Improved Self-Referenced Parallel MRI imaging in EPI by using UNFOLD to Remove Nyquist Ghosts

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Introduction: The quality of parallel MRI (pMRI) reconstructions is directly dependent on the data used for coil sensitivity estimation in SENSE [1] and/or GRAPPA [2] reconstruction coefficient calibration. In many applications, it is desirable to use self-referenced pMRI approaches over a prescan approach, to limit the effect of changes (such as motion) that occur between acquisition of the prescan pMRI calibration data and the accelerated image data.

In EPI acquisitions, self-referenced approaches are confounded by the presence of Nyquist ghosts, which are a persistent artifact in EPI. These artifacts occur when data sampled along positive and negative read-out gradients is inconsistent. A well-accepted way, [3], to correct for Nyquist ghost artifacts is to measure the shift in k-space between positive and negative readout data and realign the two data sets before reconstructing the images. Unfortunately, this approach also commonly uses reference scan data.

More recently, methods such as 2D phase-mapping [4] and phase labeling (PLACE) [5] have been proposed to remove Nyquist ghosts. These methods use a slightly modified EPI k-space trajectory and then interleave the data from *two* frames to produce one image data set acquired only on positive read-outs and a second image data set acquired on only negative readouts. While each separate image is free of Nyquist ghosts, the disadvantage is that interleaving reduces the temporal sampling rate by half. We propose an approach that employs UNFOLD [6] in place of interleaving. This approach effectively eliminates Nyquist ghosts, which enables self-referenced parallel imaging while simultaneously maintaining a high temporal imaging rate.

Theory: Employing a PLACE sampling trajectory modulation, we propose to use UNFOLD instead of interleaving to form images that satisfy the Nyquist sampling criterion. UNFOLD uses temporal encoding to alternate the polarity of aliasing artifacts in a temporal sequence. That is, a shift in the sampling grid ($1\Delta k$) will introduce a phase change in the image domain. This induces aliasing artifacts which result from sub-sampling to alternate in polarity from frame to frame—e.g. to 'flicker' at the temporal Nyquist rate. These temporal encoded aliasing artifacts can then be subsequently removed using a narrow high-frequency notch filter in the temporal dimension. Consider that shifting the EPI data sampling grid by ($1\Delta k$), as in PLACE, introduces a temporal modulation. Separating the data into two sets—one for a positive read-outs and the other for negative read-outs—will result in the sub-sampling commonly used with UNFOLD. Each set can then be processed separately using a temporal UNFOLD filter, and then combined to produce an image series free of Nyquist ghosts.

Methods: Data was acquired on a GE Signa 1.5T scanner using a standard 8-channel head coil. The EPI trajectory was modified to shift the sampling grid on alternate frames by ($1\Delta k$) along *ky*. Further, the EPI blip table was modified to provide variable density sub-sampling, acquiring 8 *ky* lines ($1\Delta k$) apart near the center of k-space, and gradually increasing the gap between *ky* lines to ($5\Delta k$) in the high frequency region. An acceleration factor of 3.2x was used, producing 40 *ky* lines for the 128x128 images acquired. A self-referenced double-pass (DP) GRAPPA algorithm with a 2x5 kernel was used to reconstruct the images [7]. On the first pass, data in the ($2\Delta k$) region was reconstructed using 8 central ACS lines for self-calibration. On the second pass, 16 ACS lines from the output of the first pass was used for self-calibration to reconstruct the remaining k-space data.

Results: Fig 1 shows images of a water phantom reconstructed from (a) self-referenced DP GRAPPA with Nyquist ghost correction as in [3], (b) GRAPPA using 20 lines from a reference frame with Nyquist ghost correction as in [3], and (c) self-referenced DP GRAPPA using UNFOLD for Nyquist ghost correction. The image in (c) demonstrates that using UNFOLD to remove Nyquist ghosts yields a significant improvement in image quality over previous methods, enabling self-referenced pMRI in EPI with significantly lower artifact levels as shown by the arrows.

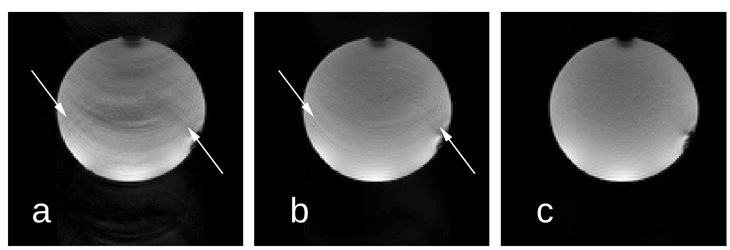

Fig 1: pMRI Images of a water phantom acquired at 3.2x acceleration.

Discussion: The ability to successfully reconstruct self-referenced pMRI images in EPI—free of Nyquist ghosts—opens many opportunities, such as the scenario shown in Fig 2, where three 3.2x self-referenced pMRI images can be acquired after a single excitation, by sampling through 3 sweeps of k-space in quick succession---demonstrating the transition from T1 to T2 weighting as the time from excitation grows longer. Other applications such as accelerated real-time fMRI can now be considered. The cost of using UNFOLD is a small loss in the temporal bandwidth (~ 10%) which depends on the bandwidth of the aliasing artifact suppression filter.

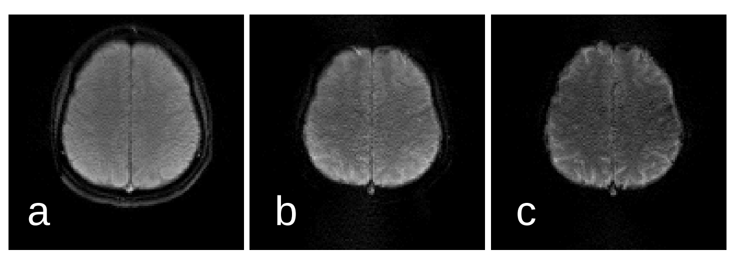

Fig 2: Self-referenced pMRI EPI Images acquired after a single excitation. (a) first pass, (b) second pass, (c) third pass through k-space.

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