Navigator-Free Self-Gated Dynamic Cine Imaging Using 2D Cartesian Golden Step Phase Encoding

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INTRODUCTION. The central phase encode (PE) has been traditionally used as a projection-based navigator to measure motion in 2D Cartesian dynamic imaging [1, 2, 3], where imaging acquisition is periodically interrupted to traverse k_y=0. To maintain reasonable imaging efficiency, the temporal rate of central-PE traversal is very limited (e.g. once per cardiac phase). Near-center PEs (|ky|>0) have been used to correct 2D rigid-body motion [4] and to reject nonrigid-body motion [5]. This increases the rate of motion measurement, but the rate itself remains fixed for a particular scan. In this work, we propose a retrospective self-gated acquisition strategy for nonrigid-body cine imaging that is not only free of the navigator cost, but also achieves high and retrospectively flexible temporal resolution of motion measurement, utilizing near-center PEs and golden-step phase encoding [6].

THEORY. **Motion tracking using near-center PEs**: In this work, it is assumed that, centered on ky=0, within a limited region (the "navigation zone"), the *x*-inverse Fourier transform of a near-center PE is capable of describing motion in the same way that the true ky=0 projection does. The temporal stream of these off-center projections ("pseudo-navigators") acquired during an ungated scan will be used to extract motion for retrospective gating. **Golden step phase encoding**: As in the original golden angle implementation [7], in this work we use golden step PE to achieve flexible temporal resolution. We use an integer variation Cartesian golden step [6]: for an image comprising F_N lines, the PE is advanced F_{N-1} lines per TR, i.e. PE(k) = (k F_{N-1}) mod F_N, where F_{N-1} and F_N are consecutive Fibonacci numbers (for example, F_{N-1}=144, F_N=233). This way, all PEs in the k-space is covered exactly once every F_N TRs, and as Fig. 1a shows, the temporal coverage within any region of the k-space is practically uniform. Thus the navigator zone width can be freely adjusted to achieve desired navigator temporal resolution while maintaining uniform temporal coverage (updated on average every 1/p TRs, where p is navigator zone width in fraction of k-space. E.g. every 5TR if p=20%).

METHODS: **Pulse sequence**: an integer golden step Cartesian bSSFP sequence was implemented for the Siemens platform (Siemens Medical Solutions, Erlangen, Germany), with through-slice dephasing features [8] to reduce eddy current effects. **Human subject studies**: 3 normal volunteers received cardiac scans on a 1.5T Espree system (15-channel spine/body coil array), and 1 normal subject received a knee scan on a 3T Verio system using a standard 8-channel knee coil (permitted 20° knee motion), with TRs=3.10~3.20ms, FOV=$(256mm)^2$ or $(300mm)^2$, matrix size 256×233, 8mm slice thickness, and 35° tip angle. For cardiac imaging, standard ECG-gated breath-hold cines were acquired as a reference, followed by a 20sec non-ECG breath-hold ungated golden step scan, and a 1-min free-breathing golden step scan. For knee imaging, sequential-PE stationary knee images were acquired as a reference, followed by a 1-min golden step scan, during which the subject was asked to repeatedly extend and flex the knee at a comfortable pace of his own choosing within the confines of the standard knee coil. No rhythmic cueing was given. **Retrospective motion detection**: The central 20% of k-space was used as the navigation zone, resulting in a navigator temporal resolution of 5TR or ~16ms. The stream of pseudo-navigators is smoothed in time using a simple average window (corresponding to full coverage time of k-space or 233×20%≈47 navigator frames) to smooth out PE-dependent magnitude variations. From the navigator stream, motion-detection automatically identified motion periodicity from a presumed range (60~110 cycles/min for the heart, 10~40 for respiration, and 10~20 for the knee), and regions on the navigators that reflect such motion. Without assuming perfect motion periodicity, in each retrospectively assigned temporal phase, imaging data was further selected based on its consistency as indicated by the navigator stream [9].

RESULTS. Fig. 1 top row shows an example of pseudo-navigator stream from central 20% ky, clearly showing cardiac and respiratory motion (approx. 16 beats and 4 breathes). Fig. 2 shows frames from two self-gated cine reconstructions using the pseudo-navigator streams. Although self-gated reconstructions were successful for breath-hold non-ECG cardiac and free-moving knee studies, flow and eddy-current artifacts were noticeable in some cardiac acquisitions.

CONCLUSION AND DISCUSSION. We have demonstrated that near-center Cartesian PEs provide adequate information for self-gating in multiple scenarios. The motion sampling rate can be freely adjusted retrospectively, permitting minimal knowledge about the motion and planning prior to the scan. Our approach shares grounds with the more complex, low-resolution image-based gating techniques [10, 11] (where near-origin radial k-space data is reconstructed for motion detection), but is conceptually more straightforward. While golden step offers great flexibility, it does increase the risk of eddy current artifact, requiring extra techniques [12, 13] to address in the future. More cardiac studies and post-processing development are needed for high-quality free-breathing reconstructions. But given its high data efficiency and motion-detection flexibility, our proposed method would permit otherwise-impractical cine scans such as on the moving joint or the heart without ECG.

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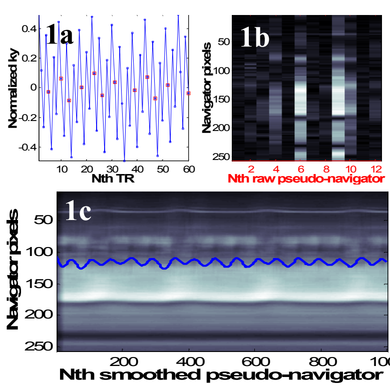

Fig. 1: Integer golden step PE ordering (1a) with the central 20% of ky as the navigation zone (red), and corresponding raw pseudo-navigators before (1b) and after (1c) magnitude correction. (Note difference in time scales.)

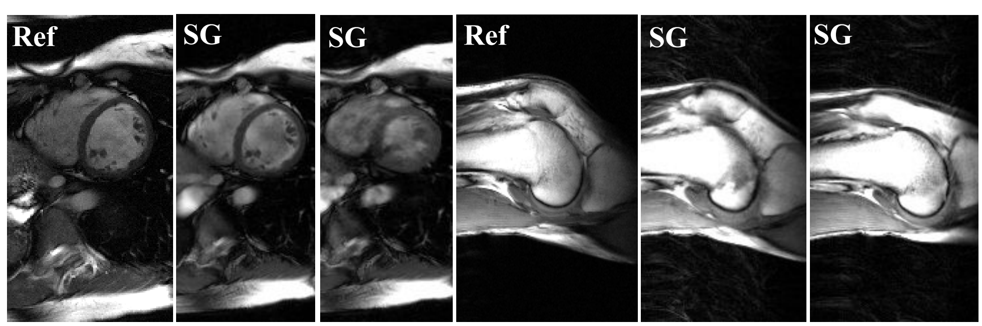

Fig. 2: Reference (Ref) and self-gated (SG) cine frames from a self-gated cardiac cine (20sec breath hold, 1.2×1.3×8mm voxels, reconstructed to 12 frames) where motion detection was used in place of ECG, and those from a self-gated knee cine (1×1×7mm voxels, reconstructed to 20 frames).