A Method to Remove Nyquist Ghosts from Echo Planar Images (EPI) using UNFOLD

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Introduction: Nyquist ghosts are a persistent artifact in echo planar imaging (EPI), and occur when data sampled along positive readout gradients and negative read-out gradients is inconsistent. There are many approaches to correct such artifacts including double-sampled (DS) EPI [1], 1D phase-correction with an algorithm developed by Ahn and Cho (AC) [2], 2D phase-mapping [3], and phase labeling (PLACE) [4]. 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 scanners, yet often leaves residual ghosts behind. PLACE and 2D phase-mapping use an echo-interleave strategy which typically performs better than AC, but cuts the temporal sampling rate in half. As an alternative to these methods, we introduce the use of UNFOLD [5] instead of interleaving, to eliminate Nyquist ghosts while maintaining more than 90% of the temporal sampling bandwidth.

Theory: The goal of all Nyquist ghost removal strategies is to correct the data sampling mismatch that occurs between the positive and negative read-out gradients 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 negative read-out data to form two separate images that satisfy the Nyquist sampling criteria (PLACE).

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

Shifting the data sampling grid on alternate frames by ($1\ \Delta k$), as in PLACE, 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.

Our method is robust to sampling variations that can occur from frame to frame as well. In practice, positive readout data from one frame may not *exactly* line up with positive readout data from successive frames. With UNFOLD, these sampling errors will cancel when the positive and negative readout data is combined. For a given odd frame n, the image P associated with positive readout data will contain raw acquired odd lines from frame n, Po, plus even lines that have been generated by UNFOLD. These UNFOLD lines, Pe, may be corrupted by additional phase errors, ϕ, due to sampling mismatch between the frames. Thus, the image associated with positive readouts is $P = Po + \phi Pe$. Similarly, the image N associated with negative readout data will contain raw acquired even lines from frame n, Ne, plus odd lines generated from UNFOLD that also contain the same potential phase errors, ϕNo. Since each image, N and P, separately satisfies the Nyquist criteria along the phase-encoding dimension, it is a simple matter to identify a operator Ψ, with $\Psi N \approx P$, that corrects the k-space shift between $P=Pe+\phi Po$ and $N=No+\phi Ne$. Combining the two data sets as

$$P+\Psi N=(Pe+\phi Po)+\Psi(No+\phi Ne)=(Pe+\phi Po)+(Po+\phi Pe)=(1+\phi)(Po+Pe)$$

demonstrates that the phase error *between frames*, ϕ, will not produce residual Nyquist ghosts since it affects both odd and even lines equally.

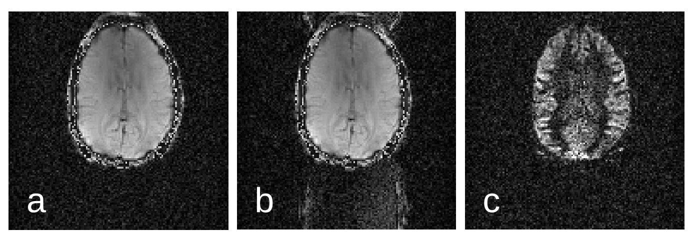

Fig 1: EPI images from a PASL series. Nyquist ghosts corrected via (a) UNFOLD, (b) Ahn and Cho. (c) The associated UNFOLD-EPI perfusion image.

Methods: 124 EPI images of a healthy volunteer were acquired after informed consent using a pulsed arterial spin labeling paradigm, Q2TIPS [6], 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). To generate the perfusion signal, alternating Control and Label images were acquired. 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. For processing, first the Control (C) and Label (L) images were separated and then odd (O) and even (E) lines separated. Each of the four data sets (CE,CO,LE,LO) were processed with UNFOLD, CE/LE and CO/LE images were phase corrected as above, and then combined to form the unaliased C and L sets.

Results: Fig. 1a shows one image from the Q2TIPS series reconstructed using this approach. A significant reduction in Nyquist ghosting is visible compared to the AC corrected image in Fig 1b. Note that in both (a) and (b) the image values outside the brain have been amplified 15 times to increase Nyquist ghost visibility. The corresponding UNFOLD-EPI perfusion image is shown in (c), where it is clear that no Nyquist ghosts are present in the differences between Control/Label pairs.

Discussion: The cost of using UNFOLD is a slight loss (~10%) in temporal resolution, depending on the width of the stop-band in the high-frequency notch filter. This loss is marginal, however, compared to the temporal resolution of competing methods and the subsequent gain in Nyquist ghost elimination.

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