IMPROVED PASL EPI ACQUISITIONS WITH PARALLEL IMAGING AND UNFOLD

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ABSTRACT

Pulsed Arterial Spin Labeling (PASL) has been shown to be an effective method for quantitatively measuring cerebral blood flow. Quantification errors with PASL may result from patient motion, however, so Echo Planar Imaging (EPI) is commonly used to acquire PASL images due to its high temporal resolution. EPI achieves high temporal resolution through long echo trains, which can result in image distortions due to magnetic field inhomogeneities. Thus, perfusion weighted EPI could be further improved with shorter echo trains and faster image acquisitions. This paper investigates the use of UNFOLD and parallel MR imaging to reduce EPI image acquisition time. We demonstrate how the use of varied sampling patterns and UNFOLD can completely remove the 'Nyquist ghosts' that are common in EPI acquisitions. This allows one to greatly improve the effectiveness of parallel imaging in EPI, and to reduce field inhomogeneity artifacts by reducing the echo train length.

1. INTRODUCTION

Cerebral perfusion can be measured using pulsed arterial spin labeling (PASL) [1]. This method uses blood water as an endogenous tracer to measure blood flow from a set of tagged (label) and untagged (control) images. The arithmetic difference between the label and control images generates a residual signal which is proportional to blood that has perfused into the imaging plane. In order to minimize motion artifacts and maximize imaging slice coverage, image acquisition time must be kept to a minimum. Echo planar imaging (EPI) is a common MRI method for acquiring PASL perfusion data. While EPI has a high temporal resolution, it is still often unable to achieve full brain coverage in a time required by perfusion imaging. Furthermore, EPI is known to suffer from inherent artifacts, such as Nyquist (or N/2) ghosts caused by sampling errors and image distortions which occur due to magnetic field inhomogeneity at tissue interfaces with different magnetic susceptibility.

One way to reduce susceptibility artifacts in EPI acquisitions is to reduce the echo train length (ETL)—the data read-out time after the excitation pulse. Parallel MR imaging (pMRI) [2] can provide a substantial reduction in data acquisition requirements, which directly reduces negative susceptibility effects [3]. The effectiveness of pMRI is dependent, however, on the quality of the calibration data used in the reconstruction. The persistence of Nyquist ghosts in EPI, which occur due to inconsistent data sampling on positive and negative readout gradients, can limit both the quality of the pMRI calibration data and the subsequent reconstruction.

In this paper we present an approach to completely eliminate Nyquist ghosts in a temporal series of EPI images, which subsequently improves the image quality in *self-referenced* pMRI techniques. The combined approach effectively reduces both EPI artifacts, enabling one to acquire perfusion images with minimal susceptibility distortion and no Nyquist ghost artifacts.

2. THEORY

Nyquist ghosts are an inherent artifact in EPI, and there are many approaches to correct them including double-sampled (DS) EPI [4], the 1D phase-correction approach of Ahn and Cho (AC) [5], 2D phase-mapping [6], and phase labeling (PLACE) [7]. Although DS-EPI completely eliminates Nyquist ghosts it has the disadvantage of doubling the echo train length, which leads to greater susceptibility artifact distortion. The AC method is widely implemented on commercial MRI scanners, yet is often unable to completely eliminate Nyquist ghosts. The more effective PLACE and 2D phase-mapping techniques use an echo-interleave strategy, but this reduces the temporal sampling bandwidth to 50%. As an alternative to these methods, we introduce the use of UNFOLD [8] instead of interleaving, to eliminate Nyquist ghosts while maintaining more than 90% of the temporal sampling bandwidth.

The goal of all Nyquist ghost removal strategies is to correct the data sampling mismatch between positive and negative read-out gradients when sampling in EPI. In the methods listed above, this is achieved by acquiring either the same line in k-space twice (DS-EPI), e.g. once for both positive and negative read-outs, acquiring a reference scan to estimate the shift between the sampling grids (AC), or by shifting the EPI sampling trajectory and then interleaving the positive or neg-

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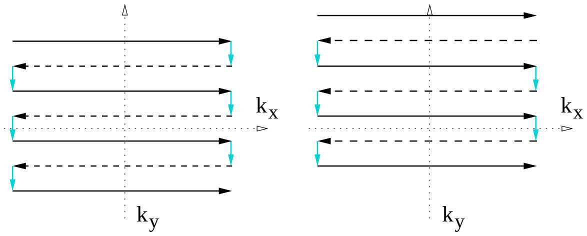

(a) odd frames [2n+1] (b) even frames [2n]

Fig. 1. The PLACE sampling pattern alternates between two EPI sampling grids, shown in (a) and (b) and shifted by $(1\Delta k)$ between them. Data along solid lines are collected during positive readout gradients. Data along dashed lines are sampled during negative readout gradients.

ative read-out data to form two separate images that satisfy the Nyquist sampling criteria (PLACE).

We propose to use the PLACE sampling trajectory, shown in Fig. 1, with UNFOLD to eliminate the Nyquist ghosts. UNFOLD employs temporal encoding to alternate the polarity of aliasing artifacts in an undersampled temporal sequence. When only odd k_y lines are sampled the aliasing artifacts have positive phase. When even k_y lines are sampled, the aliased portion of the point spread function (PSF) changes polarity and exhibits negative phase. In this way, aliasing artifacts can be tagged to 'flicker' at the temporal Nyquist rate. This flicker can be subsequently removed using a narrow-band high-frequency notch filter in the temporal dimension.

When sampling a temporal image sequence with EPI, shifting the data sampling grid on alternate frames by $(1\Delta k)$ will introduce the same temporal modulation as required by UNFOLD. Separating the data into two sets—one for positive read-outs and the other for negative read-outs—will introduce the sub-sampling commonly used with UNFOLD. Each set can then be processed using a temporal UNFOLD filter to produce two fully sampled image series, which can then be combined to produce the final images.

Significantly, our method is robust to sampling variations along k_y that can occur from frame to frame as well. In practice, positive readout data from an odd frame may not fall exactly between the positive readout data from the even frames used to generate missing lines with UNFOLD. However, these sampling errors will cancel when the positive and negative readout data for the same time point is combined. To illustrate, consider that before processing the image formed from data sampled at an odd frame $2n+1$, is a combination of data from odd lines from positive readout gradients, P_o, and even lines from negative readout gradients, N_e, or $I = P_o + N_e$. In our method, the data from positive readout gradients are separated from negative readout data, and the missing k-space lines in each set are re-generated using UNFOLD. The image P associated with positive readout data will thus come from raw acquired odd lines, P_o, plus even lines that have been generated by UNFOLD, P_e. This generated image data may contain phase errors, ϕ, due to a sampling mismatch along k_y between the shifted sampling grids. We include this possibility here in the expression for the image associated with positive readouts, $P = P_o + \phi P_e$.

Similarly, the image N associated with negative readout data will contain raw acquired even lines from I, N_e, plus odd lines generated from UNFOLD that also contain the same potential phase errors, ϕN_o. This ϕ is the same as before, resulting from the same sampling mismatch along k_y. Since each image, N and P, separately satisfies the Nyquist criteria along the phase-encoding dimension, one can identify an operator Ψ, with $\Psi N \approx P$, that corrects for the k-space shift along k_x between $P = P_e + \phi P_o$ and $N = N_o + \phi N_e$. (This shift is the same as calculated by the AC method.) Combining the two data sets as

$$\begin{aligned} P + \Psi N &= (P_e + \phi P_o) + \Psi(N_o + \phi N_e) \\ &= (P_e + \phi P_o) + (P_o + \phi P_e) \\ &= (1+\phi)(P_o + P_e) \end{aligned}$$

demonstrates that any phase error resulting from sampling mismatch between frames, ϕ, will not produce residual Nyquist ghosts since it affects both odd and even lines equally.

We showed in [9], that the quality of parallel MRI (pMRI) reconstructions is directly dependent on the data used for calibrating the reconstruction coefficients. In many applications it is desirable to use self-referenced pMRI approaches over a prescan approach, for example, 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.

Our approach of combining UNFOLD with PLACE, however, completely eliminates Nyquist ghosts while maintaining the same SNR and nearly the same temporal resolution as the raw measured data. This enables one to apply self-referenced pMRI techniques in EPI with no reference scans needed—for either Nyquist ghost correction or parallel imaging. Below, we demonstrate the effectiveness of our approach at removing Nyquist ghosts, and the subsequent improvement in reconstructing accelerated parallel MRI data using a self-referenced approach.

3. METHODS

To demonstrate our approach, two MRI scans were acquired from a healthy volunteer after informed consent. In both cases, 124 image frames were acquired using an EPI sequence modified to perform the PASL paradigm, Q2TIPS [1], on a GE EXCITE 1.5T scanner (image size 128x128, TR/TE=2.5s/55.1ms, slice thickness=8mm, FOV=28mm x 28mm, 8 channel head coil). Two images, a control and a

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label, are needed to generate a perfusion signal. The magnetization of the blood flowing into the imaging plane for the control image was the opposite of the label image, achieved by a pair of global and slice-selective inversion pulses. The control image is subtracted from the label image, with the remaining signal being from blood that perfused into the imaging plane. 62 control and label pairs (124 frames) were acquired and averaged together to produce one perfusion weighted image. The pulse sequence was modified to introduce a temporal variation in the sampling grid as well, shifting by $(1\Delta k)$ every other control/label pair.

In the first scan, no acceleration was used and 128 lines of k-space were acquired after each excitation. In the second accelerated scan, the EPI blip-table was modified to sample a variable density distribution of k-space lines. For the accelerated data presented here, the acquisition pattern employed 8 k_y lines near the center of k-space separated by $(1\Delta k)$. The gap along k_y between sampled k-space lines gradually increased to $(5\Delta k)$ in the high frequency region. An acceleration factor of 3.2x was used, which produced (128/3.2=) 40 k_y lines for each accelerated image acquired.

To reconstruct the data, in both scans first the Control (C) and Label (L) images from the temporal series were separated and then, for each set, data (P) associated with positive readout gradients was separated from data (N) acquired using negative readout gradients. Each of the four data sets (CP,CN,LP,LN) were then processed with UNFOLD, and the phase difference between the P and N images was calculated to correct any k_x shift. in In both the C and L sets, the P and shifted N images were then combined to form C' and L' sets. In the unaccelerated case, C' and L' thus contained images free of Nyquist ghosts.

In the accelerated case, a complete image reconstruction required addition processing. We employed two self-referenced pMRI reconstruction algorithms, both described in [9]. First, GRAPPA [10] was used with a 2x5 kernel to reconstruct data in regions with local acceleration factors of $2\Delta k$, using data from the $(1\Delta k)$ region for self-calibration. This output was then reconstructed using either a second pass of the GRAPPA algorithm to reconstruct all missing k-space lines, or coil sensitivity maps were estimated using the central k-space region of 16 k_y lines (formed from 12 measured lines and 4 GRAPPA estimated lines) and used to reconstruct an unaliased image using the LSQR-Hybrid SPACE RIP algorithm [11].

4. RESULTS

The image in Fig. 2(a) shows one image reconstructed from the PASL image series using our Nyquist ghost removal approach. Note that the signal outside the brain tissue has been amplified 15 times to increase N/2 ghost visibility. A significant reduction in Nyquist ghosting is visible compared to the AC corrected image in Fig. 2(b). The corresponding perfusion image generated from the EPI data processed using our method is shown in Fig. 2(c), which clearly shows that no Nyquist ghosts are present in the (C'-L') difference.

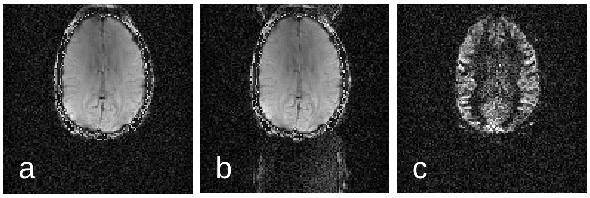

Fig. 2. EPI images from the unaccelerated PASL series. Nyquist ghosts corrected via (a) UNFOLD, (b) Ahn and Cho. (c) The associated UNFOLD-EPI perfusion image.

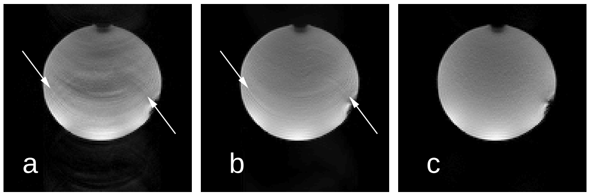

Fig. 3. EPI images of a water phantom reconstructed using (a) self-referenced GRAPPA using standard Nyquist ghost correction, (b) GRAPPA with pre-scan data to generate the reconstruction parameter values and standard Nyquist ghost correction, and (c) self-referenced GRAPPA using UNFOLD to perform the Nyquist ghost correction.

Fig. 3 demonstrates the improvement to self-referenced parallel imaging methods provided by our Nyquist ghost removal strategy. Images of a water phantom were acquired using the same acquisition protocol as the in-vivo data, yet reconstructed using (a) self-referenced double-pass GRAPPA with Nyquist ghost correction as in [5], (b) GRAPPA using 20 lines from a reference frame with Nyquist ghost correction as in [5], and (c) self-referenced double-pass 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. 4 shows the perfusion images generated from the accelerated PASL acquisition. It is notable that the noise level present in the GRAPPA reconstruction overwhelms the perfusion signal, which is typically on the order of 1-2% of the static tissue levels. By contrast, a regularized reconstruction approach can sufficiently suppress the reconstruction noise, allowing the perfusion signal to be visible. In comparison with the unaccelerated perfusion signal, Fig. 2(c), there is a significant loss in SNR in the GEYSER+SPRIP reconstruction due to the scan acceleration as well as pMRI reconstruction artifacts which appear outside the cerebellum. This loss in SNR can be recovered by sampling the data in multiple sweeps after a single excitation. While this will reduce the

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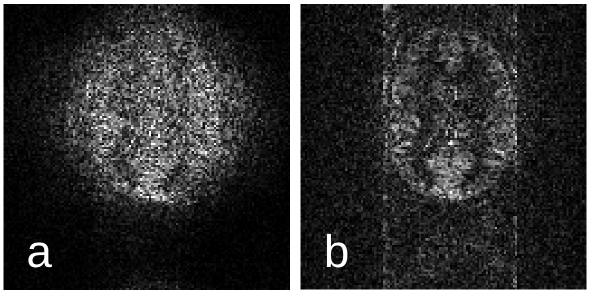

Fig. 4. Blood perfusion signal generated from accelerated EPI PASL images, reconstructed using (a) double-pass GRAPPA, and (b) GEYSER + SPACE RIP

overall image acquisition efficiency gains achieved with parallel imaging, these images will still have less geometric distortion then images acquired with unaccelerated EPI.

5. SUMMARY AND DISCUSSION

We presented a novel approach to Nyquist ghost removal and its significant improvement to self-referenced reconstruction of accelerated EPI data acquired with multiple coils. Our method employs UNFOLD to generate two sets of images for each time point in a temporal series. One image corresponds to data acquired on positive read-out gradients, while the other image corresponds to data acquired on negative readout gradients. We demonstrated that after correcting for phase differences along the readout dimension between these two sets, adding these two images together produces images free of Nyquist ghosts. Methods such as self-referenced parallel imaging—which can be sensitive to the sampling errors in EPI acquisitions that produces Nyquist ghosts—greatly benefit from our approach, as evidenced by the substantial reduction in pMRI reconstruction artifacts compared to previous methods.

The advantage of using UNFOLD for Nyquist ghost removal in EPI is two-fold. First, Nyquist ghosts are completely eliminated while 90% of the temporal resolution is maintained. Second, SNR is maintained as well, as the approach uses the same measured data as current methods, just manipulated and combined in a novel way to form the EPI images. The cost of using UNFOLD is a slight loss ($\sim$10% in our implementation here) in temporal resolution, depending on the width of the stop-band in the high-frequency notch filter. This loss is small, however, compared to gains made in maintaining temporal resolution, SNR, Nyquist ghost elimination, and reduced image distortion.

The effectiveness of pMRI in PASL perfusion imaging is a focus of future work. We demonstrated that our regularized pMRI reconstruction approach can produce perfusion images from highly accelerated acquisitions. These images tend to exhibit lower SNR than unaccelerated approaches, however. This indicates a need to acquire more images over which to average, or alternatively, a limit on the spatial resolution available to accelerated PASL imaging.

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