Cartesian Sampling Manual for Dynamic MRI

Date Modified: August 25, 2021

Mihir Joshi,[1] Aaron Pruitt,[1] Chong Chen,[1] Yingmin Liu,[2] Rizwan Ahmad,[*1,2,3]

1 Biomedical Engineering, The Ohio State University, Columbus OH, USA

2 Davis Heart & Lung Research Institute, The Ohio State University, Columbus OH, USA

3 Electrical and Computer Engineering, The Ohio State University, Columbus OH, USA

***** Corresponding author:

Name	Rizwan Ahmad
Department	Biomedical Engineering
Institute	The Ohio State University
Address	460 W 12th Ave, Room 318
	Columbus OH 43210, USA
E-mail	ahmad.46@osu.edu

Abstract

This manual enlists several pseudo-random Cartesian sampling patterns that we have developed for dynamic MRI. For methods that have not been published, a brief description is also included. For every method, a link to its MATLAB implementation is provided. In the future, sampling patterns for 3D dynamic applications, including 4D flow imaging, will be presented.

Keywords: 4D flow, phase-contrast, self-gating, Cartesian, Bayesian, CMR

1 Techniques for sampling in the k_y–t domain

1.1 VISTA

VISTA stands for Variable density Incoherent SpatioTemporal Acquisition.

1. The sampling is based on Fekete points
2. Download: `https://github.com/OSU-CMR/VISTA`
3. Related publication: `https://onlinelibrary.wiley.com/doi/abs/10.1002/mrm.25507`
4. Notes: VISTA is computationally slow, especially for large problems. For clinical real-time cine, it has been replaced with GRO sampling at our institute.
5. Applications: 2D dynamic MRI, e.g., cardiac cine and first-pass perfusion.

1.2 GRO

GRO stands for Golden Ratio Offset sampling.

1. The sampling is based on Golden Ratio shifts between adjacent frames
2. Download: `https://github.com/OSU-CMR/GRO-CAVA`
3. Related publication: This method has not appeared in a peer-reviewed publication. A brief description of the method is provided in Section 2.
4. Notes: GRO is preferred over VISTA due to fast computation speed. Also, GRO supports sampling for phase-contrast MRI, with multiple velocity encoding directions.
5. Applications: 2D dynamic MRI, e.g., cardiac cine, phase-contrast MRI, first-pass perfusion.

1.3 CAVA

CAVA stands for CArtesian sampling with Variable density and Adjustable temporal resolution.

1. The sampling is based on Golden Ratio shifts between adjacent samples
2. Download: `https://github.com/OSU-CMR/GRO-CAVA`
3. Related publication: `https://onlinelibrary.wiley.com/doi/abs/10.1002/mrm.28059`
4. Notes: The acquisition based on CAVA allows retrospective adjustment of temporal resolution at the cost of marginally sacrificed uniformity compared to GRO. Due to large k-space jumps, this pattern may not be suitable for SSFP-based sequences.
5. Applications: 2D dynamic MRI, e.g., cardiac cine and phase-contrast MRI

2 GRO Description

2.1 Background

For an effective application of compressive sensing, which exploits the underlying compressibility of an image, one of the requirements for the undersampling artifact is to be incoherent (noise-like) in the sparsifying transform domain. Several random and pseudo-random sampling methods have been proposed that yield a high level of incoherency. For dynamic applications, we recently proposed one such method, called VISTA. VISTA offers many advantages over other pseudo-random Cartesian

sampling methods, including (i) incorporating variable density, (ii) ensuring that the time-averaged data is fully sampled, and (iii) limiting eddy currents by controlling the extent of jumps (in k-space) from one readout to the next. Computation of VISTA, however, is slow and requires pre-computed look-up tables. In this work, we describe a new sampling method, which, in addition to offering the above-mentioned benefits of VISTA, is computationally efficient. The proposed method, called Golden Ratio Offset sampling (GRO), is capable of generating a large number of samples in a fraction of a second, making it suitable for clinical application.

2.2 Methodology

Generating GRO sampling on $N \times T$ grid, with N being the number of phase-encoding lines and T being the number of frames, involves following steps:

1. For the first frame, distribute M samples uniformly on a $N_s \times 1$ grid, with $N_s = N/s,\ s \geq 1$
2. For the next frame, circularly rotate the sampling pattern in the previous frame by gN_s, with $g = (1 + \sqrt{5})/2$
3. Repeat Step 2 for all the remaining frames.
4. Now project all the samples from the resulting $N_s \times T$ grid to the larger, final $N \times T$ by nonlinear stretching operation, where a point with phase-encoding index, p_s, on $N_s \times T$ grid is moved to phase-encoding index, p, on $N \times T$ grid

$$p = \left[p_s - k \operatorname{sign}\left(\frac{N_s}{2} - p_s \right) \left| \frac{N_s}{2} - p_s \right|^{\alpha} + \frac{1}{2}(N - N_s) \right], \qquad [1]$$

   where s controls the relative acceleration rate at the center of k-space compared to the overall acceleration rate, with $s > 1$ ensuring that the sampling density is higher at the center of k-space, $\alpha > 0$ controls the transition from high-density central region to low-density outer region, $[\cdot]$ represents the rounding operation, and constant k is selected such samples $p_s = 1$ and $p_s = N_s$ are mapped to $p = 1$ and $p = N$, respectively.

An example of GRO pattern is shown in Figure 1. Figure 2 shows the time-average sampling mask, displaying a fully sampled central region that can be used to estimate sensitivity maps. To reduce jumps in k-space, which is important for SSFP-based sequences, the phase encoding indices in the odd frames are collected in the ascending order and the phase encoding indices in the even frames are collected in the descending order. Figure 3 shows the index of all phase-encoding lines and the order in which they were collected. Figure 4 shows in vivo dataset collected using GRO and reconstructed using compressed sensing. GRO is applicable to real-time cine, phase-contrast MRI, and first-pass perfusion imaging.

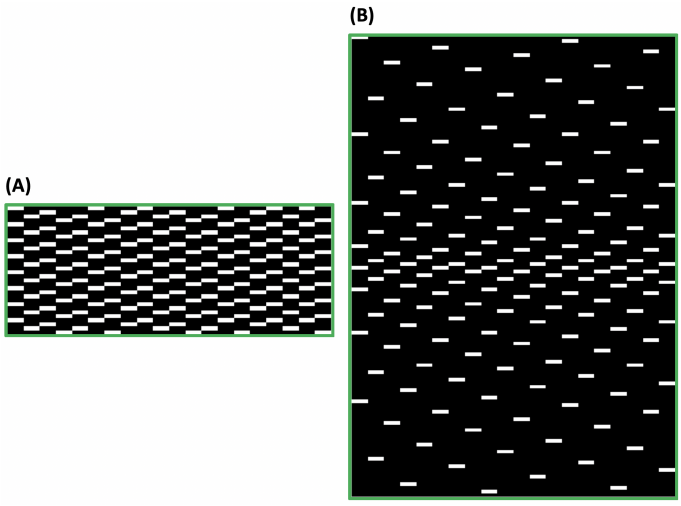

Figure 1: An example of GRO for $N = 128$, $s = 4$, $T = 20$, $M = 8$, and $\alpha = 2.2$. (A) Sampling on the $N_s \times T$ grid generated using Step 1 and Step 2. The horizontal axis indicates frames and the vertical axis indicates the phase encoding direction. (B) Sampling on a $N \times T$ grid generated from (A) by nonlinear stretching describe in Equation 1.

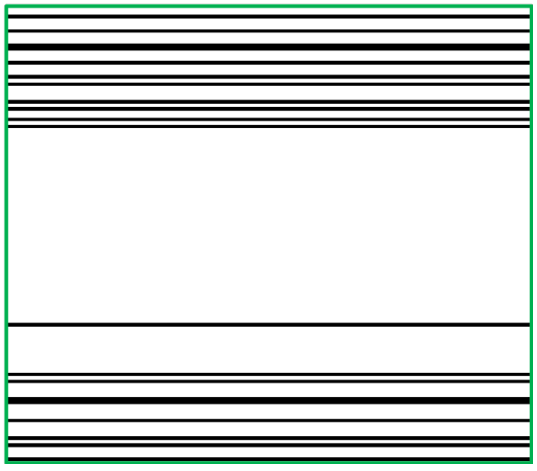

Figure 2: Time integration of the sampling pattern in Figure 1. Horizontal axis represents readout, and the vertical axis represents phase encoding index. White represents locations that were sampled at least in one of the frames.

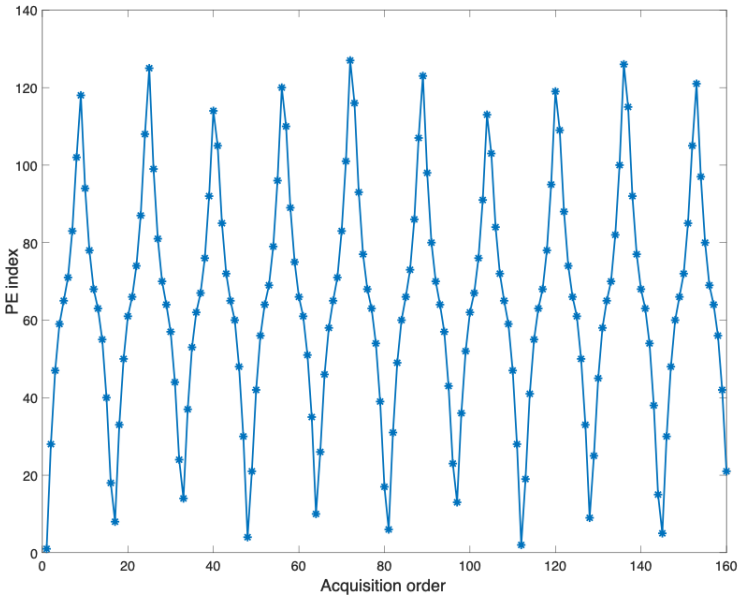

Figure 3: Phase encoding (PE) index plotted against the order in which the lines was collected.

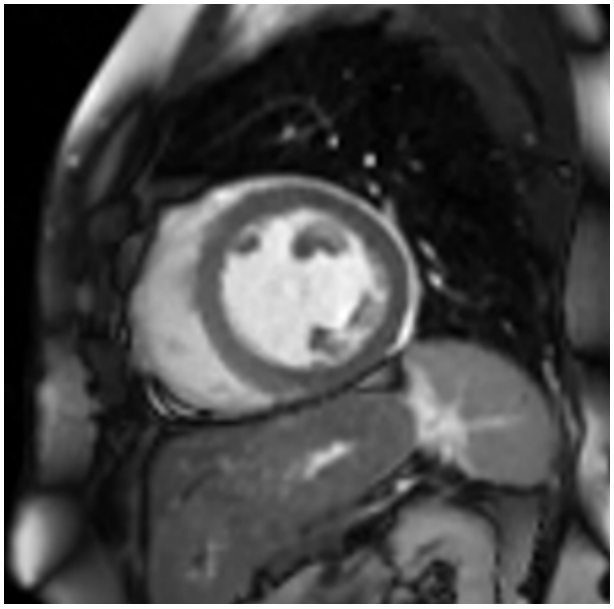

Figure 4: A diagnostic quality real-time cine series acquired in a clinical setting using GRO.