Optimized acquisition strategy for reference-free reduction of Nyquist ghosting in EPI at 7 T

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Introduction

fMRI commonly employs the echo planar imaging (EPI) sequence because of its favourable sensitivity, and its very high sampling efficiency which allows 'single-shot' imaging of a brain slice within typically ~70 ms. This is achieved by traversing *k*-space under an oscillating readout gradient, and so every other *k*-space line needs to be time-reversed ('flipped') before Fourier reconstruction. This makes EPI sensitive to non-symmetric gradients which lead to a 'periodicity-of-two' (zig-zag) pattern along the phase encoding direction, thereby causing so-called Nyquist (N/2) ghosting where a ghost image shifted by half the FoV is superimposed on the primary image. Under most circumstances the line displacement can be assumed constant and a standard correction approach [1] -without need for separately acquired reference scan [2-5]- works well up to 3T: One acquires two or three non-phase encoded 'navigator' echoes with opposite gradient polarity immediately after excitation at maximal SNR; after Fourier transformation to projection space, all odd and even *k*-space lines are corrected by conjugate phase multiplication by the corresponding navigator scan. However, residual ghosting can become an issue at ultra-high field [5] related to higher mechanical forces at specific switching frequencies, given by readout BW or echo-spacing (ES). Often, residual ghosting can be reduced by an empirical choice of a 'good' ES, but especially at high field the freedom is restricted by other demands for the scan protocol, such as echo time, resolution or low geometric distortions.

For these situations we propose a simple sequence modification that allows good standard ghost correction to be achieved also for the 'bad' echo-spacings on a human 7 T system, by realizing that (a) under the standard correction the residual ghosting in what is usually considered 'bad' ES data is caused by a phase mismatch between navigator and image data, and (b) such a mismatch is the result of changing gradient delays along the readout, making the timing of navigator acquisition critical.

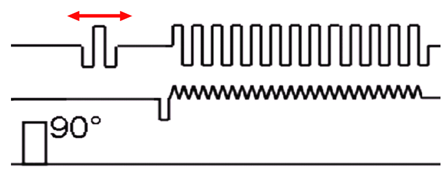

Fig 1: *EPI sequence with flexible positioning of phase-correction scans.*

Methods

On a Siemens Magnetom 7T system a modified EPI sequence was implemented which permits the time point of navigator echo acquisition to be moved freely within the time between excitation and imaging readout (Fig. 1) for a given echo time. EPI scans with and without phase-encoding were made for different positions of the navigator scan (matrix 64x64, FoV=200mm, 9 slices with 5mm, TE=30ms, 'bad' ES of 0.70ms, 8-channel head coil). The line-displacement was calculated from the non-PE data and plotted for each line pair along the readout: The shift in *k*-space is proportional to the phase gradient obtained by dividing the line pairs after (read-)Fourier transformation. The position of the navigators was varied by varying the delay after the excitation pulse, and related to the ensuing (mis-)match between the 'reference shift' and 'actual shift' near the *k*-space center, as well as the ghost-to-signal ratio in the images that were reconstructed with the vendor-provided algorithm.

Results and Discussion

Fig. 2 shows phantom and *in vivo* results for the default and optimized sequence. The crucial findings are:

1) Most critical factor for residual ghosting is the match between 'reference shift' as obtained from the navigators (dotted line), and the 'actual shift' near *k*-space center (arrows). The curves illustrate the time varying displacement between adjacent lines. The top panel shows the result for the typical 'bad' ES in the default sequence: clearly there is a severe mismatch between the reference and actual shift, causing a 19.2% residual ghost-to-signal ratio after standard 'correction'. By moving the navigators by 1.9ms towards the readout, a near-perfect match is achieved, yielding a much cleaner image (only 5.2% ghost, bottom curve). These phantom results were validated *in vivo* where the ghost was reduced from an unacceptable 29.2% to an easily tolerable 6.9% (here the optimal delay was 0.5ms, due to the different slice angulation).

2) While the standard correction assumes a constant gradient delay and hence shift between lines, this is clearly not the case for the protocols used here: instead, the line shift along the readout has an oscillatory behavior, which leads to situations in which the wrong value is applied in the phase correction. Moreover, the changing line shift (given by curve amplitude) causes a spatial-frequency dependence of the ghost. Also this effect is markedly reduced by the proposed sequence modification.

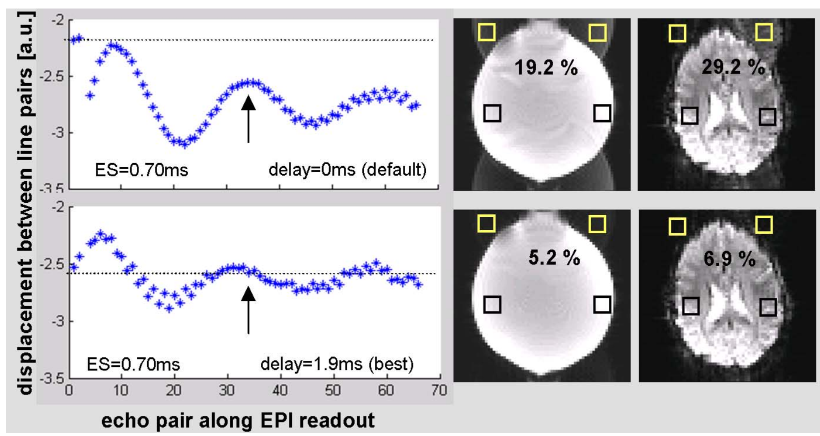

Fig 2: *Considerable ghost reductions can be achieved by appropriate timing of the phase correction scan. In a 'bad' echo-spacing protocol ghost reduction from 19.2% to 5.2% is achieved by adding a 1.9 ms shift and thereby removing the mismatch between navigator and imaging data. The factor four improvement was also observed in vivo, where the 29.2% ghost could be reduced to a tolerable level of 6.9%.*

Using optimized navigator delays in combination with the standard approach to ghost correction as implemented in the scanner software provides an easy and effective way of removing the restrictions often encountered in practice when setting up scan protocols. Since no reference scan is required the method is invulnerable to the risks associated with reference scan based methods.

References [1] Schmidt, F.(ed.) 1989 Echo planar imaging (ISBN 3540631941) [2] Chen, N et al. MRM 51:1247–1253 (2004) [3] Schmithorst, V. et al IEEE Trans Med Imaging 20:535–539 (2001) [4] Xiang, Q and Ye, Q. MRM 57:731–741 (2007) [5] v.d. Zwaag, W et al. JMRI 30:1171–1178 (2009)