3D Cones Reordering Design Methods for Whole-Heart Coronary MR Angiography

Mario O. Malavé[1], Nii Okai Addy[1], R. Reeve Ingle[1], Joseph Y. Cheng[1], and Dwight G. Nishimura[1]
[1]*Electrical Engineering, Stanford University, Stanford, California, United States*

Introduction/Purpose: For whole-heart coronary MR angiography (CMRA), we are developing a sequence based on alternating-TR steady state free precession (SSFP) and 3D cones k-space sampling. The free-breathing scan is segmented over many heartbeats. With a sequential readout ordering, the 3D cones trajectory lacks the ability to sample a spread-out region of k-space given the limited number of readouts in each heartbeat. With a modified readout ordering, a more distributed k-space coverage is achieved and can be helpful for self-navigation and motion correction [2]. With SSFP imaging, the order in which each readout is acquired must be carefully chosen to avoid unwanted eddy current effects [3]. In this work, multidimensional golden means [4] and phyllotaxis [2] design were developed for the 3D cones trajectory to sample a more distributed region of k-space during each heartbeat without introducing eddy current artifacts. For verification of signal quality and eddy current reduction, these methods were compared to the default sequential ordering.

Method:

Readout Ordering: The readout ordering methods were tested on a 9,142 readout 3D cones trajectory designed to image a 28x28x14 cm^3 field of view (FOV) with 1.2 mm isotropic resolution. Fig. 1 illustrates the 3D k-space sampling structure with the three methods for an 18-readout segment corresponding to one heartbeat. In Fig. 1, each cone readout begins at the center of k-space and moves outward at different polar angles [5]. The polar angle is defined by an azimuthal angle, φ, and elevation angle, θ. Following an initial radial traversal, the trajectory traverses in a spiral-like fashion.

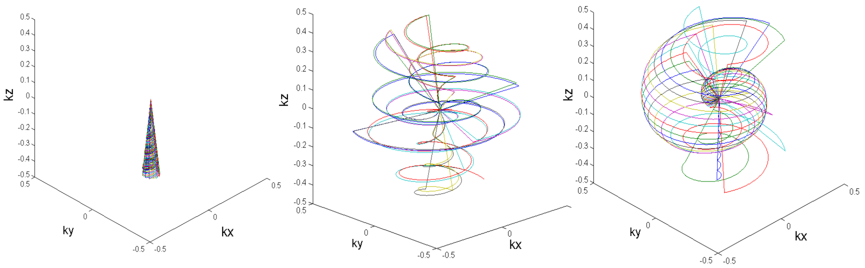

Fig. 1. The 18 readouts for the 5th heartbeat are shown for all three methods: sequential ordering (left), multidimensional golden means (middle) and phyllotaxis (right).

Method 1:
The default sequential ordering method acquires 9,142 readouts by progressing incrementally through the elevation angles from -π/2 to π/2. For each elevation angle, readouts at all azimuthal angles are collected first before progressing to the next elevation angle.

Method 2:
The multidimensional golden means method orders the readouts by using the equations: $\theta=\arccos(m\varphi_1)$ and $\varphi=2\pi(m\varphi_2)$ where m:<1:# of readouts> $\varphi_1=0.4656$ and $\varphi_2=0.6823$ are the 2D golden means derived from a modified Fibonacci sequence [4]. Once the polar angle is calculated, the closest two polar angles from method 1 (to allow for "pairing" [3]) were selected before changing the polar angle using 2D golden means. "Pairing" was implemented to alleviate some of the eddy current effects associated with SSFP imaging. This method also used 9,142 readouts.

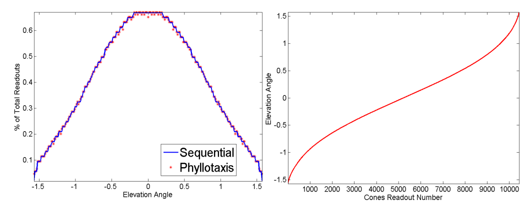

Fig. 2. The graphs above show the distribution of readouts for varying elevation angles, θ, (left) which has been matched for the phyllotaxis design. The θ function used to design the phyllotaxis sampling (right) was calculated using the sequential ordering histogram data.

Method 3:
A phyllotaxis 2D fast cardiac sequence, originally proposed in [6], was expanded to 3D in [2] for the reduction of eddy current effects. In [2], the phyllotaxis pattern defined the 3D radial trajectory polar angle in k-space. To apply the phyllotaxis method to 3D cones, the number of readouts is calculated by multiplying the desired samples/heartbeat times a Fibonacci number. In this case, a desired 18 samples/heartbeat and, to satisfy the spatial resolution and FOV constraints, the Fibonacci number 610 was used which gives 10,980 readouts (18*610). Also, for application to cones, the phyllotaxis pattern in [2] required modifications to ensure that the correct number of readouts were acquired per elevation angle. This was done by matching the distribution of readouts in method 1. A plot of elevation angles versus the number of readouts can be seen in Fig. 2. The phyllotaxis pattern then defines the polar angle with $\rho=1$, $\varphi=m\varphi_{gold}$ (where φ_{gold} is the golden angle defined as $\pi(3-\sqrt{5})$) and θ is the function shown in Fig. 2 (right). When using cone readouts, modifying the θ function (previously a square root function) in [2] corrected for nonuniform sampling on the unit sphere in k-space, specifically undersampling at the equatorial and oversampling at the pole regions. The sequential ordering and phyllotaxis polar angles can be seen in Fig. 3. The phyllotaxis pattern in Fig. 3 (right) spreads out the data more evenly through the use of the golden angle, φ_{gold}, parameter.

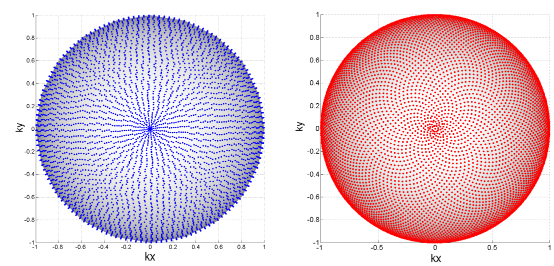

Fig. 3. The plots above show a top view of the sequential ordering (left) and the phyllotaxis (right) polar angle patterns for each cone readout on the unit sphere.

CMRA Sequence:
The 3D cones CMRA [1] method acquires leading sagittal 2D image-based navigators (iNAVs) and trailing coronal 2D iNAVs to track the motion of the heart along all three primary axes. Using both iNAVs, estimates for the S/I, A/P and L/R respiratory-based translation of the heart can be retrospectively corrected [1]. Density compensation values for the trajectories were calculated with an iterative algorithm for all 3 ordering methods and were used for gridding the data [7]. Scans using each of the 3 methods were run on a 1.5T GE scanner with 18 readouts per heartbeat for a temporal resolution of 98 ms.

Results and Discussion: As seen in Fig. 4, the sequential ordering and phyllotaxis cones ordering methods give clear images of the right ventricle while the multidimensional golden means design introduced eddy current artifacts due to rapid changing of the x, y and z gradients. In Fig. 4 (middle), the artifacts can be seen by the signal loss in the ventricles.

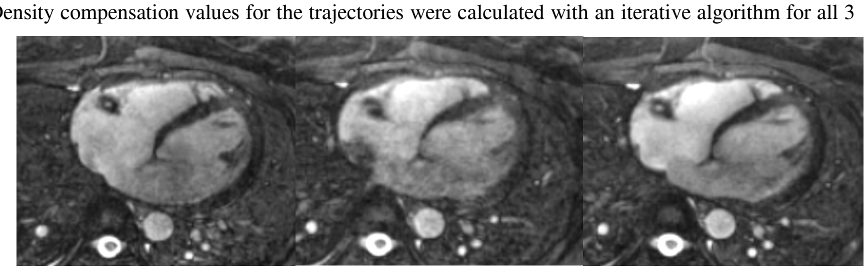

Fig. 4. The axial slices above show the right and left ventricles of a volunteer that was scanned using the sequential ordering (left), multidimensional golden means (middle) and phyllotaxis (right) methods.

Conclusion: These results suggest a new approach for 3D cones sampling using a modified phyllotaxis ordering method. The default sequential ordering method is limited to acquiring small regions of k-space per heartbeat. The multidimensional golden means design, despite using pairing, introduced eddy current artifacts. Using the phyllotaxis design, we are able to preserve the signal integrity while traversing through a larger region of k-space. Future work includes applying the phyllotaxis method for reconstruction of low resolution images each heartbeat which could be used as self iNAVs for motion correction.

References:

[1] Wu, HH., et al, MRM 2012 [2] Piccini, D., et al, MRM 2011 [3] Bieri, O., et al, MRM 2005 [4] Chan, R., et al, MRM 2009 [5] Gurney, P., et al, MRM 2006 [6] Cline, H., et al, ISMRM 1999 [7] Johnson, K, et al, MRM 2009