

# A Looping Trajectory for Single-Shot 3D Imaging

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**Introduction:** When the rapid production of 3D images is required, e.g. for the assessment of relative neuronal activation timing in the context of fMRI, single-shot 3D k-space acquisition must be considered (1). For single-shot 3D MRI, a long readout duration ( $T_{RO} \sim 50$ ms) is necessary to sample even a small matrix volume, e.g.  $14 \times 14 \times 14$  in (1), a result of gradient slew rate, or trajectory acceleration, constraint. Images produced with long  $T_{RO}$  suffer from off-resonance artifacts, a particular concern for high field imaging. It has recently been shown that centre-out, 3D acquisition with radial evolution that slows to maintain constant sampling density (Eq. [1]) can greatly reduce off-resonant artifacts (2). In this abstract centre-out, radial evolution slowing, 3D ‘looping’ methodology is introduced for single-shot 3D imaging.

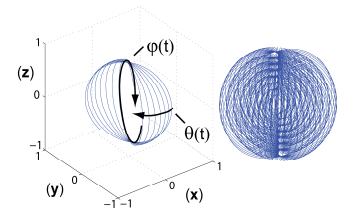
**Theory:** The proposed methodology is made to evolve as one may wind a ball of yarn (**Figure 1**). While radial evolution slows to maintain a constant number of samples within spherical shells of increasing radius, trajectory ‘winding’ ( $\dot{\phi}$ ) and ‘winding-rotation’ about the z-pole ( $\dot{\theta}$ ) are proposed to ‘uniformly’ distribute the sampling throughout each shell (Eqs. [2, 3]).  $\tau_{max}$  is the relative duration of the winding portion of the trajectory; the relative duration of a trajectory without radial slowing is 1 (3). For ‘spoke’ projections filling a set of discs rotated through the z-pole,  $2\pi^2 R$  projections are required for sufficient sampling. For the proposed methodology this number can be reduced as  $p^2$ , facilitating sufficient sampling with only 1 projection when  $p = 1/(\sqrt{2}\pi R)$ .

**Methods:** A ‘yarn-ball’ trajectory was implemented to sample a spherical ( $R = 8.68$ ) matrix volume of 2744 (or  $14^3$ ) with a  $T_{RO}$  of 48 ms and an FoV of 200 cm, as used for the ‘back-and-forth’ methodology in (1). A single trajectory was created by numerically solving Eqs. [1-6] for  $p = 0.0259$ , in  $\sim 4 \times 10^5$  segments, from  $r(-p/3) = 0$  to  $r(\tau_{max}) = 1$  with  $\tau_{max} = 496$ . Calculated  $|\dot{G}(t)|$  is plotted in **Figure 2**. Acceleration was constrained to equal the value at the end of the trajectory by increasing the duration of trajectory segments in proportion to the square root of each relative acceleration increase over the end segment; as a result the total relative projection duration ( $\tau_{tot}$ ) was increased to 596. This trajectory, stretched over 48 ms, was sampled at  $3\mu s$  intervals, yielding a gradient waveform with maximum  $|\dot{G}(t)|$  of 12.7 mT/m and  $|\dot{G}(t)|$  of 157 mT/m/ms. A total of  $R \cdot \tau_{tot} = 5174$  k-space locations are required for full sampling along the trajectory. An approximation of sampling density was produced by gridding ‘ones’ at each sample location using a narrow Kaiser convolution kernel of width = 4 and  $\beta = 12$  (to reduce ‘smearing’ of actual sampling density). A preliminary 3D single-shot image was obtained from a cylindrical oil phantom with only basic manual shimming on a 4.7 Tesla Varian Inova scanner (Hard RF pulse, TE = 0.3 ms, TR = n/a).

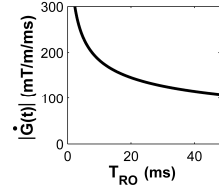
**Results and Discussion:** There are no visible undersampled locations in the yarn-ball trajectory’s approximated sampling density (**Figure 3**). k-Space is critically sampled along the edge of the sphere. Sampling density increase toward the centre of k-space is the result of constraining acceleration, and increase around the z-pole is inherent to the methodology. As a result of oversampling, the yarn-ball trajectory is inefficient to a factor of 5174 (required number of samples) / 2744 (grid locations in volume) = 1.89; a design goal remains to reduce this factor. The acceleration constrained yarn-ball trajectory yields a similar  $\dot{G}(t)$  to that of the ‘back-and-forth’ methodology in (1) for the same  $T_{RO}$ , FoV, and sampled matrix volume. However, more rapid sampling of the locations surrounding the centre of k-space theoretically yields improved off-resonance performance. The yarn-ball trajectory may also be ideal for resolution increase with ‘random’ undersampling design (4). A preliminary 3D image is shown in **Figure 4**. Unfortunately, large oil off-resonances will adversely affect this image; as well, considerable work remains to quantify and compensate for eddy-current generation. Human images with fat saturation, volume (‘slab’) selection, and rigorous shimming remain to be acquired.

**References:** (1) Lindquist, M.A., *et al.* JMR, 191, 2008 (2) Nagel, A.M., *et al.* MRM, 62, 2009 (3) Boada, F.E., *et al.* MRM, 37, 1994 (4) Lustig, *et al.* MRM, 58, 2007

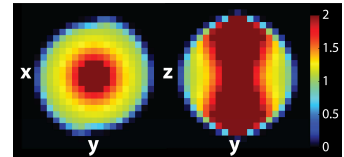
$$\begin{aligned} [1] \quad \dot{r} &= p^2/r^2 \\ [2] \quad \dot{\phi} &= s_{\phi} \dot{r} r \\ [3] \quad \dot{\theta} &= s_{\theta} \dot{r} \\ [4] \quad s_{\phi} &= \frac{2(\pi R)^2}{\tau_{max}} \\ [5] \quad s_{\theta} &= \frac{\pi R}{\tau_{max}} \\ [6] \quad \tau_{max} &= \frac{1-p^3}{3p^2} \end{aligned}$$



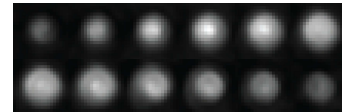
**Figure 1:** (a) A portion of the ‘yarn-ball’ trajectory. (b) full trajectory



**Figure 2:** Rate of gradient change along the ‘yarn-ball’ trajectory.



**Figure 3:** Slices of approximated sampling density for the acceleration constrained ‘yarn-ball’ trajectory.



**Figure 4:** A preliminary 3D image of a cylindrical oil phantom created with the acceleration constrained ‘yarn-ball’ trajectory in 48 ms at 4.7 Tesla.