voxel. Application of SURE-SENSE to increase the spatio-temporal resolution of fMRI is presented. Unlike standard SENSE, which is constrained to acceleration of phase-encoding dimensions, SURE-SENSE in this case allows two-dimensional acceleration of the echo-planar acquisition. Application to MRSI of human brain is presented as a method to reduce lipid contamination and to enhance the spatial resolution of the metabolite maps in two dimensions.

Methods

Superresolution SENSE (SURE-SENSE)

The goal of superresolution SENSE is to reconstruct a single image with higher resolution from fully-sampled low resolution images acquired with multiple receiver coils using high resolution coil sensitivity maps (Fig. 1). Since the image acquired by each coil is weighted by the corresponding spatial sensitivity of the coil, super-resolution reconstruction is feasible if the different sensitivities are varying within the low resolution image voxel.

SURE-SENSE is formulated in the image domain following the generalized parallel imaging model for arbitrary sub-sampling trajectories (Sodickson and McKenzie, 2001) considering that image data are acquired from a central k-space region and coil sensitivity data are acquired from an extended k-space region. Both data sets are acquired on a grid given by the Nyquist sampling distance ($\Delta k = 1/$

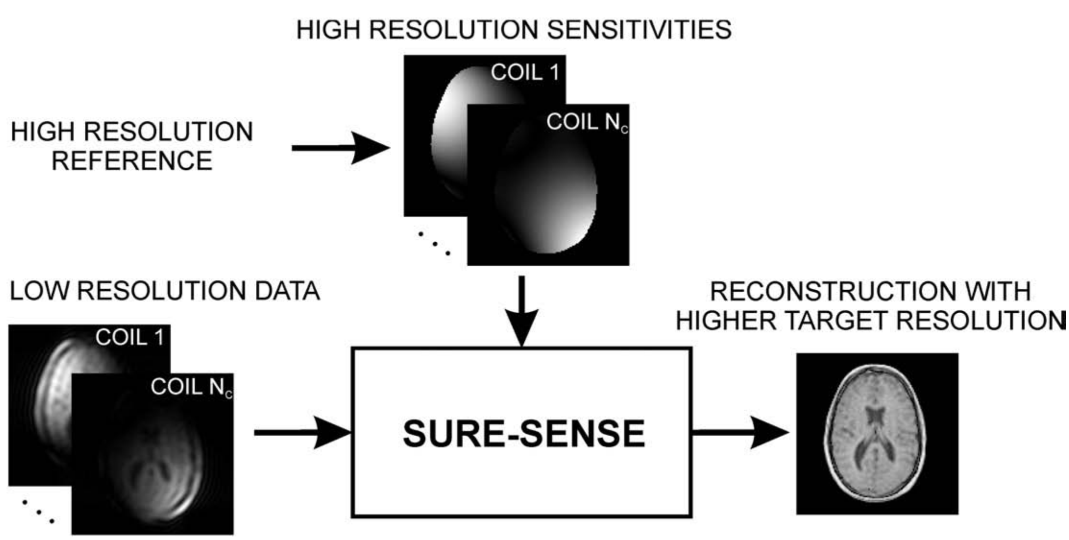

Fig. 1. Conceptual illustration of the superresolution parallel MRI technique. The low resolution multi-coil data are combined into a single image with higher resolution by performing an intra-voxel reconstruction with high spatial resolution coil sensitivity maps.