Rapid 3D Spoiled Steady-State Imaging with Yarn-Ball Acquisition

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Introduction: SPoiled 3D GRadient echo (SPGR) is very common. It facilitates a wide range of applications from volumetric imaging, to field mapping (1) to magnetization transfer (2), etc. However, image acquisition is time consuming, as only line of k-space is acquired per excitation. A novel centre-out strategy is proposed which allows much greater 3D sampling per readout, and makes possible the creation of much higher resolution images than standard gradient-echo (GRE) for the same short scan duration. A single-shot version was presented in (3); this is a multi-shot extension.

Theory and Methods: The proposed methodology is made to sample k-space as one may wind a ball of yarn (**Figure 1**). As radial evolution slows beyond radial fraction (ρ) to maintain a constant number of samples within spherical shells of increasing radius (Eq. [1]), trajectory 'winding' ($\dot{\varphi}$) and 'winding-rotation' about the z-pole ($\dot{\theta}$) 'uniformly' distribute the sampling throughout each shell (Eqs. [2, 3]). The initial projections of each trajectory (of which there are N) lay on a set of (N_{discs}) discs rotated through the z-pole. Full sampling is achieved when Eq. 4 is satisfied and $N_{discs} = \sqrt{N/2}$. The consequence of decreasing ρ (as a result of decreasing N) is an increased number of 'winds' per readout, and increased rates of gradient change ($\dot{G}$). This is a design constraint, as maximum $\dot{G}$ is limited by peripheral nervous stimulation. While trajectory winding is tight near the centre of k-space, it is much looser in the periphery. To achieve a constant 160 mT/m/ms (and maximum sampling speed), incremental trajectory segments were stretched and contracted in the centre and periphery of k-space respectively. Unlike GRE, the acquisition number requirement is dependent on readout duration (τ_{RO}). For τ_{RO} = 1, 5, & 10 ms the number of acquisitions required to fully sample k-space to an isotropic field-of-view (FoV) of 220 mm (selected for human brain) was compared to 3D GRE for isotropic voxels.

[1] $\dot{r} = \rho^2/r^2$

[2] $\dot{\varphi} = 2\pi^2 R^2 \dot{r} r/N$

[3] $\dot{\theta} = 2\pi\dot{r}/N_{discs}$

[4] $\rho = N/(2\pi^2 R^2)$

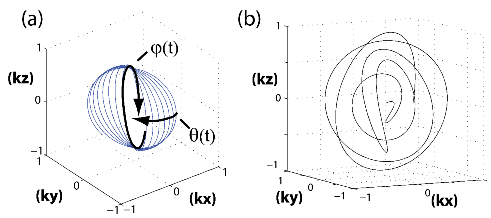

Figure 1: **(a)** Yarn-Ball evolution. **(b)** A typical multi-shot Yarn-Ball trajectory

Both SPGR and SPoiled Yarn-Ball (SPYB) sequences were implemented on a 4.7T Varian Inova console with TR = 35 ms and flip angle = 10°. A resolution phantom was scanned requiring a 260 mm FoV (used for both SPGR and SPYB). To demonstrate SPYB a τ_{RO} = 10 ms chosen. This enabled k-space sampling to a spherical volume of 0.335 1/m^3 (Cartesian equivalent voxel width of 1.44 mm) with only 2592 trajectories (sampling bandwidth = 500 kHz). However, 2500 acquisitions allow for only 50 phase-encodes in each of the 2nd and 3rd dimensions for GRE, producing large voxel widths of 5.2 mm. A τ_{RO} = 1 ms was selected for GRE. While both SPGR and SPYB are ~90 second sequences, a waveform memory limitation of our 15 year old Inova console required that SPYB be split into 216 separate parts (~15 seconds of loading time each). Thus, proof of concept is here limited to phantoms.

Results and Discussion: Yarn-Ball facilitates full sampling of k-space with much fewer trajectories than GRE (> 100x fewer for very rapid scanning with large voxels) (**Figure 2**). This advantage increases as τ_{RO} increases. For the same effective scan duration, FoV, and full k-space sampling, the maximum isotropic resolution (and image quality) that can be achieved with SPGR falls far short of that possible with SPYB (**Figure 3**). Note, however, that SPGR resolution could be increased in the readout direction without a time penalty (yielding anisotropic voxels); partial Fourier acquisition can also increase resolution. The advantages of parallel imaging are equally applicable to both SPGR and SPYB. Newer scanners with increased gradient waveform memory will realize the full potential of Yarn-Ball acquisition for human application.

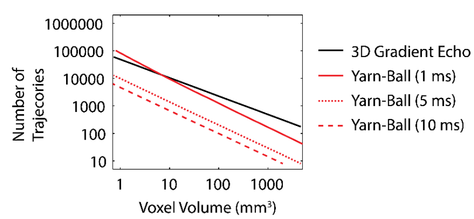

Figure 2: Yarn-Ball requires much fewer trajectories that 3D-GRE for isotropic FoV and voxels. (τ_{RO} given in brackets, and $\dot{G}$=160 mT/m)

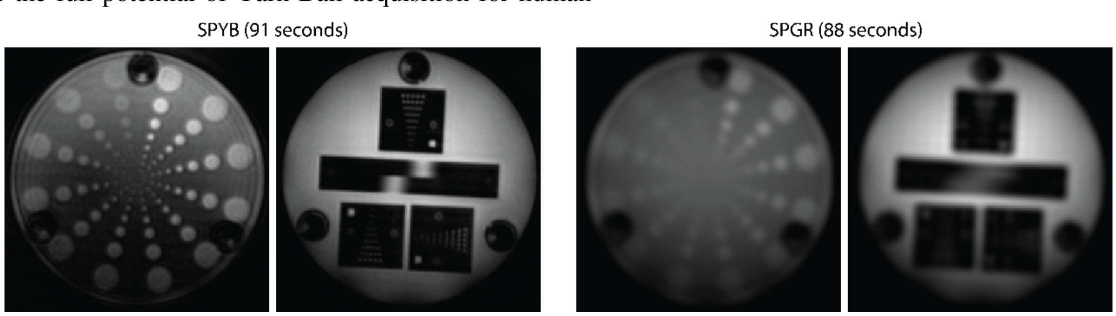

Figure 3: For the same scan duration and isotropic 3D FoV, the maximum isotropic resolution that can be achieved with standard SPGR (5.2 mm isotropic) falls far short of SPYB (1.44 mm isotropic).

References: (1) Reeder, S. *et al.* JMRI, 644, 2007 (2) Giulietti, G., *et al.* Neuroimage, 1114, 2012 (3) Stobbe, R.W., *et al.* ISMRM, 2011