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

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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. *In vivo* brain scans demonstrate that the technique can be used either to achieve a significant acceleration and/or to reduce off-resonance artifacts.

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 undersample 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_x, the distance between target (open) and source readout line Δk_y and the orientation of the operator θ.

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 = 18^0. 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_a = 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.

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.

References

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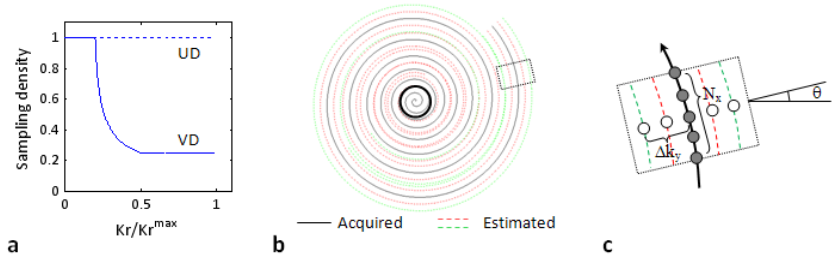[6] Lustig M, et al. *Magn Reson Med* 2010; 64: 457-471.

Figure 1 Basic principle of GROWL operator for VD spiral. (**a**) Sampling density of VD vs. uniform-density (UD) spiral. (**b**) GROWL operators are used to expand each acquired VD spiral line into a wider band with a flexible width across the k-space. Fully-sampled central circle is used for calibration. (**c**) A GROWL kernel with source (solid) and target (open) data points.
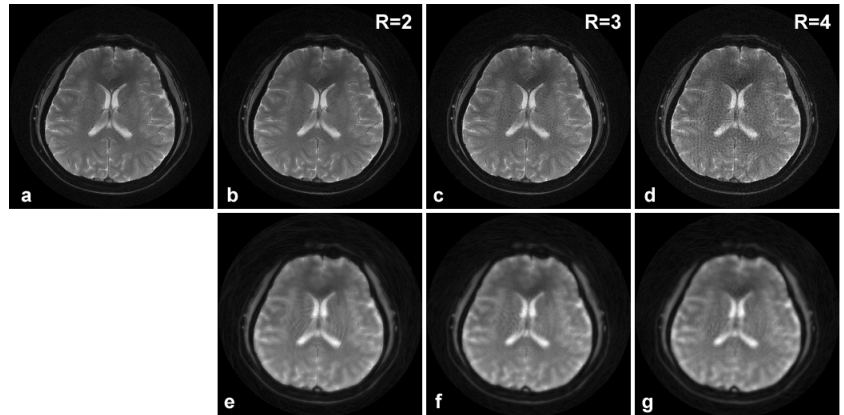

Figure 2 Multi-shot brain scans (256×256). (**a**) Fully-sampled uniform density spiral reference. (**b-d**) Undersampled VD spiral scans with GROWL reconstruction at acceleration factors R = 2, 3, 4. (**e-g**) Regridding reconstruction using the same datasets as those used in (b–d).
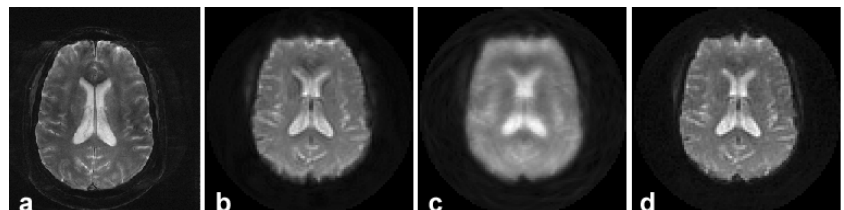

Figure 3 Off-resonance artifact reduction with single-shot VD spiral. (**a**) Reference Cartesian image (256×256, scan time = 2 min). (**b**) Single-shot UD spiral (96×96, readout window T_a = 50ms). (**c**) – (**d**) Single-shot VD spiral (96×96, readout window T_a = 20ms), with direct regridding (c) and GROWL reconstruction (d).

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