Reconstruction of Undersampled Non-Cartesian Data using GROG-Facilitated Random Blipped Phase Encoding

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Introduction: K-space based parallel imaging techniques for non-Cartesian trajectories have become a subject of interest due to advantages of some non-Cartesian acquisition schemes over standard Cartesian trajectories. Most of the k-space methods are based on exploiting specific symmetries in the imaging trajectories, such as radial or spiral. To date, only the image-based conjugate gradient (CG) SENSE method [1] is able to reconstruct undersampled arbitrary trajectories in an efficient manner. Moriguchi et al. [2] have shown that some acquisitions can be accelerated by employing the generalized sampling theory of Papoulis [3] to generate images using non-uniformly sampled data. The generalized sampling theorem states that unaliased images can be reconstructed even when the Nyquist criterion is violated in portions of k-space, as long as the average sampling rate is equal to the Nyquist rate. In the work of Moriguchi, bunched datapoints are collected along a blipped phase encoding (BPE) or zig-zag-shaped trajectory, such that some areas of k-space are densely sampled, and fewer phase encoding lines than strictly necessary are acquired. Using these bunched points, unalised images can be reconstructed from the undersampled data with a conjugate gradient (CG) algorithm. Instead of generating these blipped datapoints with gradient encoding, the blipped trajectory can be mimicked using a standard "straight" trajectory with the GRAPPA Operator Gridding (GROG) method [4]. Using GROG, each acquired datapoint can be randomly shifted by a small amount in k-space, thereby generating a cloud of additional points surrounding the original point. These new bunched datapoints can then be used with the CG optimization to reconstruct accelerated images. The GROG-BPE method is advantageous because an arbitrary number of random blipped points can be generated using GROG (Fig. 1), and no special gradient performance is required. In addition, for radial and rosette trajectories, this method is completely self-calibrating. It is important to note that the CG step employed here does not use parallel imaging; no coil sensitivity maps are required for this step.

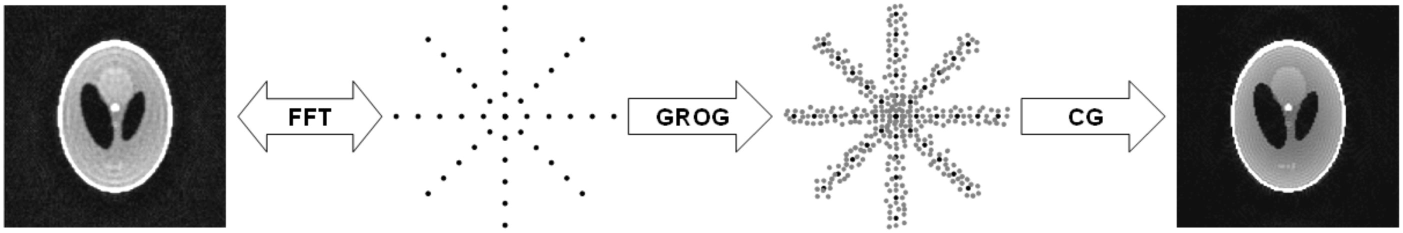

Figure 1: An undersampled radial image (far left) and the corresponding acquired k-space points (middle left). Using GROG, random points (gray) are generated surrounding the original points, thereby mimicking the BPE acquisition scheme (middle right). After a CG reconstruction, an unaliased image results (far right).

Methods: A 12-channel receiver coil was used for the acquisition of radial (256 projections, 512 read-out points, base matrix of 256^2) and rosette (60 rosette loops, 1000 read-out points, base matrix of 128^2) datasets, and a 32-channel head coil was employed for the spiral (4 spiral arms, 7289 read-out points, base matrix of 256^2) dataset. The radial, spiral, and rosette datasets were retrospectively undersampled to R=5, R=2, and R=4, respectively. The GROG weights for the radial and spiral trajectories were calculated using the self-calibrating GROG approach[5]; for the rosette dataset, the central portion of k-space was gridded and employed as the calibration data for GROG. Using the GROG weights, 50 random blipped points were generated for each acquired point, where the maximal shift sizes were $0.3\Delta k$, $1.0\Delta k$, and $1.0\Delta k$ for the radial, spiral, and rosette data, respectively. These new datapoints were fed into a CG reconstruction algorithm[2] and allowed to iterate 20 times with an oversampling factor of 10.

Results: Figure 2 (top row) shows the radial reference image (left), the R=5 undersampled image (middle), and the R=5 reconstruction with the GROG-BPE approach (right). As can be seen by comparing the reconstruction with the undersampled image, the addition of blipped points followed by the CG operation clearly improves the image quality. Figure 2 (center row) shows the reference spiral image, the R=2 undersampled image, and the R=2 reconstruction with blipped points and CG optimization, and Figure 2 (bottom row) shows analogous results for the R=4 rosette image. The aliasing artifacts present in the undersampled images are removed after the GROG-BPE reconstruction with the CG algorithm.

Discussion: The GROG-BPE method demonstrated here is advantageous as it can be employed to reconstruct any undersampled trajectory. Compared to previous blipped phase encoding approaches, no additional pulse sequences or gradient performance above that needed for the non-Cartesian trajectory are required because the "blipped" points are generated after the acquisition using the standard non-Cartesian trajectories. Unlike with acquired blipped points, those generated with GROG can be random, which is beneficial due to the less coherent artifacts produced by random sampling. In addition, this method is self-calibrating for many undersampled trajectories, included radial, rosette, dual-density spirals, 1D non-Cartesian, and PROPELLER/BLADE, and does not employ a sensitivity map. The only requirement for this method is a coil array which provides sufficient sensitivity variations to calculate and apply the base GROG weights. An examination of the optimal shift distances and number of shifted points for GROG-BPE is currently work-in-progress.

References:
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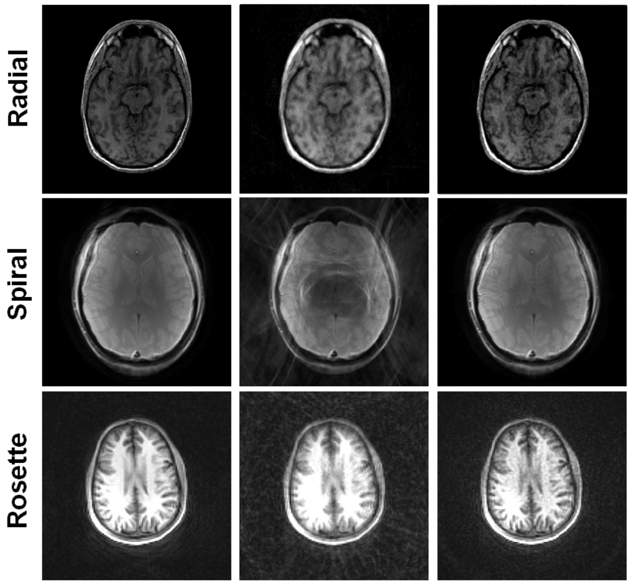

Figure 2: Examples of the GROG-BPE reconstruction for R=5 radial, R=2 spiral, and R=4 rosette data. The fully sampled reference images are shown on the left, the undersampled images in the center, and the reconstructed images on the right.