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Ghost artifact removal in EPI using projection in hybrid-space

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Abstract: Ghost artifacts occur in magnetic resonance imaging (MRI) reconstruction because odd and even echoes have different phase offsets. A method based on the projection in hybrid-space is described to remove ghost artifacts. First, the projection of the even and odd lines along phase-encoding direction in hybrid-space was used to estimate the phase difference between odd and even echoes. Secondly, we fit the phase difference and used it to correct the phase of even or odd echoes. Finally, the corrected image was obtained by performing the inverse Fourier transform along phase-encoding direction in hybrid-space. The experimental results show that linear and nonlinear differences can be corrected and the intensity of ghost artifacts is significantly reduced. The effectiveness of the proposed method is demonstrated in ghost artifact removal.

Key words: echo planar imaging; ghost artifact; magnetic resonance imaging; projection of phase

Functional magnetic resonance imaging (FMRI) provides high resolution maps of neural activity. This is possible due to small variations in magnetic susceptibility, caused by local blood oxygenation changes in active brain areas. To measure these changes with high temporal resolution, a fast image acquisition sequence is required. Echo planar imaging (EPI) is such an acquisition method, with the capability of acquiring images within fractions of a second. A problem specifically related to EPI is that every second line in *k*-space is read under a negative gradient; i. e., every other line is registered in the opposite direction from the conventional two-dimensional gradient echo (2D-GRE) *k*-space coverage. Modulations of the signal cause ghost images that are shifted beyond-half the FOV, hence the name *N*/2 ghosting. All ghost images are caused by phase effects in the Fourier domain, either linear phase shift or nonlinear phase shift[1].

To date, a number of methods have been developed to correct the ghosting, which can be divided into two groups: image-based methods[2 – 10], and methods using reference or calibration scans[2,11]. The imaged-based methods can be further divided into methods that require separate reconstruction of odd and even lines of *k*-space[2 – 5], and methods that seek to minimize a metric of image ghosting through iterative searching[6 – 10]. Searching is computationally expensive, and one group has sought to improve efficiency by combining it with reference scans[10]. Reference scan correction can provide excellent results. However, one disadvantage of reference scans is that each one is specific to the acquired slice. Different slices will be influenced by slightly different magnetic field variations and, thus, acquire a different phase response, necessitating a new reference measurement. Furthermore, any change during the interval between the reference and actual scan may also invalidate the reference scan. In addition, the use of projection onto convex sets (POCS) to correct for the ghost in EPI was proposed[12]. However, the method of POCS depends on the signal to noise ratio (SNR) of the chosen line and it can only correct linear phase variation. Lee used the method of generalized projections (MGP) for ghost removal, but his method did not work well when ghost and image overlapped[13]. In this paper, we propose a method which uses the projection of odd and even lines in hybrid *k*-space to identify the phase difference between the odd and even lines. It corrects not only linear variation but also nonlinear variation.

1 Theory and Methods

In echo planar imaging, hardware imperfection, for example, the presence of eddy current, gives rise to a gradient field and a B_0 field. The gradient field results in a translational shift between odd and even echoes. The B_0 field results in a change of resonance frequency, and, hence, phase is also changed between odd and even echoes. These phase offsets create an artifact image, called ghost shifted by half of the total pixels of

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the field of view relative to the parent image in the phase encode direction. Therefore, fundamental to ghost removal is the identification of the phase disparities between the even and odd sampling points.

Normally, the reconstructed image can be decomposed into two complex images, one reconstructed from the odd lines of k-space and the other from the even lines. The image is given by

$$S(t,k_y) = \iint M(x,y)\exp(-i\gamma G_x tx)\exp(-ik_y)\mathrm{d}x\mathrm{d}y$$
$$k_y = n\Delta k_y,\ n \text{ is even},\ -N/2 \leqslant n \leqslant N/2-1 \quad (1)$$

$$S(t,k_y) = \iint M(x,y)\exp(+i\gamma G_x tx)\exp(-ik_y)\mathrm{d}x\mathrm{d}y$$
$$k_y = n\Delta k_y,\ n \text{ is odd},\ -N/2 \leqslant n \leqslant N/2-1 \quad (2)$$

where $M(x, y)$ is the object being reconstructed, k_y is the phase encode spatial frequency, Δk_y is the phase-encoding spatial frequency increment, G_x is the strength of the frequency-encoding gradient, and t is a time point of data acquisition.

But even and odd lines must be time reversed, which results in alternating offset of the lines. In addition, eddy currents actually delay or advance the time of refocusing of the spins as a function of spatial position. So the actual reconstruction should be

$$S(t,k_y) = \iint M(x,y)\exp(i\theta(x))\exp(-i\gamma G_x tx)\cdot \exp(-ik_y)\mathrm{d}x\mathrm{d}y$$
$$k_y = n\Delta k_y,\ n \text{ is even},\ -N/2 \leqslant n \leqslant N/2-1 \quad (3)$$

$$S(t,k_y) = \iint M(x,y)\exp(-i\theta(x))\exp(+i\gamma G_x tx)\cdot \exp(-ik_y)\mathrm{d}x\mathrm{d}y$$
$$k_y = n\Delta k_y,\ n \text{ is odd},\ -N/2 \leqslant n \leqslant N/2-1 \quad (4)$$

where $\theta(x)$ represents phase errors at the echo center due to gradient dependent main field offset, echo delays, and echo drifts.

Buonocore and Gao[5] suggested retrieving the phase disparities by making use of regions in which the parent is not encumbered by ghosts, but identification of non-overlapped regions requires user intervention. In fact, fundamental to ghost removal is the identification of the phase disparities between the even and odd sampling points. Therefore, we estimate the phase difference directly and compensate for the odd lines.

Let us define the projection of the phase along k_y in the (x, k_y)

$$E_e(x) = \sum_{n(\text{even})} S(x, n\Delta k_y) \quad (5)$$

$$E_o(x) = \sum_{n(\text{odd})} S(x, n\Delta k_y) \quad (6)$$

as calculated over either the even or odd k_y lines, where x is the position in readout direction after the Fourier transform along k_x, k_y is the index of a sample point in phase-encoding direction, and $S(x, k_y)$ the signal value at location (x, k_y).

Suppose that $\theta_{\text{CORR}}(x)$ is the difference between odd and even echoes, then

$$\exp[i\theta_{\text{CORR}}(x)] = \frac{E_e(x)E_o^*(x)}{|E_e(x)E_o^*(x)|} \quad (7)$$

where * denotes the complex conjugate.

Several researchers have supposed that the phase variation between odd and even lines is approximately linear, but this approximation cannot significantly remove the ghost artifact. In this paper, we suppose $\theta_{\text{CORR}}(x)$ is a quadratic function along the readout direction, i. e.

$$\theta_{\text{CORR}}(x) \approx \theta_0 + \theta_1 x + \theta_2 x^2 \quad (8)$$

The parameters θ_0, θ_1 and θ_2 can be obtained by fitting $\exp[i\theta_{\text{CORR}}(x)]$ vs. the experimental data computed from Eq. (7). Multiplying odd lines by the phase factor $\theta_{\text{CORR}}(x)$ and performing a Fourier transform along the phase-encoding direction, a corrected image can be obtained.

2 Experiments and Results

The images were acquired on a 1.5T MR system (Siemens Sonata, Erlangen, Germany). A spin-echo EPI sequence was used to acquire 16 slices with the following parameters: repletion time is 5 s, echo time is 72 ms, slice thickness is 5 mm, matrix size is 128 × 128, and FOV is 24 cm. The raw data were transferred to a PC, and imported into Matlab (The Mathworks, Inc.).

There are two ways to measure the existence of a ghost image. The first method is to sum intensity of pixels outside the region of interest (ROI). The magnitude of the summation will be proportional to the worse of ghost images. The second method is to get the ratio of intensities of inside ROI and the intensities of outside ROI. This ratio provides an acceptable range of corrected images. In this paper, we use the percentage of ghosting to describe the amount of ghosting in a slice. It is defined as

$$\text{percentage of ghosting} = \frac{\text{sum of pixel values outside ROI}}{\text{sum of pixel value in ROI}} \times 100\% \quad (9)$$

The ROI is drawn around the parent image, manually or automatically. Tab. 1 shows the amount of ghosting before and after correction. Figs. 1 (a), (b), (c) and (d) are original images, Figs. 1(e), (f), (g) and (h) are corrected images using our method, Figs. 1(i), (j), (k) and (l) are corrected images using the method described in Ref. [12].

Tab. 1 Comparison of ghosting before and after correction using our method

Slice	Sum of pixel values within ROI		Sum of pixel values outside ROI		Percentage of ghosting	
	Before correction	After correction	Before correction	After correction	Before correction	After correction
1	17 987	18 551	5 389	2 187	30. 0	11. 8
4	36 830	37 686	8 615	3 218	23. 4	8. 5
13	33 884	34 654	8 145	3 140	24. 0	9. 1
16	13 125	13 484	4 547	1 240	34. 6	9. 2

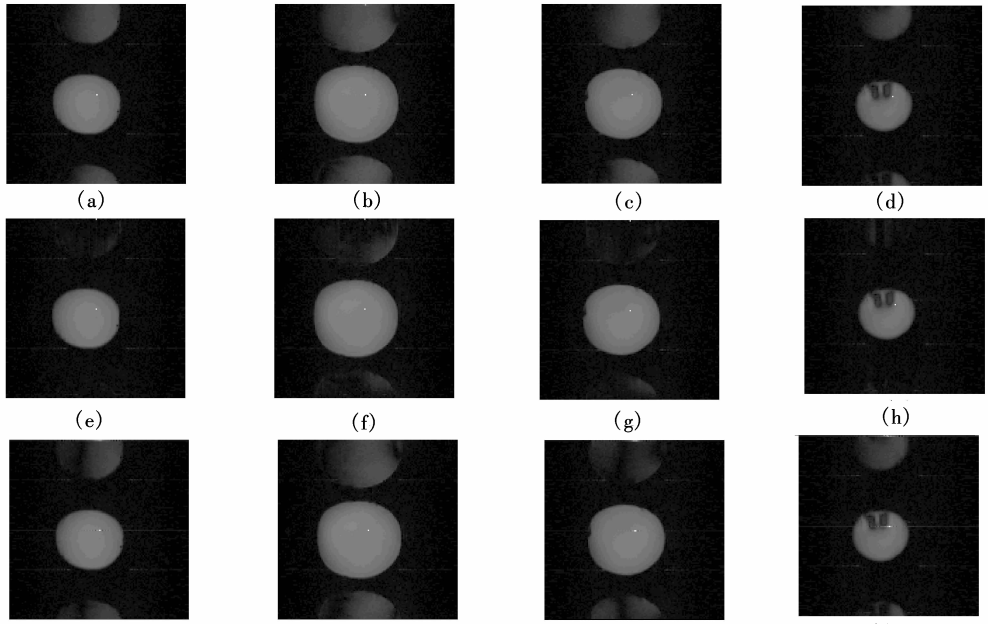

Fig. 1 Comparison of images. (a), (b), (c) and (d) are original images; (e), (f), (g) and (h) are corrected images using our method; (i), (j), (k) and (l) are corrected images using the method described in Ref. [12]

The experimental results demonstrate that our method gives a significant reduction in the ghost intensity in EPI. However, a still visible artifact 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 would become severe with increasing order in x of $\theta_{CORR}(x)$. It can be seen from Figs. 1(i) to (l) that the ghost artifacts were not removed because the phase disparity was not linear.

3 Discussion

The aim of this method is to correct for ghost artifacts that arise in EPI caused by a relative phase offsets between odd and even k-space echoes. The method is based on computing the projection of the even and odd lines along phase-encoding direction in hybrid space to estimate the phase difference between odd and even echoes. Linear and nonlinear difference can be corrected. It is shown that applying these corrections will reduce the ghost artifact evidently. The experimental result obtained shows our success. However, ghost artifacts cannot be removed completely due to higher order spatial components of the phase shift which were not included in our procedure or for other reasons. In fact, our method has some limitations. First, it is successful only if all lines share the same phase correction (and similarly for even lines). Secondly, we suppose that the phase difference between odd and even lines is related to x. Relaxing these constraints means that the method cannot always work well.

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基于混合空间投影的平面回波成像中 ghost 伪影校正

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摘要:为了消除在磁共振成像过程中奇、偶回波之间的相位移动产生的 ghost 伪影,提出了基于混合空间投影的方法. 首先运用混合空间沿相位方向的投影来计算奇、偶回波的相位差,然后对相位差进行非线性拟合并对奇偶回波的相位进行恢复,最后沿相位编码方向作傅立叶逆变换得到校正图像. 实验结果表明运用该方法线性和非线性相位差均可以被校正,可以明显降低 ghost 伪影的强度. 实验结果证明了算法消除 ghost 伪影的有效性.

关键词:平面回波成像;ghost 伪影;磁共振成像;相位投影

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