An x,y phase correction method to eliminate image ghosts in single and multi shot EPI

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Single and Multi shot EPI sequences are used in a wide variety of clinical and research applications. However, reconstruction is prone to ghost artifacts due to inconsistency of k space lines acquired during alternate gradient polarity or during different shots. This means that there is a phase difference $\Psi_0(x, y)$ between sub-images reconstructed from each set of k space lines. In this work, we describe a reconstruction algorithm and a pre-scan that enables us to calculate $\Psi_0(x, y)$ along the readout (x) and phase (y) directions and eliminate the ghost artifact. This method is superior over conventional correction methods, which assume that the phase errors are only a function of the readout (x) direction.

Method

The proposed pre-scan is identical to the scan, but the phase encode amplitude is halved, so an image with double Field Of View (FOV) in y is obtained. For clarity, we shall explain the single shot EPI reconstruction and then present the general solution for multi shot.

Single Shot EPI: The purpose is to compute $\Psi_0(x, y)$ between even and odd k space lines. The double FOV image is separated into $F_{1/2}$ and $\Im_{1/2}$, where $F_{1/2}$ is the FT of the even lines with positive readout gradient and the odd lines set to zero, and $\Im_{1/2}$ is the FT of odd lines with negative readout gradient and even lines set to zero. The subscript ½ indicates that these images are half size in y. Since the ghost and main image of $F_{1/2}$ and $\Im_{1/2}$ do not overlap, we zero out the ghost. The phase difference between $F_{1/2}$ and $\Im_{1/2}$ is $\Psi_0(x, y/2)$. To find $\Psi_0(x, y)$ we "stretch" each voxel by doubling its position along y. After the scan is acquired, we divide the dataset of the full scan into F, the FT of the even lines, and $\Im$, the FT of the odd lines. In the scan, the image and ghost overlap. Our task is to separate them using $\Psi_0(x, y)$. The full separated image F_0 is:

$$F_0 = \frac{\exp[-i\Psi_1(x,y)] \cdot F + \Im}{\exp[-i\Psi_1(x,y)] + \exp[-i\Psi_0(x,y)]} \qquad [1]$$

Where $\Psi_1(x, y)$ in Eq. [1] is the phase $\Psi_0(x, y)$ shifted by half a Field Of View.

Multi Shot EPI: A multi shot sequence with L shots generates 2L ghosts across the FOV, since there are L shots with a positive gradient and L shots with a negative gradient. Furthermore, the L shots of the positive (negative) gradients are not equally sampled on the ky grid. For example, with L = 2 shots, the lines at ky = 1,2, 5, 6, 9, 10 … etc are acquired with a positive readout gradient, and the lines with ky = 3, 4, 7, 8, 11, 12 etc with negative readout gradient. We recalculate the raw data on an equally sampled ky grid using the generalized sampling theorem of A. Papoulis (1). The reconstruction is carried out in two steps: 1) The double FOV pre-scan dataset is recalculated so that the lines with positive readout gradient are resampled on an equally sampled grid ky = 1, 3, 5, 7, 9, … and the lines with negative gradient are resampled to ky = 2, 4, 6, 8, …. The phase $\Psi_0(x, y)$ is now calculated as in the single shot case. 2) After the scan is acquired, we use $\Psi_0(x, y)$ to reconstruct the artifact-free image $F_0(x, y)$ using the generalized sampling theorem (1). The general solution for L shots is:

$$M \cdot F = \Re \quad \text{where} \quad M = A \bullet P \qquad [2]$$

M, A and P are 2L by 2L square matrices, and F and $\Re$ are column vectors with 2L elements. The sign $\bullet$ in [2] means element-by-element multiplication. The j element of F is F_0 shifted by j/(2L)·FOV along y, i.e. $F_j(x, y) = F_0(x, y - j/(2L)\cdot \text{FOV})$ and j = 0, 1, …, 2L - 1. Element j of $\Re$ is the FT of the ky lines of shot j (with either a positive or negative gradient polarity) and all other ky lines set to zero. Element k, l of A is $A_{k,l} = \exp(i \cdot m_k \cdot m_l \cdot \pi/L)$, where m_k is element k of the vector m = (0, 1, …, 2L – 1). To define P in Eq. [2] we define $C_j = \exp[-i\Psi_j(x, y)]$, where Ψ_j is $\Psi_0(x, y)$ shifted by j/(2L)·FOV along y, i.e. $\Psi_j(x, y) = \Psi_0(x, y - j/(2L)\cdot \text{FOV})$ with j = 0, 1, …, 2L - 1. The rows of P that correspond to the first L lines sampled with a positive gradient are all 1, and the rows that correspond to the first L lines sampled with a negative gradient are the vector C_j with j = 0 to 2L - 1. For example, for single shot EPI (L = 1) where the first ky line is sampled with a positive readout gradient and the second with a negative gradient, $P = \begin{pmatrix} 1 & 1 \\ C_0 & C_1 \end{pmatrix}$. The desired image F_0, which is the first element of F in Eq. [2], is calculated by inverting M.

Results and Discussion

y dependent phase errors are caused by 1) Spatially dependent eddy fields; small deviation of the gradient coil from axial symmetry causes y-dependent eddy fields. 2) Anisotropy (i.e. small difference) between the x, y or z physical gradient channels; y phase difference is created during oblique EPI scans (2), especially in case of ramp sampling. 3) Field inhomogeneity during echo readout; the echo signal is flipped in time during negative gradient lobes, but field inhomogeneity is the same. Hence phase accumulation during each readout causes a phase difference in x and y.

EPI reconstruction was implemented as a MATLAB tool, where data collected from a carefully calibrated scanner was reconstructed with the standard product software or using Eq. [1] and [2] for L = 1, 2 and 4 shots using a 16 cm diameter water phantom. We compared image quality and ghost suppression of the two algorithms and y dependent eddy field (derived from $\Psi_0(x, y)$). In most cases, our algorithm eliminated the ghosts below detection level. We noticed significant y dependent eddy fields for sagittal and coronal slices that caused severe ghosts (~15%) with the product reconstruction. These ghosts were eliminated with our algorithm. For axial slices we obtained ~5% ghosts with the product software and 0% with our algorithm. Finally, we removed the short-term compensation of the x gradient to increase the anisotropy of x with y and z. Data was acquired for oblique directions of Axial and Coronal slices. The ghost level was 10% to 30% with the product reconstruction and 0% to 4% with the new algorithm.

Conclusion

The new reconstruction method is much less sensitive to system imperfection. Significant ghosts in Sagittal and Coronal directions were eliminated with the new reconstruction algorithm.

References

(1) A. Papoulis "Signal analysis" McGraw-Hill 1977 pages 191 to 196. (2) B. Aldefeld and P. Bornert, Mag. Res. Med., 39(4), 606 - 614, 1998.