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Two-dimensional deghosting for EPI

Franciszek Hennel *

FORENAP, Rouffach, France

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Abstract

A residual ghost artefact in echo-planar imaging (EPI) remains after the standard correction procedure based on a 1-dimensional phase-modulation of the spectra of even or odd echoes. A better reduction of this artefact is demonstrated using a 2-dimensional phase correction. The phase correction map is measured inside the ghost-free region of the image, preferably in a reference scan with an increased field of view, as the phase difference between complex images reconstructed separately from even and odd echoes. An extrapolated map consisting of spatial components up to the second order (constant, x, y, xy and $x^2 - y^2$) is then found by a fit to the measured values. This map is used to correct the phase of even- and odd-reconstructed images before adding them. This procedure may cause some spatially dependent loss of signal, but if the level of the residual artefact is less than 20% of the image intensity, such losses are negligible. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

One of the troubles inherent to the EPI technique is the presence of a persistent artefact, resembling the original image and shifted by one half of the matrix size in the phase-encoding direction, usually called the $N/2$ ghost. The first and the most simple way to remove it — using only even or only odd echoes for the reconstruction — was shown in the Mansfield's first paper on this technique [1]. Obviously, this was not optimal. Taking all echoes for one image and thus doubling the measurement speed for free has always been a temptation and motivated numerous works on the $N/2$ ghost suppression. However, none of the proposed deghosting methods is ideal. The residual artefact, typically at the level of 5–10% of the main image intensity, is a serious problem when EPI is used with a long effective gradient echo time, e.g. in fMRI. In that case the interference of the ghost with the original image gives a pattern which strongly depends on the magnetic field homogeneity. As a result, pixel intensity fluctuations comparable with the ghost amplitude can arise due to slight changes in the field map caused, e.g. by object displacement. Image registration procedures, normally successful in correcting displacements, will not remove such ghost-related fluctuations.

It can be deduced from the cyclical $N/2$ shift of the ghost that its origin is related to some inconsistency of even and odd data lines (profiles) which exist before the Fourier transformation (FT) in the phase encoding direction. The standard deghosting strategy is based on the assumption that this inconsistency can be represented by a 1-dimensional (1D) phase modulation of the profiles. Once the modulation is measured in a reference scan [2–4] or derived from the ghost region of the image [5], it can be removed from the profiles before the FT in the phase encoding direction. However, as shown recently by Buonocore and Gao [6], the phase inconsistency of even and odd profiles is 2-dimensional (2D) in a general case. This explains why a residual ghost with a strange 2D intensity modulation remains after the 1D phase correction. In this work, an application of the 2D phase correction of EPI data is demonstrated and it is shown that a better reduction of the $N/2$ ghost can be obtained in this way.

* Present address: CEA-SHFJ, 4, Pl. du Gén. Leclerc, 91401 Orsay, France. Tel.: + 33-1-69867864; fax: + 33-1-69867868.

2. Method

Due to linearity, the 2DFT of an entire data matrix is equal to the sum of 2DFT's of two matrices containing only even and only odd rows of the original data with the remaining ones zero-filled. As shown in Ref. [6], such even-reconstructed and odd-reconstructed images are given by

$$\rho_e(x, y) = \rho(x, y)e^{i\Theta(x, y)} + \rho(x, y \pm \tfrac{N}{2})e^{i\Theta(x, y \pm N/2)} \quad (1)$$

$$\rho_e(x, y) = \rho(x, y)o^{-i\Theta(x, y)} - \rho(x, y \pm \tfrac{N}{2})o^{-i\Theta(x, y \pm N/2)} \quad (2)$$

where ρ is the spin density and Θ is the phase shift of the transverse magnetisation related to the polarity of the readout gradient (x direction). The double sign, used to represent the cyclical folding of the ghost, should be read '+' for the bottom half of the image and '−' for the upper one. This convention will be kept for the rest of the paper. The phase shift is due mainly to eddy currents induced by the gradient switching. Additionally, a linear term in x can be contributed to Θ by a delayed response of the gradient system or by a timing error of the sequence, as well as by a time-lag of the audio filters. However, Θ is in general a 2D function representing the map of the magnetic field generated by eddy currents.

In order to remove the phase factor from the data so that ρ_e and ρ_o can be added without generating the ghost, the $\Theta(x, y)$ function has first to be measured. In the current implementation this is done in a calibration experiment in which the EPI sequence is run once with the field of view in the phase encoding direction (y) big enough to avoid overlapping of the main image and its replication (the two terms in Eq. (1)). The value of Θ is calculated pixel by pixel as one half of the phase difference between ρ_e and ρ_o in the region of the main image.

A difficulty of this procedure is that the calculation of the phase difference is very sensitive to noise in regions of low signal. In particular, Θ can not be measured outside of the object. This would cause a severe problem if the object moved between the reference and the actual scan. Additionally, Θ remains unknown in the regions where the ghost overlaps with the image if such regions still exist in the reference scan. Thus, smoothing and extrapolation of $\Theta(x, y)$ to the entire field of view is necessary. The strategy taken here resembles the procedure of magnetic field shimming. The phase shift is assumed to be composed of spatial terms up to the second order:

$$\tilde{\Theta}(x, y) = A_0 + A_1x + A_2y + A_3 2xy + A_4(x^2 - y^2) \quad (3)$$

and the A coefficients are found by a fit to the experimental values. This is done in polar co-ordinates. The experimental values of $\Theta(r, \phi)$ are taken on a circle centred in the field of view and having a radius which fits within the ghost-free region of the object, as shown in Fig. 1. The A coefficients are then easily found by a Fourier analysis.

Once the estimate of the phase shift in the form given by Eq. (3) is known, it is used to calculate a de-ghosted image as:

$$\begin{aligned}\tilde{\rho}(x, y) &= \rho_e(x, y)e^{-i\Theta(x, y \pm N/2)} + \rho_o(x, y)e^{i\Theta(x, y \pm N/2)} \\ &= \rho(x, y)\cos[\tilde{\Theta}(x, y) - \tilde{\Theta}(x, y \pm N/2)] \\ &\quad + i\rho(x, y)\sin[\tilde{\Theta}(x, y) - \tilde{\Theta}(x, y \pm N/2)] \quad (4)\end{aligned}$$

This image still contains a residual ghost (the last term). Its amplitude depends on the difference between the actual phase shift and our 2nd order estimate. We can expect however, that this procedure will give a significant reduction with respect to standard, 1D phase correction which would correspond to taking only the first two terms in Eq. (3). However, a new problem arises, namely that the amplitude of the original image (the first term in Eq. (4)) is perturbed. Worse still, this perturbation has a discontinuity on the central line of the image ($y = N/2$) which can produce quite a visible effect. Note, that this problem is specific to the 2D

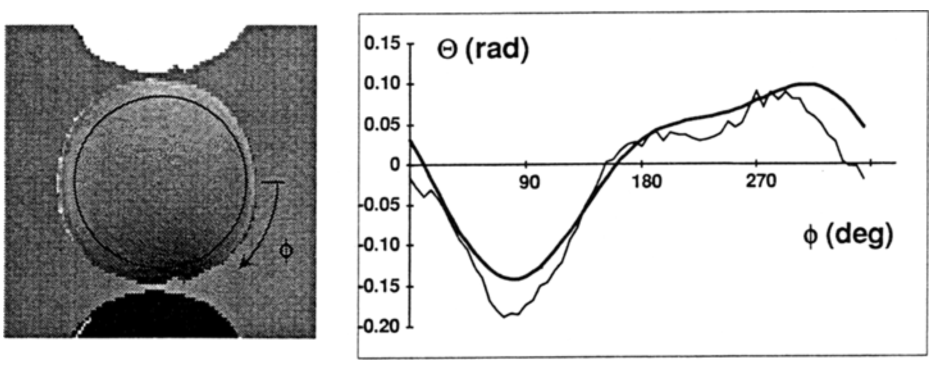

Fig. 1. Phase difference Θ between images calculated from even and odd echoes of a reference EPI scan. A second order 2D fit to this function is performed in polar co-ordinates to obtain a phase-correction map for the actual EPI acquisition. The plot shows the measured values of Θ (thin line) taken on the white circle and the fit (thick line).

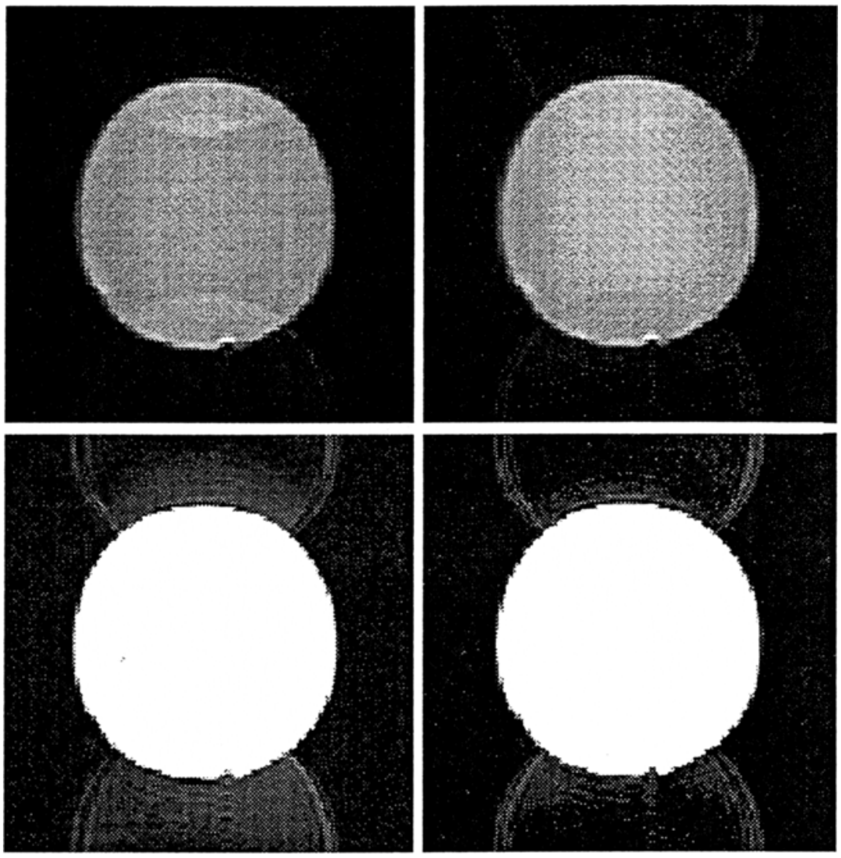

Fig. 2. Comparison of the standard ghost reduction method using 1D phase correction of odd profiles (A, C) with the 2D method described in the text (B, D). The bottom images are printed with a five-fold intensity enhancement. The ghost intensity in the marked region is 6.6% of the main image intensity with the 1D correction and 1.6% with the 2D correction.

correction. If $\tilde{\Theta}$ did not depend on y, there would be no discontinuity. To reduce this effect, the final image is divided by

$$\cos[\tilde{\Theta}(x, y) - \tilde{\Theta}(x, y \pm N/2)] \quad (5)$$

In practice however, the loss of image intensity should not be too important. From Eq. (4), for small magnitudes of $\Theta(x, y)$, the intensity loss is given by

$$\tfrac{1}{2}[\Theta(x, y) - \tilde{\Theta}(x, y \pm \tfrac{N}{2})]^2 \quad (6)$$

If $|\Theta|$ and $|\tilde{\Theta}|$ do not exceed some maximum value of Θ_{max}, the image loss will be less than $2\Theta_{max}^2$. On the other hand, in the same approximation, Θ_{max} is the maximum level of the ghost in the uncorrected image (as can be seen by adding Eqs. (1) and (2), the ghost is modulated by sin Θ). Thus, if the artefact level before 2D correction does not exceed 20%, the loss of the image intensity will be less than $2 \times 0.2^2 = 8\%$ which is quite an acceptable trade-off for the benefit of a better ghost suppression.

The 2D ghost reduction method described here was applied to spin-echo EPI data obtained for a transverse section of a 20 cm water filled sphere. The experiment was performed at 3Tesla using a Bruker Medspec Avance spectrometer equipped with a 38 cm shielded gradient coil. Gradient amplitude of 16 mT/m with a rise time of 150 μs was used for the EPI readout. The resolution was 2 × 2 mm with a matrix of 128 × 128 points.

3. Results

Fig. 1 shows a map of 2Θ (the phase difference between even-reconstructed and odd reconstructed images) measured in a calibration scan. On the right, the values of the phase difference taken on the marked circle as well as the result of the second order fit are plotted as a function of the azimuthal angle. The image reconstructed using the 2D correction is shown in Fig. 2B. For comparison, the standard EPI image calculated with the 1D linear phase correction with parameters derived from the ghost region of the image, as described in ref. [6], is represented in Fig. 2A. Both images are printed in the same intensity scale. The 2D correction gives a significant improvement in of the ghost suppression. The strongest ghost region, marked by the circle, is reduced from 6.6 to 1.6% of the main image intensity. This is better visible with a five-fold intensity enhancement (Fig. 2B and C).

4. Discussion

Our results demonstrate that the two-dimensional phase correction gives a significant reduction of the residual ghost intensity in EPI. However, a still visible artefact remains due to higher order spatial components of the phase shift which were not included in the fit applied in our procedure. The reason for which such terms were ignored was that the problem of image intensity loss, mentioned in the discussion of Eq. (5), would become more severe with the increasing order in y. The current solution is a compromise between the ghost reduction and preserving the image intensity. It is applicable only when the eddy-current related phase errors, precisely, their y-dependent components, do not exceed 0.1–0.2 radians. Put differently, the 2D method will bring an improvement with respect to the 1D phase correction, only if the level of the residual ghost which survives the 1D correction is less than 20%. Otherwise, losses of the main image intensity will be too strong.

It should be mentioned that, although the y-dependent phase shifts can not be corrected by post-processing without any image loss, at least the linear term in y can be reduced to 0 be an adjustment of the sequence. This requires increasing the amplitude of the even phase encoding blips and reducing the odd ones (or vice versa) as has been proposed for the reduction of the oblique ghost, which appears with oblique orientations of the readout and different response delays of gradient channels [7]. This procedure is advisable to limit the residual value of Θ and thus to reduce image losses due to the 2D correction.

The method presented here differs from the one proposed by Hu and Lee [7] who apply a 2D correction in the (x, k_y) domain aiming at the ghost effect due to magnetic field inhomogeneities. The current method concerns ghosts caused by eddy-current related phase shifts which may appear even in a perfectly homogeneous field.

5. Conclusions

An improvement in the ghost reduction procedure for EPI has been demonstrated by extending the phase-correction of even- end odd-reconstructed images to two dimensions. The drawback of the presented method is that it causes some loss of the main image intensity. However, if the ghost intensity does not exceed several percent, the reduction works well without significant perturbation of the main image.

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