Accelerated Variable Density Spiral at 7 Tesla using Parallel Imaging

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Introduction

Spiral imaging [1] is a very efficient and versatile sampling scheme, allowing for very short effective echo times (forward [1]) or alternatively for very long TEs (reverse [2]), facilitating strong T2* contrast, desired in fMRI [3] or susceptibility weighted imaging [4]. But the spiral is sensitive to off-resonance effects, which represents a serious problem especially at 7T, resulting in loss of spatial resolution. Parallel imaging could be used to reduce off-resonance artifacts by shortening the acquisition window. However, sensitivity encoded spiral image reconstruction can be rather time consuming [5] and becomes difficult in the case of main field inhomogeneities. In this work, a rapid non-iterative *k*-space-based parallel imaging reconstruction method, adapted to the spiral, is proposed. In contrast to earlier approaches [6,7] here a set of Generalized GRAPPA for wider readout line (GROWL) operators [8] is used to estimate the missing k-space data. After appropriate image combination off-resonance correction is performed using standard approaches. The basic applicability of this approach for 7T imaging is investigated in vivo with respect to performance and achievable image quality improvements.

Methods

The basic spiral data acquisition scheme, using variable density sampling, is shown in Fig.1. The central part is sampled with a fixed radial sampling density, fulfilling the Nyquist criterion. Using a smooth transition, radial under-sampling is performed in the outer k-space (Fig. 1a) for acceleration. Corresponding data interpolation kernels can be estimated from the central k-space data (Fig. 1b). These kernels are used to estimate missing coil data in the corresponding neighborhood [8]. In the current implementation 32 basis directions (in the range of 0 to π) were used to train 32 GROWL kernels. The entire reconstruction is described in Fig.1c. After estimating the missing k-space data for each individual coil, image reconstruction is performed. The individual images are combined in a SNR-optimal way, using a signal phase preserving reconstruction (e.g. Roemer [9]), taking receive coil sensitivities S(r) into account, which are estimated from the central k-space data. Off-resonance correction based on a known field-map (ΔB_0) can be added using the single combined image, resulting in an improved reconstruction performance.

Single-shot and interleaved spiral imaging experiments were performed using a 7T scanner (Achieva, Philips Medical Systems, Cleveland). An integrated transmit / receive array head-coil (Nova Medical) was employed, allowing to switch between single channel (volume-coil mode) and 16-channel phased array acquisition mode. Imaging performance was tested for 2D acquisitions using a fixed FOV: 230×230mm², but different under-sampling regimes (uniform / variable density) and spatial resolutions (interleaved spiral: matrix: 256², interleaves: 20, AQ window: 20 ms (uniform) / 10 ms (VD-accelerated); single-shot spiral: matrix: 96², AQ window: 42 ms (uniform) / 16 ms (VD-accelerated)). For the VD-spiral 20% of the central k-space was sampled at Nyquist, while the outer part was under-sampled by a factor of 2.5 - 4, respectively. A spoiled, low tip angle (15°) gradient echo acquisition (TR: 1 sec) was used with different TEs (1-20 ms). No higher order shimming and no fat suppression was employed. Image reconstruction was performed off-line. Receive coil sensitivities to support image combination via Roemer (9) were measured with a SENSE reference scan, not estimated from the central k-space data. B_0-mapping was performed to allow for multi-frequency based off-resonance correction [10]. Four healthy adults (23-37 years) were scanned in this study. Informed consent was obtained according to local IRB requirements.

Results and Discussion

Figure 2,3 show representative images. The experiments confirmed that variable density spiral sampling supports k-space based parallel image reconstruction with no loss of quality (see Fig.2). However, Fig. 3 shows that the ΔB_0-corrected fully sampled spiral is of significantly lower spatial resolution than the VD-accelerated spiral scan, which is an essential feature making this approach interesting for 7T applications. The phase conservative image combination allows for efficient field map based deblurring or future trajectory corrections to improve image quality at affordable numerical efforts.

Conclusion

Variable density spiral parallel imaging could find interesting applications in ultra-high field imaging. It can help to facilitate single-shot applications at reasonable spatial resolution useful for arterial spin labeling (short TE) or for fMRI (long TE). For the latter VD-sampling could be combined with reverse sampling to further increase susceptibility contrast.

References: [1] Ahn B, et al. IEEE TMI 1986; 5:2. [2] Börnert P, et al. MRM 2000; 44:479. [3] Noll D, et al. JMRI 1995; 5:49. [4] Haacke EM, et al. MRM 2004; 52:612. [5] Pruessman K, et al. MRM 2001;46:638. [6] Heidemann RM, et al. MRM 2006; 56:317. [7] Yeh E, et al. MRM 2005; 54:1. [8] Lin W, et al. MRM 2010; 64:757. [9] Roemer P, et al. MRM 1990; 16:192. [10] Man LC, et al. MRM 1997; 37:785.

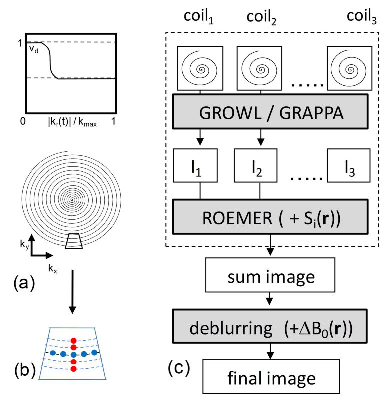

Fig.1. Variable density spiral. (a) Sampling: the central part of k-space fulfills Nquist, the outer is under-sampled. (b) GROWL operators are used to estimate missing spiral data (red) based on the acquired (blue) data. (c) Basic recon flow chart. After GROWL, images are combined and field map based deblurring can be added.

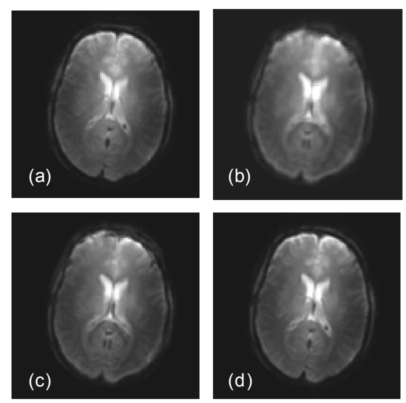

Fig.2. Multi-shot spiral (TE:10ms, 256×256). (a) fully sampled (AQ_w: 20ms), ΔBo corrected for comparison. (b) VD-spiral, R_{netto} = 2 (AQ_w: 10ms) re-gridded - loss of resolution due to under-sampling. (c) GROWL-recon of the data in (b), (d) GROWL + ΔBo correction.

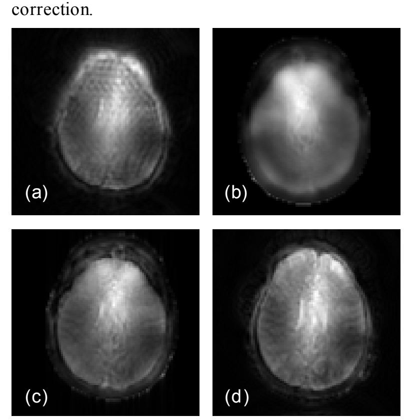

Fig.3. Single-shot spiral (TE:1ms, 96×96). (a) fully sampled (AQ_w:42ms), ΔBo corrected for comparison. (b) VD-spiral, R_{netto}=2.6 (AQ_w:16ms) re-gridded. (c) GROWL-recon of the data in (b), (d) GROWL + ΔBo correction. The spatial resolution is improved compared with(a).