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Improved self-calibrated spiral parallel imaging using JSENSE

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ABSTRACT

Spiral MRI has several advantages over Cartesian MRI such as faster acquisitions and reduced demand in gradient. In parallel imaging, spiral trajectories are especially of great interest due to their inherent self-calibration capabilities, which is especially useful for dynamic imaging applications such as fMRI and cardiac imaging. The existing self-calibration techniques use the central spiral data that are sampled densely in the accelerated acquisition for coil sensitivity estimation. However, the resulting sensitivities are not sufficiently accurate for SENSE reconstruction due to the data truncation. In this paper, JSENSE which has been successfully used in Cartesian trajectories is extended to spiral trajectory such that the coil sensitivities and the desired image are reconstructed jointly to improve accuracy through alternating optimization. The improved sensitivities lead to a more accurate SENSE reconstruction. The results from both phantom and in vivo data are shown to demonstrate the effectiveness of JSENSE for spiral trajectory.

1. Introduction

In many dynamic MRI applications, it is desirable to reduce imaging time to achieve high spatio-temporal resolution. A classical approach is to use fast-scan methods that traverse quickly through *k*-space. Among these methods, spiral trajectory is known to have several advantages over the Cartesian trajectory due to its reduced influence from T_2-decay and its robustness against bulk physiologic motion [1,2]. When combined with the recent parallel MRI technique, which takes advantage of spatial sensitivity information inherent in an array of multiple receiver surface coils to reduce the number of gradient encoding steps, the imaging speed can be further enhanced. The parallel spiral imaging is especially useful in high-resolution fMRI, arterial spin labeling, diffusion imaging, and cardiac imaging [1,3].

Over the past few years, a number of parallel magnetic resonance imaging (pMRI) techniques have been proposed in reconstructing a complete MR image from reduced *k*-space data in Cartesian trajectories, such as SMASH [4], SENSE [5,6], and GRAPPA [7]. Although many advances have been made in Cartesian reconstruction for parallel imaging, spiral reconstruction techniques still need further improvement. Most existing techniques for spiral parallel imaging still require a separate calibration scan with full field of view before or after the accelerated scans. In spiral SENSE, these scans are used to derive sensitivities [5,6], and in spiral GRAPPA, they are used to estimate the fitting coefficients [3,8]. This calibration scan can prolong the total imaging time, partially counteracting the benefits of reduced acquisition time associated with parallel MRI. Another practical problem with this technique is that misregistrations or inconsistencies between the calibration scan and the accelerated scan result in artifacts in the reconstructed images, which is a major concern in dynamic imaging applications. The self-calibrated technique [9] is known to be able to address the above problems in SENSE reconstruction. In spiral and radial SENSE, even with reduced number of interleaves, the central *k*-space is automatically sampled beyond Nyquist rate, and thus can be used for estimation of sensitivities without the need for additional encodings to acquire the self-calibration data as in Cartesian case. This inherent self-calibration capability makes the self-calibrated technique especially of interest for spiral and radial trajectories. However, as noted in [9], the data that satisfy the Nyquist rate only provide low spatial frequencies of coil sensitivity. In addition, the accuracy is not guaranteed in the regions where the image has low intensity. The resulting errors in sensitivity is propagated to the final reconstruction.

In this paper, we extend to spiral trajectories our earlier joint estimation technique [10] which has shown to be able to improve coil sensitivity accuracy for Cartesian trajectory. The method jointly estimates the coil sensitivities and reconstructs the desired image through alternating optimization so that the sensitivities are estimated from the full data recovered by SENSE instead of the center *k*-space data only, thereby increasing high frequency information without introducing aliasing artifacts. The method was tested on a number of scanned parallel imaging data sets, and the recon-

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struction results are shown to be superior to the conventional self-calibrated spiral SENSE.

2. Method

In this study, we used an approximation of the desired constant-linear-velocity Archimedean spirals [11,12]

$$k(t) = \alpha\theta(t)\ e^{i\theta(t)}, \tag{1}$$

where $\theta(t) = 2\pi\omega\sqrt{t}$. The real and imaginary parts of the complex function $k(t) = k_x(t) + ik_y(t)$ give the trajectory in the x–y coordinate, the constant ω gives the number of rotations, and the constant α determines the rate of increase in the radial direction with respect to the rate of rotation. For multiple interleaves, a phase shift of $2\pi(n-1)/N_{\text{leaf}}$ is added for the n-th interleaf, where N_{leaf} is the total number of interleaves. The actual trajectory approaches this constant-linear-velocity spiral under the hardware constraints of the gradient system. Fig. 1(a) shows a single interleaf of a constant-linear-velocity spiral trajectory and (b) shows the central k-space trajectory with 24 interleaves. As seen in Fig. 1(b), the center k-space is automatically sampled densely enough to satisfy the Nyquist sampling criterion even in the accelerated scan where some interleaves are skipped [9]. This so-called self-calibrating property is desirable in parallel imaging where the central reduced data can be used for sensitivity estimation without the need for additional acquisition. To estimate the sensitivity functions, these truncated central k-space data are Fourier transformed to generate several low-resolution reference images for all channels, and the sensitivity functions are obtained by normalizing these reference images by their sum-of-squares reconstruction. The estimation can be mathematically expressed as

$$\hat{s}_l(\vec{r}) \approx \frac{[\rho(\vec{r})s_l(\vec{r})] \times h(\vec{r})}{\sqrt{\sum_l |[\rho(\vec{r})s_l(\vec{r})] \times h(\vec{r})|^2}} \tag{2}$$

where $\hat{s}_l(\vec{r})$ and $s_l(\vec{r})$ are the estimated and true sensitivities, respectively, $\rho(\vec{r})$ is the image, and $h(\vec{r})$ is the point spread function of the k-space sampling trajectory inside the circle with a chosen radius. This estimation method implicitly assumes the sensitivity weighting and convolution with the point spread function are commute [13], which is not satisfied in general. As shown in Ref. [9] and can be calculated using Eq. (1), the radius inside which the Nyquist rate is satisfied for the reduced scan is

$$k_0 = \frac{N_{\text{red\_leaf}}}{2\pi \text{FOV}}, \tag{3}$$

where $N_{\text{red\_leaf}}$ is the number of interleaves in the reduced scan and FOV denotes the field of view. This radius is shown as a circle in Fig. 1(b) for a reduction factor of 2. When the truncation radius is less than k_0, the corresponding point spread function has no aliasing artifacts, but is so wide that truncation effect is serious. As the radius of truncation circle increases, the point spread function becomes sharper, but the aliasing artifacts start to appear. This tradeoff between reduced truncation effect and reduced aliasing artifacts leads to inaccurate sensitivity functions, which becomes serious especially at locations where the object transverse magnetization has high spatial frequency components. Consequently, the self-calibrated SENSE reconstruction suffers from residual aliasing artifacts.

We extend the JSENSE method [10] to improve the self-calibrated spiral SENSE. Specifically, we treat both the sensitivities and the desired image as unknowns in the imaging equation

$$d_{l,m} = \sum_n s_l(\vec{r}_n)\rho(\vec{r}_n)\ e^{-i2\pi\vec{k}_m\cdot\vec{r}_n}, \tag{4}$$

where $\vec{k}_m$ is the mth sampling location on a spiral trajectory in k-space, $d_{l,m}$ is the corresponding k-space data point acquired at that location from the lth channel, $\vec{k}_n$ is the nth pixel location of an image on a Cartesian grid, and $s_l(\vec{r}_n)$ and $\rho(\vec{r}_n)$ are the corresponding sensitivity and image values at that pixel location, with both m and n in lexicographical order. To reduce the degree of freedom for the unknowns to be solved for, we use a polynomial parametric model instead of a pixel-based function for the coil sensitivities:

$$s_l(\vec{r}) = \sum_{p=0}^{N}\sum_{q=0}^{N} a_{l,p,q}(x-\bar{x})^p(y-\bar{y})^q, \tag{5}$$

where $(x, y) = \vec{r}$ denotes the location of a pixel, $(\bar{x}, \bar{y})$ denotes the image center location, and $a_{l,p,q}$ is the coefficient of a polynomial, forming an unknown vector **a**. Several other models, such as wavelet and spline, are also appropriate for the smooth sensitiv-

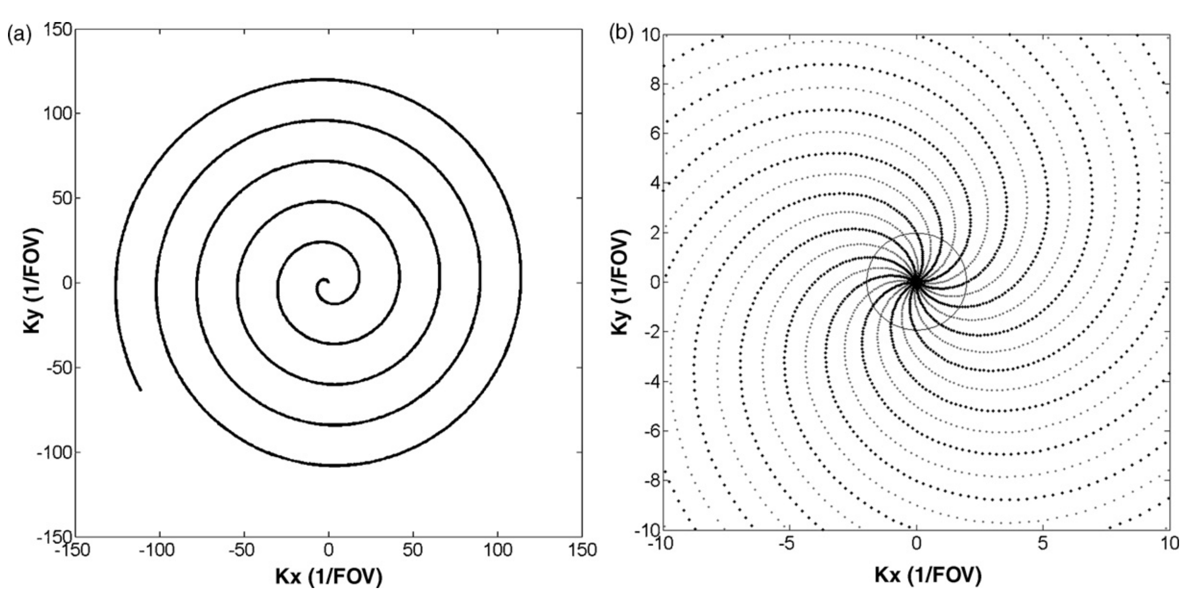

Fig. 1. The spiral trajectory used in this study, with a single interleaf shown in (a), and all 24 interleaves in (b). The dashed curves in (b) denote the interleaves to be skipped in an accelerated scan when $R = 2$. Inside the circle in (b), the Nyquist sampling rate is satisfied for the accelerated scan with $R = 2$.