Rotation Angle Optimization for a K-space Segmented 4D Radial Stack-of-Stars Acquisition

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TARGET AUDIENCE: Scientists and clinicians interested in incorporating dynamical imaging using k-space segmented pulse sequences.

INTRODUCTION: Golden angle interleaving of radial k-space lines allows retrospective reconstruction of the data with different temporal resolution[1-4]. In coronary MRI with radial k-space sampling, data is usually acquired at the quiescent period to minimize the impact of cardiac motion. However, this timing is variable between subjects and also varies between different anatomical targets (e.g. right vs. left coronary arteries). Recently a segmented acquisition scheme where radial k-space data is acquired over a larger acquisition window was proposed to allow retrospective reconstruction of a subset of the data with minimal amount of cardiac motion[6]. To enable reconstruction of a subset of radial k-space lines with minimal artifacts, uniform distribution of the radial lines becomes desirable. However, a reconstruction window may only partially cover the acquisition window, and such coverage is dependent on the pulse sequence parameters; thus, golden-angle interleaving over multiple segments does not necessarily result in a uniform distribution. In this study, an empirical approach is developed to determine the optimal rotation angle that evenly distributes the radial k-space spokes for any subset of the acquisition window in a 3D k-space segmented radial stack-of-stars coronary MRI.

METHODS: In the proposed segmented radial stack-of-stars approach, each k_z-plane was sampled sequentially. The acquisition of each k_z-plane lasted multiple heartbeats, and the radial spokes in a given k_z-plane were rotated by an angle θ at each repetition time (TR). The k-space distribution is a function of 4 parameters: i) rotation angle between different radial spokes (θ); ii) the number of projection lines in each heart beat (nTR); iii) the number of heartbeats per k_z plane (nHB); iv) the number of projections in each heartbeat used for reconstruction, i.e. the reconstruction window (nRCW). For this study, we set nHB = 14. To allow reconstruction for a flexible choice of nRCW, we aim to enforce a uniform spacing of the radial spokes and to minimize the clustering of spokes in any area of the k-space, over a range of nRCW values. Accordingly, we define the objective function which we seek to minimize as follows:

$$C(\mathrm{nTR},\mathrm{nHB}) = \arg\min_\theta \sum_{\mathrm{nRCW=Nmin}}^{\mathrm{Nmax}} \left\| \Delta\Theta_{\theta,\,\mathrm{nTR}}^{\mathrm{nHB,\,nRCW}} - \Delta\Theta_{LI,\,\mathrm{nTR}}^{\mathrm{nHB,\,nRCW}} \right\|_2^2 + \lambda \cdot \max\left(\left| \Theta_{\theta,\,\mathrm{nTR}}^{\mathrm{nHB,\,nRCW}} - \Theta_{LI,\,\mathrm{nTR}}^{\mathrm{nHB,\,nRCW}} \right| \right) \; \ldots [1]$$

where $\Theta_{\theta,\,\mathrm{nTR}}^{\mathrm{nHB,\,nRCW}}$ is a vector corresponding to the angles of the nHB·nRCW radial spokes acquired within the reconstruction window over multiple heartbeats when a θ rotation is used between subsequent spokes, $\Theta_{LI,\,\mathrm{nTR}}^{\mathrm{nHB,\,nRCW}}$ is the same vector of radial angles for the linear case with a 180º/(nHB · nRCW) rotation between subsequent spokes, and $\Delta\Theta$ is the first derivative of Θ. The first (left) term enforces uniform spacing, while the second (right) one minimizes clustering. We note the right term is not rotation invariant, thus the first element of angle of $\Theta_{\theta,\,\mathrm{nTR}}^{\mathrm{nRHB,\,nRCW}}$ was chosen such that the $\Theta_{\theta,\,\mathrm{nTR}}^{\mathrm{nRHB,\,nRCW}}$ was best aligned with $\Theta_{LI,\,\mathrm{nTR}}^{\mathrm{nRHB,\,nRCW}}$, by minimizing $\left\| \Theta_{\theta,\,\mathrm{nTR}}^{\mathrm{nRHB,\,nRCW}} - \Theta_{LI,\,\mathrm{nTR}}^{\mathrm{nRHB,\,nRCW}} \right\|_2^2$. For numerical optimization of [1], θ was varied between 0.01 and 179.99º in step size of 0.01. Additionally, integer divisors of the GA (GA/1 thru GA/15) were additionally considered for θ.

RESULTS: Figure 1 demonstrates the optimization for nTR = 48 for two different reconstruction windows. The GA/n angle that yielded the minimal objective function yields a uniform distribution of the radial spokes. Figure 2 shows the best GA/n reconstructions for nTRs between 32 and 64 (in step sizes of 4). There are four angle distributions (within boxes) that visually display clustering in the top set, for which λ=0. The bottom set shows the best GA/n terms when λ=0.7, where a different GA/n was selected for these 4 cases, while the remaining cases yielded the same GA/n as λ=0. Figure 3 shows examples of coronary MR images acquired at nTR = 48, nHB = 14, and nRCW = 1, 10 and 25, respectively; θ was varied between GA = 111.246 and GA/7 (optimal GA/n case for nTR = 48), showing less streaking artifacts when using the GA/7 scheme over the GA acquisition.

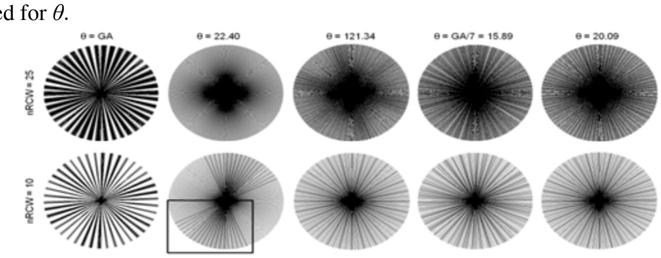

Figure 1. Simulation results with nTR = 48, nRHB = 14. Top column shows the reconstruction with 25 consecutive TRs, bottom with 10. The leftmost column shows the k-space GA=111.246, where the spokes are clustered. Optimizing with λ = 0 yielded θ = 22.40, which shows even distribution of the spokes at nRCW = 25, but shows clustering in a sector at a smaller reconstruction window. The middle column optimized for the right term only, yielding θ = 121.34, where clustering in a sector was minimized. The final two columns were optimized using Eqn [1] with λ = 0.7; showing θ = GA/7 = 15.89°, and θ = 20.09, respectively.

DISCUSSIONS: The proposed approach addresses the sub-optimal distribution of k-space spokes in a segmented radial stack-of-stars acquisition with different acquisition and reconstruction windows. Furthermore, the proposed optimization yields a rotation angle that provides an even distribution of spokes without clustering of spokes for a wide range of the reconstructed temporal window sizes, and can be used to generate the best GA/n angle approximation with good image quality over the typically used Golden Angle.

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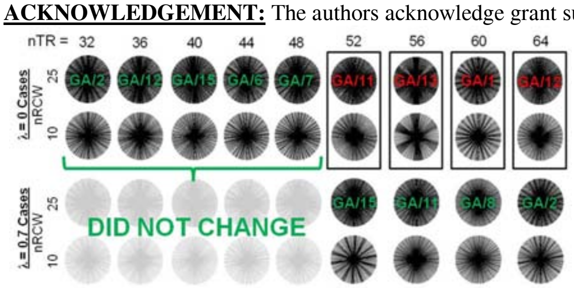

Figure 2. The best GA/n cases where the top set was calculated using λ=0, and the bottom set using λ=0.7 to also penalize for clustering within a sector, which is successfully performed here.

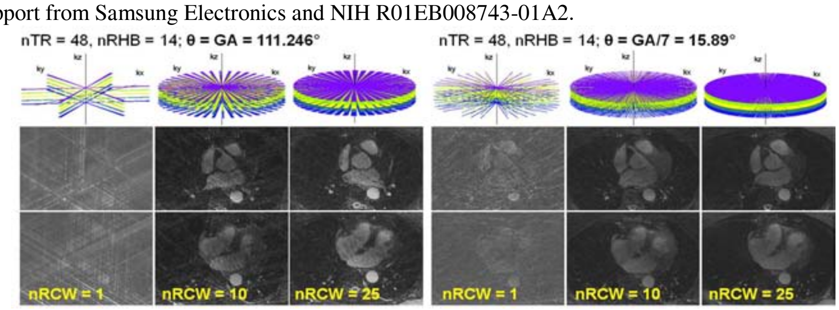

Figure 3. Whole-heart coronary MRI acquired using θ = 111.246 [GA] (left) and θ = 15.89 [GA/7] (right). nRCW was varied between 1, 10 and 25.

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