Golden Step Phase Encoding: Simultaneous real-time and ECG gated-Cine Parallel MRI with Retrospective Selection of Temporal Resolution, Acceleration Rate and Acquisition Duration

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Introduction: MR imaging involves an inevitable trade-off between spatial resolution, temporal resolution, field-of-view (FOV), acquisition duration and signal-to-noise (SNR) ratio. In conventional Cartesian MRI all these parameters are typically fixed prior to scanning, and images are only reconstructed for the prescribed parameters. For radial imaging, Winkelmann[1] demonstrated that advancing the projection angle in 111° steps, i.e. the Golden Fraction of 180°, provided almost uniformly distributed projections after any arbitrary number of acquisitions. In this work, we propose and demonstrate the use of Golden Step phase encoding for Cartesian type acquisitions, which provides a close-to-uniformly sampled k-space after any arbitrary number of consecutive TRs. This scheme allows the retrospective choice of temporal resolution, FOV and SNR and permits multiple reconstructions with varied parameters from the same data. Real-time imaging applications include interventional imaging, where images are required to serve multiple purposes simultaneously (e.g. instrument guidance and subject monitoring). In addition, we demonstrate that Cine images with arbitrary temporal resolution can also be reconstructed when this same "real-time" imaging data is obtained with cardiac ECG gating information. Furthermore, these Cine reconstructions can be made from acquisitions of arbitrary duration and/or incomplete (truncated) breath-holds.

Theory: In Cartesian Golden Step, the phase encoded projection is advanced by the Golden Fraction, $(\sqrt{5}-1)/2$, of the k-space support region between each TR (see Figure 1), wrapping from the top of the k-space region to the bottom as needed. As more projections are acquired, the k-space sampling pattern increases in density but remains very close to uniform (although never exactly so). The acquisition eventually becomes massively oversampled in the phase encode direction. Low temporal resolution auto-calibration reference images for each receiver coil can be reconstructed by 1D FFT in the readout direction followed by direct least squares (LS) solution of the phase encoding (PE) process. The oversampling avoids FOV wrap problems in the auto-calibration images and provides an inherent robustness for parallel imaging similar to that enjoyed by GRAPPA. For real-time and ungated imaging, a (typically undersampled) subset comprising an arbitrary number of consecutive TRs admits close to ideal image reconstructions due to the near uniformity of sampling. We employed a 1D FFT in the readout direction and direct LS solution of the PE and coil encoding processes for image reconstruction. Given ECG gating information, cardiac phases of arbitrary temporal resolution can be assembled from the same data, by including piecewise-consecutive TRs from an arbitrary number of heartbeats, and then reconstructed using the same techniques.

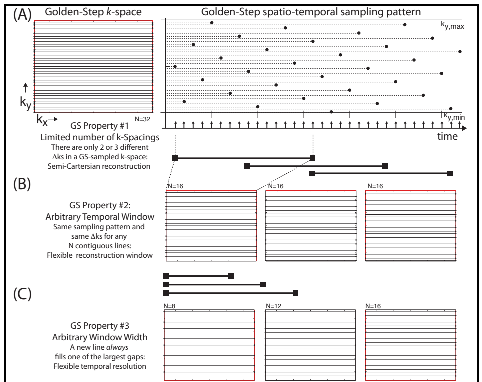

Figure 1: GS-PE encoding k-space filling strategy

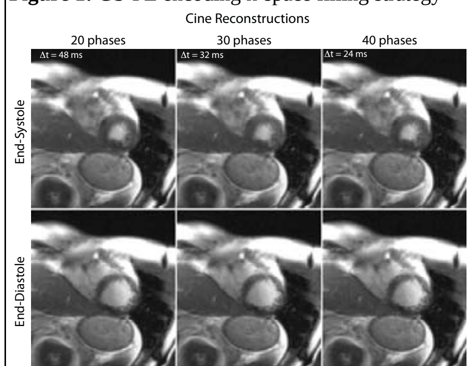

Figure 2 Cine reconstructed images. Three different sequences were reconstructed from the same dataset, all with varying temporal resolution.

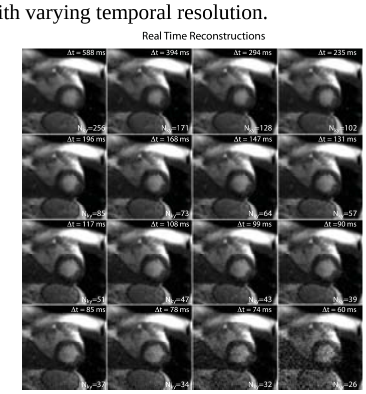

Figure 3: Ungated short axis "real-time" GS-PE cardiac images reconstructed with a range of acceleration rates (For R=1 N_{ky} = 142). As acceleration rate increases, image quality decreases, though the desired temporal resolution is arbitrary.

Methods: MRI was performed using a 1.5T Avanto system (Siemens, Erlangen, Germany), a 32-channel cardiac array coil (Rapid Biomedical, Rimpar, Germany) and RF-spoiled GRE and balanced SSFP sequences, modified for Golden Step phase encoding. Two normal volunteers were imaged with prior, written informed consent and local IRB approval. Breath-hold and free-breathing continuous imaging was performed in cardiac short- and long-axis slices over 20s intervals, recording the time since trigger at each TR. Typical imaging parameters: with a 128 samples, 1953 Hz/pixel readout and TE/TR=2.3/1.15ms provided ~5000-7500 TRs. and 2.3×2.3×8mm resolution, 45° imaging flip. Both real-time (ungated) and Cine images were reconstructed in MATLAB (The MathWorks, Natick, MA) by 1D FFT in the readout direction and 1D direct linear LS inversion of the PE and coil encoding processes as described above. For Cine images, scanner-derived ECG gating was used for the retrospective reconstruction.

Results: Example images reconstructed for differing temporal resolutions and acceleration rates a single acquisition are shown in Figures 2 and 3.

Discussion: Golden Step imaging yields close-to-uniformly sampled k-space data for any number of consecutive TRs which are suitable for self-calibrated parallel reconstruction with implicit selection of acceleration rate. The sampling non-uniformity is only in the PE direction, so reconstruction is separable into tractable 1D problems. Image noise increases with increasing temporal resolution (less acquired data, higher parallel imaging acceleration). For real-time imaging, the slight non-uniform sampling very slightly reduces SNR versus standard Cartesian grid acquisitions. The non-uniformity is more pronounced for Cine reconstructions where non-contiguous data are assembled from different heartbeats, and consequently the SNR is reduced versus a standard segmented gated CINE of equal duration.

Conclusions: Golden step phase encoding provides a remarkably flexible acquisition strategy for MRI. Real-time (ungated) images can be reconstructed with an arbitrary (and retrospectively selected) temporal window width and position. Furthermore, the same data can be reconstructed as gated Cine images with arbitrary temporal resolution and with arbitrary acquisition duration, permitting the reconstruction of images even from incomplete breath-holds.

References: [1] Winkelmann S et al, IEEE Trans Med Imaging **26**:68-76, 2007.