Rapid, Self-calibrated Parallel Reconstruction for Variable Density Spiral with GROWL

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\textbf{Introduction}

Spiral imaging has been successfully applied to important applications such as cardiac [1] and functional MRI [2]. A major challenge facing spiral MRI is the tradeoff between the desire for a higher imaging speed with a smaller number of interleaves, and the need to avoid severe off-resonance artifacts resulting from a long readout window. Previously, variable density (VD) spiral, where the \( k \)-space is undersampled at the outer \( k \)-space, has been proposed [3] to address this tradeoff. However, the amount of undersampling in a VD spiral is limited due to the concomitant resolution loss and residual aliasing artifacts.

Parallel imaging techniques can be used to achieve a higher degree of undersampling in a VD spiral, therefore resolving the dilemma between the imaging speed and off-resonance artifacts. However, most existing parallel imaging methods [4-6] either require a long computation time due to their iterative nature, or have difficulty working with VD-spiral datasets where spacing between adjacent spiral lines vary continuously across the \( k \)-space.

In this work, a rapid \( k \)-space-based parallel imaging reconstruction method is proposed for VD spiral, using a set of Generalized GRAPPA for wider readout line (GROWL) operators [7]. Each acquired spiral line is expanded into a wider band with a flexible width across the \( k \)-space, therefore eliminating any undersampled \( k \)-space region. The self-calibration of GROWL operators along various directions are performed using the fully-sampled central \( k \)-space region. \textit{In vivo} brain scans demonstrate that the technique can be used either to achieve a significant acceleration and/or to reduce off-resonance artifacts.

\textbf{Methods}

The basic principle of GROWL for VD spiral is illustrated in Fig. 1. When compared with a uniform-density (UD) spiral, VD spiral significantly undersamples the outer \( k \)-space (Fig. 1a). Using GROWL operators, each acquired spiral line is expanded into a wider band with a flexible width, fulfilling the Nyquist criterion throughout the \( k \)-space (Fig. 1b). The fully-sampled circle at the \( k \)-space center is used for the self-calibration of the GROWL operators. Figure 1c shows three parameters that determine a GROWL operator kernel: the number of source (solid) data points along the readout line \( N_s \), the distance between target (open) and source readout line \( \Delta k \), and the orientation of the operator \( \theta \).

A healthy volunteer was scanned on a 3.0T clinical scanner (Achieva, Philips, Best, The Netherlands), using an eight-channel head coil (Invivo, Gainesville, FL) and a multi-slice 2D \( T_2 \)-weighted gradient echo sequence. Scan parameters: FOV 230×230 mm, slice thickness 5 mm, TR/TE = 500/16 ms, flip angle = 18°. Several VD spiral trajectories were designed to achieve reduction factor \( R = 2, 3 \) and 4. To demonstrate the scan time reduction, multiple pairs of uniform density (UD) and VD spiral datasets (image matrix 256 × 256) were acquired with identical acquisition window length \( T_w = 7, 5 \) and 4.4 ms. UD spiral datasets contain 32, 48 and 64 interleaves, while VD spiral datasets always contain 16 interleaves. To demonstrate the reduction of off-resonance artifacts, both single-shot UD and VD spiral datasets (image matrix 96 × 96) were acquired, with acquisition windows of 50 and 20 ms, respectively.

\textbf{Results and Discussions}

Results from multi-shot VD spiral datasets (Figure 2) show that GROWL reconstruction significantly improves the image resolution compared to regridding reconstruction, while reducing the total scan time by factors \( R = 2, 3 \) and 4. Figure 3 shows results from the single-shot brain scans. Again, GROWL reconstruction (Fig. 3d) improves image resolution vs. direct regridding (Fig. 3c). Moreover, off-resonance blurring is reduced in VD vs. UD datasets (Fig. 3b) due to a shortened readout window.

The reconstruction time for each 2D image is 5-10 seconds for GROWL, which is much faster than most existing techniques [4-6]. This is due to the non-iterative nature and the small kernel size. The GROWL operator can be potentially applied to other \( k \)-space sampling trajectories as long as the curvature of the readout lines is below a certain limit.

\textbf{References}