Modulo-Prime Spoke (MoPS) Interleaving for k-Space Segmented Radial Acquisition Strategies

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Target Audience: Scientists and Clinicians interested in dynamical imaging with k-space segmented MRI pulse sequences.

Introduction: Non-Cartesian MRI sampling strategies such as radial trajectories often employ linear and sequentially increasing acquisition of radial spokes that are uniformly distributed in k-space. As an extension of this approach, a special class of rotation angles such as the Golden Angle (GA=111.246°) has been shown to improve coverage of k-space in a fewer number of repeated readouts [1,2]. In particular, the GA/n method [2] has enabled rotation-angle optimized k-space segmented 3D acquisitions, allowing a truly flexible temporal window reconstruction. Here, we propose a new interleaving scheme called Modulo-Prime Spokes (MoPS), which exploits the mathematical properties of prime numbers to distribute radial k-space efficiently for k-space segmented acquisitions. We propose a 3D stack-of-stars approach using MoPS interleaving to generate a high-temporal (15ms) gridding reconstruction with per-TR (~2 ms) sliding window resolution, and exploit the periodic nature of the acquired radial k-space spokes in the temporal frequency domain, and design a simple filtering method to mitigate radial streaking artifacts without blurring physiologic motion.

Theory: Consider a uniformly distributed radial sampling trajectories with a prime number $\boldsymbol{p}$ evenly distributed spokes. Each of these trajectories yield a rotation angle of $\boldsymbol{\theta}_{\mathbf{p}} = 180/\boldsymbol{p}°$. Exploiting the numerical property of primes, we note that for any integer value $0 < \boldsymbol{n} < \boldsymbol{p}$, a constant rotation by an angle $\boldsymbol{\theta}_{\boldsymbol{np}} = \boldsymbol{n}\boldsymbol{\theta}_{\mathbf{p}}$, would yield no two spokes within $\boldsymbol{p}$ consecutive readouts to acquire the same trajectory. This is due to the fact that for k = [0, 1, 2, …, $\boldsymbol{p}$-1], k$\boldsymbol{n}$ *modulo* $\boldsymbol{p}$ → [0, 1, 2, …, $\boldsymbol{p}$-1], where the mapping (→) is 1-to-1 and onto: all spokes are acquired once and only once. In practice, any of $\boldsymbol{p}$***-1***, $\boldsymbol{p}$, or $\boldsymbol{p}$***+1*** uniformly distributed radial spokes can be employed for the proposed MoPS approach using the prime $\boldsymbol{p}$. Figure 1a shows a simplified schematic with $\boldsymbol{p}$=11. Figure 1b demonstrates the interleaving for the proposed k-space segmented acquisition in this study, and demonstrates how the MoPS interleaving can be extended cyclically to provide periodicity over a large acquisition window (greater than the R-R interval in this case).

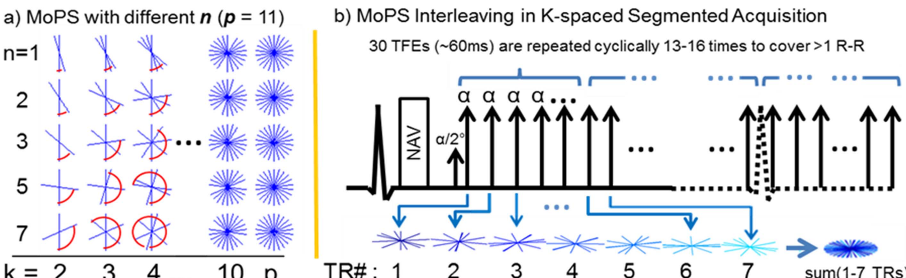

Fig 1. Schematics demonstrating MoPS Interleaving. a) p=11 numerical simulation, showing that spokes never repeat for any n < p. b) the *in-vivo* pulse sequence diagram in this study.

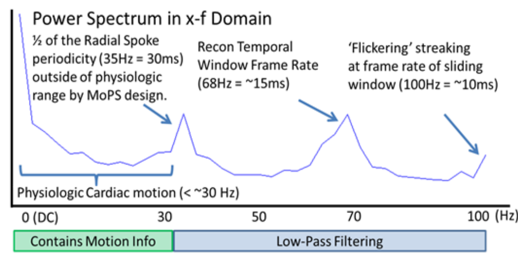

Fig 2. A representative power spectrum in the x-f domain showing radial streaking as spectral peaks that periodically rotate and recur over the sliding window (10ms in above).

Materials and Methods: The proposed MoPS interleaving was implemented using an ECG-triggered, navigator-gated and slice-followed radial acquisition (3D Stack-of-Stars) on 1.5T MRI hardware (Philips Achieva) with a 5-channel cardiac array. N=5 pigs were imaged using different ($\boldsymbol{p}$, $\boldsymbol{n}$) pairs using a scan parameter-derived look-up table [3]. Each kz-plane was sampled in a centric order. The following parameters were used for 3D imaging with radial stack-of-stars: FOV=300-330x300-330x80 mm^3; TR=2.3-2.5ms; TE=1.1ms; spatial resolution =1.7x1.7x3.4 mm^3, nTFE was set to 30 spokes per segmented for all experiments in this study. The 30-nTFE spoke acquisition was repeated 13-16 times in a cyclic manner, yielding a total acquisition window ~= 390-480 spokes, or ~900-1200ms duration, sufficiently longer than the full R-R interval of swine with HR >80 BPM (750ms). For this study, all data was reconstructed using a 15ms temporal resolution with per-TR (~2 ms) sliding window, using only radial gridding without parallel imaging or iterative reconstruction methods. This reconstruction allowed analysis of the timecourse in the temporal frequency (x-f) domain (power spectrum analysis with peak frequency >100Hz, as shown in Figure 2), and an appropriate low-pass filter (LPF) design was examined for the removal of apparent streaking artifacts without introducing temporal blurring.

Results: All examined ($\boldsymbol{p}$, $\boldsymbol{n}$) pairs were acquired successfully. Total scan times of the proposed sequence was ~3 minutes for a fully sampled 3D acquisition with 29 reconstructed z-slices. Figure 2 shows the schematics of the power spectrum analysis used for the streaking artifacts characterization. Using this analysis and the time-course of the reconstruction, it was determined that a notable source of streaking rotated around the image over a fixed nTFE (62-72ms duration) periodicity, corresponding to radial streaking from each spoke end at half this duration (~35Hz). In all cases, two additional non-physiologic peaks were observed: these were streaking artifacts that exhibited periodic recurrence at the temporal frame rate (~68Hz), and single-frame 'flickering' that corresponded to the maximum frequency component in the power spectrum (>100Hz). These frequencies were both significantly higher than the physiologic range, which held true in all pigs for all examined ($\boldsymbol{p}$, $\boldsymbol{n}$) pairs: (181, 22), (241, 36), (271, 26). The ($\boldsymbol{p}$, $\boldsymbol{n}$) affected the extent of streaking, but did not affect streaking frequency. Figure 3 shows a representative reconstruction with candidate LPF cutoffs. A frequency cutoff set below 2/(nTFE·TR)=~35Hz removed streaking without noticeable blurring.

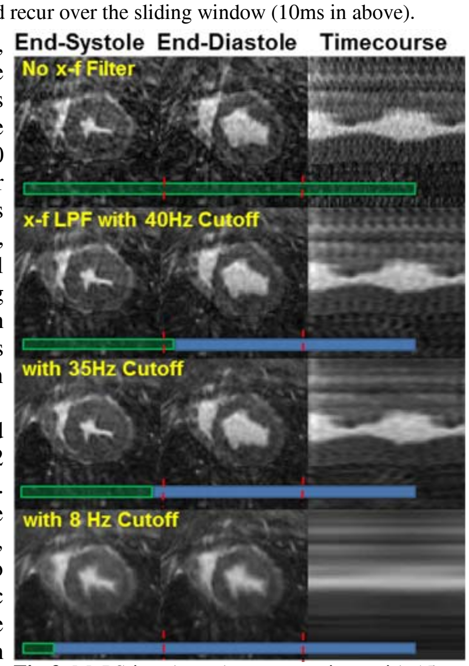

Fig 3. MoPS interleaved reconstructions with 15ms res and a 10ms sliding window: ($\boldsymbol{p}$,$\boldsymbol{n}$,nTFE) = (181,22,30), and timecourse after employing LPFs with varying frequency cutoffs. Red line shows peak frequencies of radial streaking. Note the 40 and 35Hz LPF cutoffs: with 35Hz = 2/(nTFE·TR) cutoff, the lowest frequency streaking is suppressed without introducing temporal blur (eg. 8Hz cutoff).

Discussion: The proposed MoPS interleaving requires only a simple constraint on the total number of uniformly distributed radial spokes per kz plane to be set to a prime $\boldsymbol{p}$ (or $\boldsymbol{p}$***±1***). This interleaving allows k-space segmented radial acquisition for the reconstruction of any flexible temporal window. $\boldsymbol{n}$ can be optimized for each $\boldsymbol{p}$, but was not investigated in this study. A sliding window reconstruction at per-TR increments is feasible with MoPS interleaving, which allows filtering of undersampled radial streaking artifacts in the x-f domain. Future investigation includes the development of iterative reconstructions such as radial compressed sensing that incorporates x-f thresholding, and clinical validation of the proposed acquisition.

References: 1. Winkelmann et al. IEEE Tr Med Im 2007. 2. Kawaji et al. PLoS One 2014, In Press. 3. Kawaji et al. Proc. ISMRM 2014, pp 4221.