Minimization of Nyquist ghosting for fMRI at ultra-high fields based on a 'negative read-out gradient' strategy.

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Introduction

Nyquist ghost correction approach in echo planar images typically is based on a reference scan acquired in the absence of the blipped phase encode gradient. However, although a substantial ghost reduction is achieved, residual artefacts remain. It has been reported that further artefact reduction is possible using a 'negative gradient read-out' strategy where the phase encoded image is acquired with reversed polarity of the read-out gradient (G_x) in a reference scan [1]. The aim of the present study was to extend this approach to acquiring time-series of fMRI measurements by alternating the read-out polarity, i.e. the 'positive', G_x, and 'negative', $-G_x$, echo trains and to evaluate three resulting strategies for ghost removal.

Theory

The k-space signal for EPI can be written as:

$$S(k_x,k_y)=\int\int m(x,y)\exp\left(2\pi i\left[\Delta f(x,y)\left(T_n+(-1)^n\left(\frac{k_x}{\gamma G_x}\right)\right)+k_x x+k_y y\right]\right)dxdy$$

where $m(x,y)$ represents the object's transverse magnetisation, $\Delta f(x,y)$ the frequency distribution, and T_n is the time at the centre of the nth k-space line. Because Δf depends on x and y and increases with B_0, the inconsistencies between odd and even k-space lines, responsible for Nyquist ghosting, depend on k_y as well as k_x [1] and increase with magnetic field. Inverting the polarity of G_x, which amounts to a replacement of $(-1)^n$ with $(-1)^{n+1}$ in Eq. 1, was used for Nyquist ghost correction in fMRI time series using the following three strategies: The first, denoted (P): After Fourier transformation in the read direction, (fft_x), the phase difference between the 'positive' and 'negative' image is used to correct both. 2 (A): After fft_x, the 'positive' and 'negative' images are summed and then fft_y is applied to create a new image. 3 (CP): The phase of the result of (A), before FTT along the phase-encode direction (fft_y), is combined with the amplitude of the 'positive' or 'negative' data to form 'Corrected Phase' data. In all three schemes, after phase correction, fft_y is applied to obtain images. Scheme CP and P allow a Nyquist ghost correction while preserving the temporal resolution, provided the BOLD response does not change the phase of the voxel appreciably. This change is likely minimal, as TE >>$T_2^*{}_{venous}$ at 9.4T [2].

Methods

All experiments were performed in an actively shielded 9.4 T/31-cm with 12-cm gradient (400 mT/m in 120 µs) using a quadrature ^{1}H RF-coil. The standard EPI sequence was modified to alternate the read-out direction every other volume. 300 volumes were acquired with TE=25ms, TR=2s. The first two volumes in each train were reference scans acquired without phase-encode blips. Following 2nd-order shimming with FASTMAP, 10 slices with a matrix size of 64 * 64, FOV of 25 * 25 mm and slice thickness 1 mm were acquired per volume. All images were corrected using the scans acquired without phase encoding, providing the 'comparison image'. Further correction was done using methods P, A and CP.

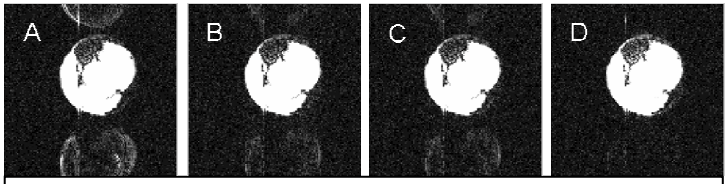

Figure 1 A: Comparison image. B: correction (P) C: Correction (CP) D: Correction (A). All images have been scaled to obtain identical image brightness in the noise.

Four male SD rats underwent an fMRI study employing a forepaw stimulation task. The employed block paradigm consisted of a 30s ON-period followed by 60s OFF, repeated 6 times. The animals were continuously monitored and maintained under good physiological conditions.

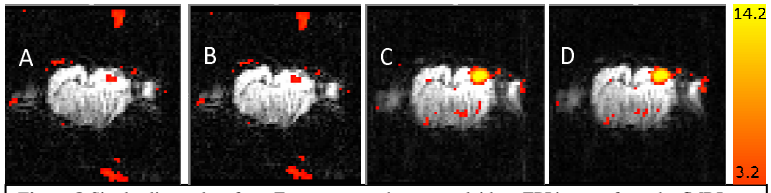

Figure 2 Single slices taken from Z-score maps shown overlaid on EPI images from the fMRI train. A: Comparison image. B: correction (P) C: Correction (CP) D: Correction (A)

fMRI analysis was carried out using FEAT in FSL. fMRI data were realigned and spatially and temporally smoothed. A GLM was formed with the BOLD signal change modelled as a box-car function convolved with the canonical HRF. Z-score maps were thresholded using clusters determined by Z>3.2 and P_{corr}=0.05. Remaining ghost levels and number of active voxels in the somatosensory cortex were measured.

Results and Discussion

EPI images of a rat brain phantom showed persistent ghosting in the comparison image (Fig 1A). Applying the three schemes resulted in similar ghosting levels of 2.5% (a 61% reduction) using schemes P and CP, while the result of scheme A was virtually ghost free (Fig.1), though this comes at the expense of a two-fold reduction in temporal resolution. In the fMRI data, ghosting intensity after correction was decreased by 41±30% for P, by 67±10% for CP and by 70±8% for A (mean±sd). When false positive activation in the ghost region was detected, it was removed using scheme CP and A (Fig.2). The average number of voxels determined 'active' in the somatosensory cortex increased significantly using scheme CP and A: by 40±17 % and 25±14 % compared to the comparison data, respectively. Using scheme P a small non-significant increase was found. Average maximum Z-scores found were: 14.0±0.7 % in the comparison data and 13.9±0.6 %, 15.5±2.9% and 14.7±2.7% using schemes P, CP and A, respectively.

In conclusion: substantial Nyquist ghost reduction is possible. While scheme CP has the advantage of preserving the temporal resolution, scheme A is readily suitable for applications requiring signal averaging, such as perfusion and/or diffusion experiments.

References 1. Hu. et al. Magn Reson Med. 1996; 36:166-71. 2. Lee et. al. Magn Reson Med. 1999; 42:919-928