Fast 3D SSFP Imaging Using a Concentric Cylinders Trajectory

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Introduction: A 2D concentric rings trajectory is inherently centric-ordered, provides a smooth weighting in *k*-space, and enables shorter scan times [1]. Due to these properties, it is well-suited for magnetization-prepared imaging. Extensions of this trajectory for 3D imaging include: 3D stack-of-rings [2] and 3D interleaved concentric cylinders [3,4]. 3D stack-of-rings trajectory directly inherits flexible trade-offs between signal-to-noise ratio, resolution, and speed from 2D concentric rings [2]. 3D interleaved concentric cylinders trajectory is similar to stack-of-rings, but it has a unique property that leads to fewer excitations and benign off-resonance effects [3,4]. In this work, we revisited the 3D interleaved concentric cylinders trajectory and have implemented an SSFP version of this sequence. Among the potential applications of this sequence is non-contrast-enhanced MR angiography based on SSFP.

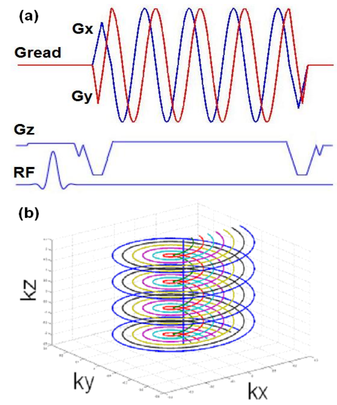

***Fig. 1.** (a) SSFP timing diagram and (b) k-space trajectory of 3D concentric cylinders for N_c = 8, N_{intlv} = 1, N_{rev} = 4.*

Methods: 2D Concentric Rings**:** The 2D concentric rings is an efficient trajectory that uses time-varying gradients to cover more of *k*-space per excitation. The *k*-space trajectory consists of a set of N_c uniformly-spaced concentric rings. Sinusoidal gradients are designed for the outermost ring and then scaled down to acquire one ring per TR [1]. It offers a factor of two reduction in scan time with respect to the corresponding Cartesian trajectory. It is also robust to off-resonance effects and system imperfections such as gradient delays. It extends to 3D stack-of-rings by adding a phase-encoding gradient in the slab-direction [2].

3D Interleaved Concentric Cylinders**:** 2D concentric rings extends to 3D interleaved concentric cylinders [3,4] by adding a constant G_z gradient during readout (Fig. 1a). The constant G_z gradient is the key feature that largely replaces blurring, a typical non-Cartesian off-resonance effect, by a benign geometric shift in the slab-direction. The number of cylinders N_c determines the in-plane resolution and FOV, while the amplitude of the constant gradient G_z and readout time determine the slab-direction resolution. Given the slab-direction resolution, the number of interleaves per cylinder N_{intlv} and number of revolutions per interleaf (shot) N_{rev} determine the slab-direction FOV (Fig. 1b). Considering RF power deposition (SAR), bigger N_{rev} is better because this sequence approximately requires a factor of $2N_{rev}$ fewer excitations than a comparable 3DFT sequence. Considering non-linear components of off-resonance effects, however, smaller N_{rev} is better because the effects increase with the readout time. N_{intlv} can be simply chosen to get a desired slab-direction FOV. The reconstruction is performed by 3D gridding reconstruction.

Results and Discussions: To demonstrate the feasibility of SSFP imaging with 3D concentric cylinders, we implemented the sequence on a GE Excite 1.5 T whole-body scanner. G_x and G_y were designed to provide in-plane FOV = 26 cm, with N_c =128 (matrix size = 256x256) and in-plane resolution = 1 mm. The slab-direction resolution = 2 mm. N_{intlv} and N_{rev} were chosen as 16 and 4, respectively, which provided 64 equally spaced k_z points for each (k_x, k_y) point. The corresponding slab-direction FOV = 12.8 cm. Flip angle = 30° and readout bandwidth = ±125 kHz, which yielded 1840 points per readout. For SSFP, TE/TR = 3/13 ms and scan time = 27 s. For SPGR, which was implemented for comparison, TE/TR = 4/16 ms and scan time = 33 s. 64 slices were reconstructed. Fig. 2 shows the phantom results when off-resonance correction was intentionally not performed to illustrate that off-resonance effects generally cause blurring for non-Cartesian trajectories such as stack-of-rings (Fig. 2a), while it only causes a shift (no blurring) for the concentric cylinders (Fig. 2b). Normally however, the rings can be designed to resolve off-resonance effects very efficiently [1]. Fig. 3 shows the in vivo results with concentric cylinders implemented in an (Fig. 3a) SPGR and (Fig. 3b) SSFP sequence, respectively. Both show detailed cross-sections of the calves including bright vessels as well as benign off-resonance effects. It demonstrates that the 3D concentric cylinders trajectory is feasible for SSFP as well as SPGR imaging. The banding artifacts in Fig. 3b come from a relatively long TR of 13 ms, which can be shortened by phase cycling or reducing the number of revolutions N_{rev} for each readout.

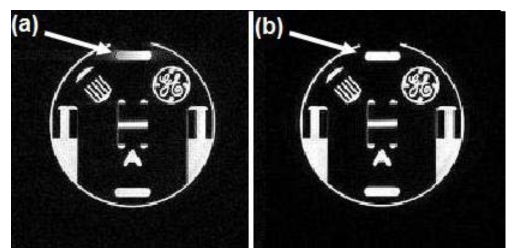

***Fig. 2.** Central slice of axial phantom dataset (SPGR) without off-resonance correction: (a) 3D stack-of-rings, (b) 3D concentric cylinders*

Conclusion: The 3D interleaved concentric cylinders trajectory is a highly viable trajectory for fast 3D SSFP imaging. It offers 1) feasibility of combining with SSFP for flow-independent blood/muscle contrast [5] 2) benign off-resonance effects 3) fewer excitations, for reduced scan time. Combined with variable-density sampling with variable interleaves [6] or radii, the trajectory can further reduce the scan time.

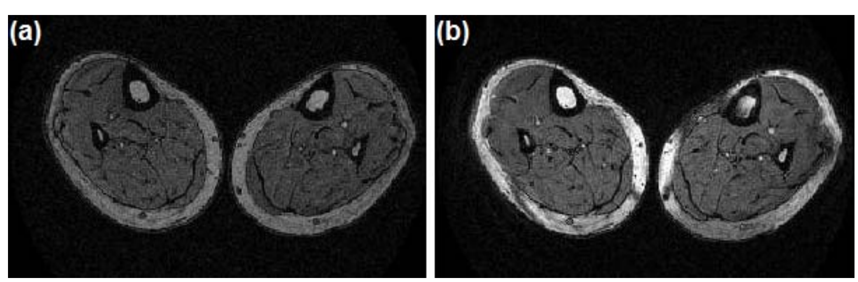

***Fig 3.** Central slice of axial images of the calf. (a) 3D concentric cylinders (SPGR) (b) 3D concentric cylinders (SSFP)*

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