# ACCELERATED TIME RESOLVED MULTI-BAND RADIAL MRI

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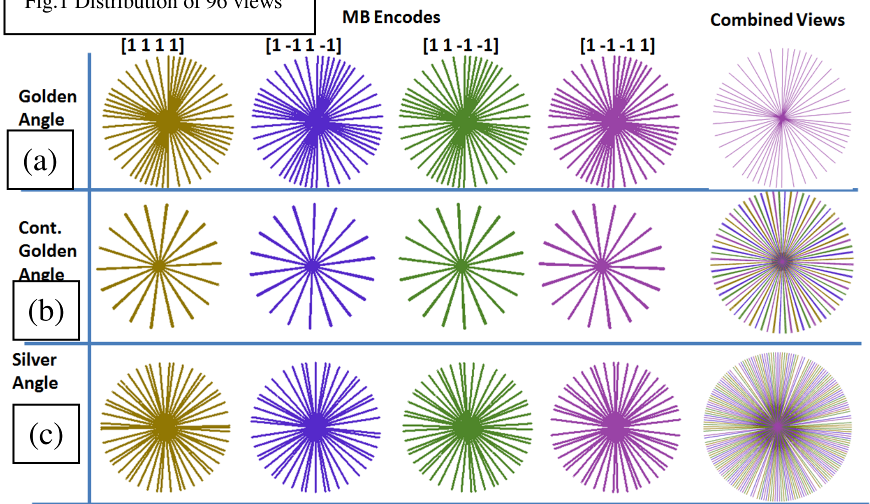
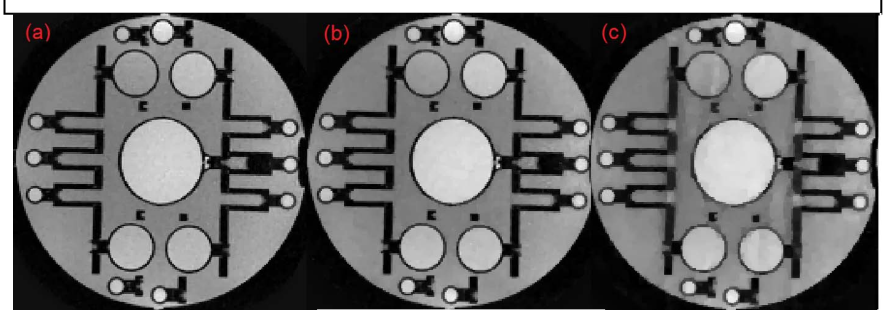
**INTRODUCTION:** Simultaneous Multislice Acquisition (SIMA) [1] using Multi-Band (MB) radio-frequency (RF) excitation has been shown to be an effective alternative to 3D volume imaging (3DFT). Compared to 2D slice-by-slice imaging, SIMA offers the benefit of increased SNR since all slices are simultaneously excited. In addition, MB excitation allows for flexible slice placement and thickness and does not suffer from ringing and truncation artifacts commonly seen in 3DFT especially when a small number of slices are acquired. In SIMA, MB RF pulses are tailored to form basis functions (usually drawn from an orthogonal basis like Hadamard) that encode the signal in the slice dimension while standard gradient encoding is used in-plane. The inherent SNR advantages and incoherent non-Fourier encoding in SIMA have been shown to be beneficial for Compressive Sensing (CS) [2]. In this work we propose a radial MB encoding method for time resolved multi-slice imaging. We present a silver-ratio based view-ordering scheme that can provide arbitrary temporal and spatial resolutions from a single radial MB encoded acquisition.

Fig.1 Distribution of 96 views




**THEORY:** The golden angle view ordering method[3] provides a nearly uniform distribution of radial views over any arbitrary time window in single slice radial imaging. This view ordering is derived using the golden means: Given an irrational number α, the sequence {k*α} (k = 1, 2,…) is uniformly distributed modulo 1. In other words, the equidistribution theorem states that the sequence {$\text{modulo}_1$(k*α)} will distribute points in a subinterval of [0, 1] proportional to the length of the subinterval[4].The golden angle view ordering follows from this theorem when irrational number α is set to the golden means of (1 + √5)/2. The sequence {$\text{modulo}_\pi$(k*((1 + √5)/2)*π)} provides the sequence of views for golden angle view ordering. Our goal in this work is to develop a view ordering method that will extend the desirable properties of golden angle view ordering to MB encoded radial acquisitions. MB RF pulses excite multiple slices simultaneously. Spatial encoding of each MB encode can be performed using gradient encoding along arbitrary k-space trajectories. It is important to note that different k-space trajectories can be used for different MB encodes (e.g. different radial views for each MB encode). For time-resolved imaging, it is desirable that the radial views satisfy the following properties for an arbitrary temporal window position and size: 1) The views for each MB encode are uniformly distributed over the range [0,π] with no overlap. 2) When the views of all encodes are collapsed onto a single combined k-space, the views are distributed uniformly over the range [0,π] with no overlap. These properties are particularly desirable for compressed sensing reconstructions since they allow aliasing artifacts to be incoherently distributed across the slices as well as spatially. Figure 1 illustrates three different view ordering schemes that can be used in MB encoded radial acquisitions. The first scheme (Fig 1a) is a straight-forward extension of the golden-angle view ordering to each MB encode. While this scheme satisfies the first condition above, it fails the second condition since all MB encodes have identical views. In the second scheme (Fig 1b), a continuous golden angle is used across the MB encodes. Thus, this view ordering satisfies the second condition. However, continuous golden angle view ordering across the encodes does not guarantee that each encode has views distributed uniformly over the range [0,π]. The third view ordering scheme is our proposed silver angle view ordering. For generating views for N slice MB encoding, the interval [0, 1] is divided into N equal bins and the sequence {k*α mod 1} is used to fill these bins. Each of the bins corresponds to a MB encode and the points falling in the bins are scaled to lie in [(m-1)π, mπ] where m = 1, 2…,N and form the views for that bin (encode). We use α=(1 + √2) which is known as the silver ratio.

**Fig2. Single time point reconstructions (a) R = 4; (b) R = 8; (c) R = 16**




**METHODS:** The reconstruction problem used in this work can be formulated as $\arg\min \| HFSx - y \|_2^2 + \lambda_1 \| TV(x) \|_1$ where *x* is the multi-slice data that we seek to reconstruct at several time points, *y* is the multi-coil data, *S* is the coil sensitivity maps, *F* is the NUFFT operator computed for the appropriate radial views and time points and *H* is an operator that represents MB encoding system. *TV* is the spatial total variation operator that enforces sparsity. A nonlinear conjugate gradient scheme was used to solve this reconstruction problem[4].

**RESULTS:** The proposed methods were implemented on a Siemens Skyra 3T scanner. Hadamard encoding pulses for four slice MB encoding were created by summing a set of sinc pulses with appropriate frequency offsets and phase modulation. A FLASH sequence was modified to use these pulses along with the proposed silver angle view ordering. The phantom and invivo results shown here were acquired with TE = 2.51 ms, TR = 5.44 ms and slice thickness of 4 mm. A single time point reconstruction with 256 total views amounts to an acceleration (R) of 4 relative to a fully sampled Cartesian single slice acquisition. Fig. 2 (a) shows one slice in the multi-slice reconstruction reconstructed at R = 4 (64 views/encode). Similarly Fig. 2(b) shows a single time point reconstruction of the same slice at R = 8 (32 views/encode) while Fig. 2(c) is reconstructed at R = 16 (16 views/encode).

**DISCUSSION:** All of the temporal window positions in the phantom reconstructions were chosen randomly and these results indicate that the proposed view ordering can reliably reconstruct images even at very short temporal window sizes. The proposed view ordering is intended to provide a good distribution of views in all the encodes for arbitrary temporal window positions and sizes while also providing extended spatial frequency coverage.

**CONCLUSION:** A radial view ordering method for time-resolved MB acquisitions was introduced. The proposed method extends the desirable properties of the golden-angle view ordering to time resolved simultaneous multi-slice imaging.

**REFERENCES:**

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