A Novel Parallel Imaging Technique for Radial Acquisitions: Parallel Rotation Operator

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Introduction: Parallel imaging has been widely used to reduce the data acquisition time in MRI. The application of parallel imaging is non-trivial, however, for non-Cartesian trajectories. A radial GRAPPA (rGRAPPA) technique with relative shifts was earlier proposed, making parallel imaging for radial trajectories feasible [1]. This method utilizes different reconstruction coefficients for several different segments along the read-out direction, but the underlying assumption is that the same set of coefficients can be used within each segment. This assumption, however, becomes increasingly erroneous when the data becomes more highly undersampled. In this abstract, a novel approach for radial parallel imaging inspired by the GRAPPA operator [2] is proposed that takes into account the specifics of radial k-space to improve the parallel reconstruction algorithm.

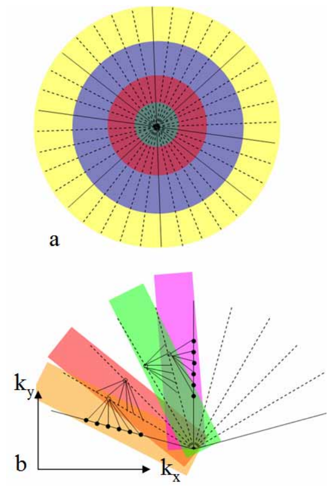

Fig. 1 (a) The radial trajectory with segmentation along the readout direction. (b) Diagram of the new algorithm. Filled circles denote acquired data; Open circles indicate missing data.

Theory and Methods: A radial k-space data $S(k_r,\theta)$ is shown in **Fig. 1a**, which is usually rearranged to form a Cartesian-like space (k_r vs. θ) prior to the application of rGRAPPA. The k-space is subsequently segmented along the readout direction (k_r) and several small GRAPPA operations are performed to recover the missing k-space data. Within each segment (e.g., red or yellow shown in **Fig. 1a**), the same set of coefficients are used to recover the missing points in that segment. However, since the spacing among data points varies with distance from the k-space center, these coefficients should also vary depending on the correlation of the k-space coil sensitivity profile. Using the same weights within each segment is a good approximation for low reduction factors (R), but becomes inappropriate as R becomes larger.

A method termed Parallel Rotation Operator (PRO) is proposed in this abstract. In this new method, missing data $S_j(k_r,\theta+\Delta\theta)$ nearest to the acquired data $S_l(k_r,\theta)$ are first recovered according to the following equation:

$$S_j(k_r,\theta+\Delta\theta)=\sum_{i=1}^{N_{seg}}\sum_{l=1}^{N_c}\Re(j,l,i)\cdot S_l(k_r+f(i)\cdot\Delta k_r,\theta) \qquad (1)$$

where $\Re$ is the weights; l and j are the coil indices; N_c is the coil number; N_{seg} is the total number of data points in one k-space line of one segment; $f(i)$ is the shift function to cover all the points in one segment. Equation (1) can be simplified using a matrix form as shown in Eq. (2):

$$\vec{S}(\theta+\Delta\theta)=\underline{\Re}\cdot\vec{S}(\theta) \qquad (2);$$

where an arrow above a parameter represents a vector, and underscore represents a matrix. The matrix $\underline{\Re}$ is similar to a rotation operator according to Eq. (2). After one missing line is recovered, the adjacent missing view can be recovered iteratively until all desired views have been reconstructed. As depicted in **Fig. 1b**, the same weights for the orange and red regions or for green and purple regions are used in this new algorithm. The general equation can be described as follows:

$$\vec{S}(\theta+n\Delta\theta)=\underline{\Re}^n\cdot\vec{S}(\theta) \quad \text{where} \quad \underline{\Re}^n(\Delta\theta)=\underline{\Re}(n\Delta\theta), \quad \underline{\Re}^{-n}(\Delta\theta)=\underline{\Re}(-n\Delta\theta) \qquad (3)$$

For improved accuracy, the recovery of the missing view is obtained only from the closest acquired line.

In effect, the primary differences of PRO compared with rGRAPPA are as follows: (1) The reconstruction coefficients vary for all points along the radial direction; (2) Acquired points from only a single view closest to a missing line are used to recover the missing data (Eq. 3).

Phantom and human studies were performed on a 3T Trio MR System (Siemens Medical Solutions, Erlangen, Germany) using 2D radial and 3D hybrid radial (in which the slice axis is phase-encoded) gradient echo pulse sequences. Imaging parameters for 2D imaging of the phantom were: FOV=200×200 mm, readout points=256, number of views=256, TR= 20 ms, TE=2.2ms. Imaging parameters for 3D imaging in vivo were: FOV = 256×256 mm, TR/TE=10/2.2 ms, 8 slices. An eight-channel head coil (MRI Devices, Waukesha, WI) was used for both imaging studies. Undersampled data sets were subsequently created by extracting every 4^{th}, 8^{th} or 16^{th} views from the full 256-view dataset, for images created with 64-, 32- and 16-views, respectively, and comparisons made between rGRAPPA and PRO reconstruction. A segmentation along θ direction for rGRAPPA was also performed to improve the image quality. Ten and five segments along the readout and azimuthal directions, respectively, were used for rGRAPPA. For PRO, 11 segments along the readout direction was used for the phantom study, and 15 for the human study. Normalized Root Mean Square (NRMS) was calculated to quantify the errors.

Results and Discussion: The results are shown in **Fig. 2**, demonstrating that the proposed method yields better image quality and lower NRMS errors than rGRAPPA for high reduction factors (32 and 16 views). Whereas residual streaking and other undersampling artifacts appear in the rGRAPPA images, those artifacts were effectively removed with the proposed technique. The results demonstrate the effectiveness of the parallel rotation operator technique for highly undersampled radial parallel imaging.

Acknowledgement:
NIH P41 RR 02305; Siemens Medical Solutions

Reference:
1.Griswold, M.A.,et al. in *ISMRM*. P2349, 2003.
2.Griswold, M.A., et al. MRM, 2005. **54**(6): p. 1553-6.

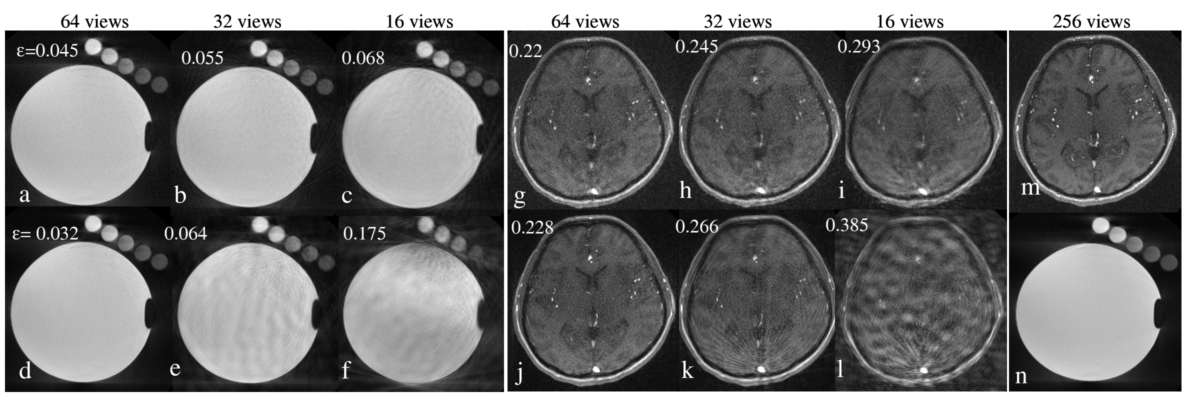

Fig. 2 (a-c) Phantom results using the PRO algorithm for 64, 32 and 16 views per image, respectively; (d-f) Corresponding results of rGRAPPA. (g-l) Corresponding PRO (g,h,i) and rGRAPPA (j,k,l) results for the human study. (m, n) 256-view in vivo and phantom images. NRMS errors (ε) are shown for each image.