Reconstruction of retrospectively-gated cardiac data using a combination of GRAPPA, SPACE-RIP, UNFOLD and an adaptive regularization scheme

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Introduction: Retrospective gating is a preferred strategy for the reconstruction of cardiac cine data, as it proves superior to prospective gating for capturing end-diastolic phases. These phases are especially important for accurate ejection fraction measurements, as the left atrium contracts to increase the left ventricle's blood volume. In the present work, desirable characteristics of UNFOLD [1], GRAPPA [2], SPACE-RIP [3] and kt-SENSE[4] have been carefully combined, leading to a fast and reliable cardiac cine reconstruction algorithm featuring very reasonable reconstruction times. The available acceleration was used here to increase the number of slices acquired per breath hold, to reduce exam duration.

Two different approaches have been proposed to combine time-varying sampling schemes with retrospective gating [5, 6]. Both were implemented, found to be fairly equivalent in terms of image quality, and the approach from Ref.[5] proved about an order of magnitude faster in terms of processing speed. Both approaches are fully capable of accommodating any existing cardiac model for the uniform or non-uniform mapping of time samples onto the cardiac phase axis (non-uniform mappings account for the fact that diastole duration tends to be much more variable than systole duration in the presence of arrhythmia). In terms of parallel imaging reconstruction, regularization is critical to minimize noise amplification in cases where the inverse problem is ill-conditioned [7]. The advantageous scheme from kt-SENSE, based on prior-knowledge, was used here. The sampling scheme was similar to that adopted in SHRUG [8], with the central region undersampled by two-fold (Fig.1), for faster imaging than if the central region were fully sampled. This central region is used for sensitivity mapping purposes, and to provide prior knowledge for the regularization scheme.

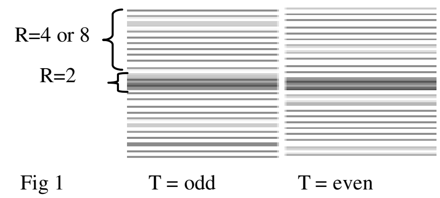
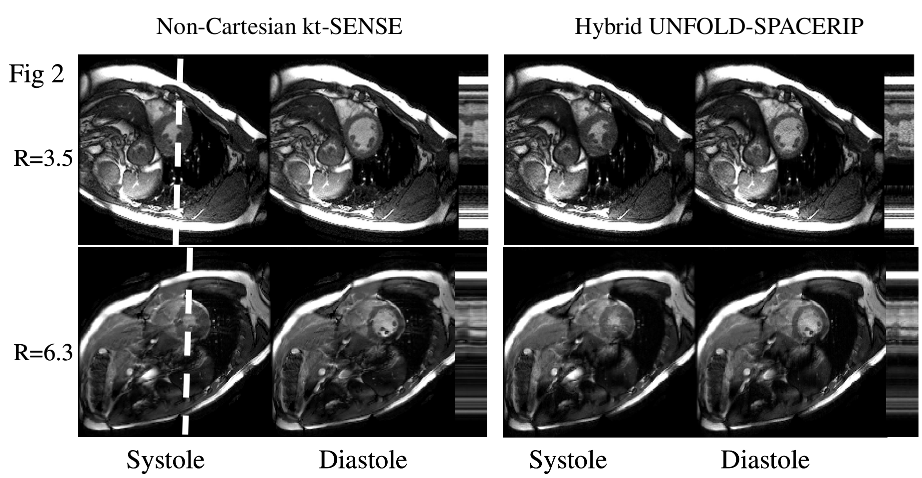


Fig 1

Methods: Eight in-vivo experiments were performed at 1.5 T (7 datasets) and at 3T (1 dataset) with an eight channel cardiac array coil, a balanced steady state free precession sequence, and the sampling function depicted in Fig.1. A central 15% region along k_y was undersampled by a factor of two, and the outer regions by a factor of 4 or 8. The net acceleration factors were 3.5 (at 1.5T) and 6.3 (at 3.0T). As an image object is not expected to rapidly change its bulk magnetization, a fully populated central k-space region can be obtained as follows. Temporal filtering was used to recover a few central-most lines, just enough to calculate GRAPPA coefficients. Subsequently, in a way similar to GEYSER [9], the entire central k-space region was reconstructed using GRAPPA and an acceleration factor of 2. After a proper retrospectively-gated reconstruction, spatially-blurred images were obtained and used to estimate the kt-SENSE signal covariance matrix **M** as well as the sensitivity maps.

For the final reconstruction, both the non-Cartesian kt-SENSE [6] and the approach from [5] were implemented. As part of the latter algorithm, low and high temporal frequencies were separated and then re-gridded with respect to cardiac phase. SPACE-RIP then unwrapped the spatially aliased components using $\mathbf{X} = (\mathbf{E}^H \mathbf{\Psi}^{-1} \mathbf{E} + \lambda \mathbf{M}^{-2})^{-1} \mathbf{E}^H \mathbf{\Psi}^{-1} \mathbf{X}_{alias}$, where **E** is the encoding matrix in hybrid x-ky space, $\mathbf{M}^{-2}$ is the regularization term assembled from the low resolution data, and λ is a weight equal to 0.01 divided by the Froebinius norm of $\mathbf{M}^{-2}$. Unlike for the high temporal frequencies, the encoding matrix **E** featured all sampled lines (odd + even frames) for the reconstruction of low temporal frequencies.

Fig 2



Results and Discussion: Cardiac cine images were reconstructed (30 cardiac phases, matrix size 192x192), and both systolic and mid-diastolic phases are shown in Fig. 2. As a whole, image qualities from the two reconstruction algorithms were similar. Images from the hybrid UNFOLD-SPACERIP method tended to be slightly noisier and slightly less blurred, possibly a consequence of our selection for the regularization weight λ.

In terms of computational complexity, the hybrid UNFOLD-SPACERIP algorithm required only a 1D conjugate gradient method whereas non-Cartesian kt-SENSE required a 2D conjugate gradient approach. Accordingly, computation time is expected to be longer with non-Cartesian kt- SENSE, as it simultaneously takes all signal variations into account during reconstruction. The hybrid UNFOLD-SPACERIP algorithm breaks the reconstruction process into smaller and faster steps, and provided similar results. Processing time on a PC having 2.2G Hz CPU with 3.0G RAM was nearly 8-fold shorter with hybrid UNFOLD-SPACERIP .

Conclusion: A cardiac cine reconstruction algorithm that carefully assembled advantageous features from GRAPPA, SPACE-RIP, kt-SENSE, UNFOLD, GEYSER and SHRUG was described. This retrospectively-gated algorithm is fast and compatible with any existing re-gridding model.

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