3D Magnetization-Prepared Imaging and Fat/Water Separation Using a Stack-of-Rings Trajectory

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Introduction: Acquiring a 3D volume in a short scan time is a high-priority goal of many MR imaging applications. This is especially true for time-sensitive studies, such as magnetization-prepared imaging and dynamic imaging, where the signal is in transition. Fast imaging trajectories, such as under-sampled 3DPR or 3D stack-of-spirals, can provide a great reduction in scan time. However, they are sensitive to system imperfections and off-resonance effects. They also over-sample the center of *k*-space, which can provide robustness to motion, but can result in mixed or unexpected image contrast. In this work, we present the 3D stack-of-rings as a readout trajectory for robust and time-efficient magnetization-prepared imaging. Based on the concentric rings 2D trajectory, it inherits flexible trade-offs between image contrast, signal-to-noise ratio, spatial resolution, and scan time [1–4]. In addition, its unique circularly symmetric sampling nature enables a time-efficient retracing acquisition for fat/water separation [3, 4], making this non-Cartesian trajectory robust to off-resonance effects.

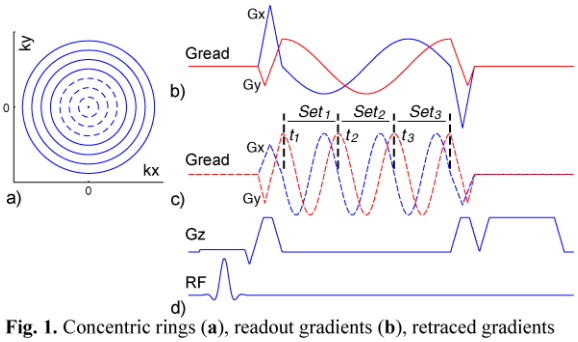

Fig. 1. Concentric rings (**a**), readout gradients (**b**), retraced gradients for the central rings (**c**), and the Gz and RF waveforms (**d**).

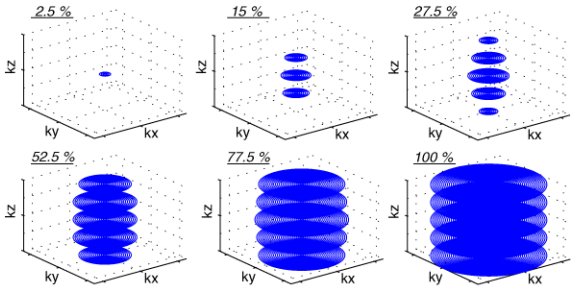

Fig. 2. 3D centric ordering. The percentage denotes the fraction of the total dataset that has been acquired.

Methods: 3D Stack-of-Rings: *N* uniformly spaced concentric rings (Fig. 1a) are used to encode (k_x, k_y). Sinusoidal gradients are designed for the outermost ring (Fig. 1b), and then scaled down to acquire one ring per TR in a spoiled gradient-echo (SPGR) sequence. This design ensures that timing errors and gradient delays only cause a bulk rotation in the reconstruction. The readout window length is held constant for all rings. Spatial coverage is extended to 3D by adding a slice-encoding gradient (Fig. 1d). To enable fat/water separation, the central *N/2* rings for each k_z slice are sampled with a time-efficient retracing method (Fig. 1c) [2]. Similar to multi-echo acquisitions, each Set_m (m=1,2,3) can be reconstructed individually to characterize the fat/water phase evolution difference at time point t_m. Reconstruction consists of a Fourier transform in k_z, followed by a series of 2D gridding operations for each slice. Water images are calculated for each slice by first demodulating each Set_m at water frequency, then using the individual images thus reconstructed in an iterative multi-point Dixon algorithm [3-5]. The single-revolution outer rings are demodulated at water frequency and added to each Set_m as common information. Fat images are obtained similarly by first demodulating at fat frequency [3]. It is also possible to perform fat/water separation with a direct spectroscopic reconstruction in (k_x, k_y, k_z, t)-space [4]. Magnetization-Prepared Imaging: To demonstrate the effectiveness of the 3D stack-of-rings, we considered an inversion-recovery (IR) experiment. The desired set of *k*-space encodings is acquired as *P* interleaved segments of *Q* encodings. After each preparatory 180° inversion pulse and a specified inversion time (TI), *Q* encodings are acquired. A delay time (TD) is observed before repeating the next preparation. Compared to other 3D trajectories such as 3DFT, 3DPR, or 3D stack-of-spirals, 3D stack-of-rings can be acquired with true centric-ordering in 3 dimensions (Fig. 2). As the stack-of-rings acquisition starts from the center of 3D *k*-space and progresses outwards in all 3 dimensions, the central region is sampled very rapidly using only a small fraction of the full set of encodings. This ensures that the prepared contrast is captured very compactly about the specified inversion time.

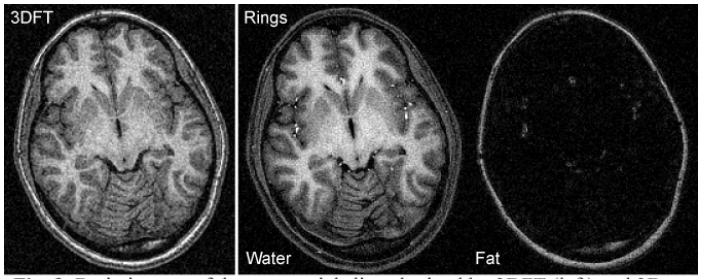

Fig. 3. Brain images of the same axial slice obtained by 3DFT (left) and 3D stack-of-rings (right). Separate water and fat images are shown for rings.

Experiments: Setup: Experiments were performed on a GE Signa 1.5 T Excite system. Axial brain images were obtained using a quadrature head coil. A 100 mm-slab was excited and encoded as 100 slices. In-plane encoding was performed using 128 rings for a 24 cm FOV (256x256 matrix), achieving isotropic in-plane resolution of 0.94 mm. The readout window was 4.8 ms for all rings and readout bandwidth was +/-125 kHz. The central 64 rings were acquired over 3 revolutions (1.6 ms / revolution) to enable SNR-efficient fat/water separation [3, 4]. We incorporated the rings into an IR-prepared SPGR sequence with TI/TD = 1 s/1 s, and TE/TR/θ = 2.1 ms/11.4 ms/15°. Partitioning *k*-space into *P*=64 segments (*Q*=200 rings per segment) resulted in a total scan time of *4 min 33 s*. Interleaved 3D center-out ordering was used for the rings. For comparison, we acquired a 3DFT dataset for the same FOV and resolution using a product IR-SPGR sequence with TI/TD = 600 ms/0 s, readout bandwidth of +/-32.25 kHz, and TE/TR/θ = 3 ms/6.9 ms/8° [6]. This product sequence partitioned *k*-space into *P*=512 segments (*Q*=50 phase encodes per segment) and had a total scan time of *8 min 07 s*. Results: Images from the same slice are shown in Fig. 3 for both scans. The 3D stack-of-rings scan requires only 56% of the scan time needed for the product 3DFT scan, produces better white/gray matter contrast, and can be reconstructed as separate fat/water images.

Conclusion: The 3D stack-of-rings trajectory inherits the desirable properties of the 2D concentric rings and offers even more flexibility in designing the acquisition strategy for efficient magnetization-prepared imaging. By using a retracing design, separate fat/water images and field maps can be calculated for each slice to ensure the robustness of this 3D non-Cartesian trajectory to off-resonance effects. This trajectory is also robust to gradient delays and timing errors. The geometry of the 3D stack-of-rings naturally suggests that it can be modified to sample a sphere in 3D *k*-space for enhanced time-efficiency [7]. Variable-density sampling along k_z and in (k_x, k_y) can be easily implemented. It is also possible to perform parallel imaging with the 3D stack-of-rings and incorporate the 3D stack-of-rings into a wide variety of imaging sequences to best suit the imaging scenario.

References: [1] Zhou X, et al., MRM 1998; 39: 23-27. [2] Wu HH, et al., MRM 2008; 59: 102-112. [3] Wu HH, et al., *Proc. 16th ISMRM*, p. 649, 2008. [4] Wu HH, et al., MRM (in press). [5] Reeder S, et al., MRM 2004; 51: 35-45. [6] Lin C, et al., MRM 2008; 59: 434-439. [7] Bernstein MA, et al., JMRI 2001; 14: 270-280.