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Single-shot compensation of image distortions and BOLD contrast optimization using multi-echo EPI for real-time fMRI

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Functional magnetic resonance imaging (fMRI) is most commonly based on echo-planar imaging (EPI). With higher field strengths, gradient performance, and computational power, real-time fMRI has become feasible; that is, brain activation can be monitored during the ongoing scan. However, EPI suffers from geometric distortions due to inhomogeneities of the magnetic field, especially close to air–tissue interfaces. Thus, functional activations might be mislocalized and assigned to the wrong anatomical structures. Several techniques have been reported which reduce geometric distortions, for example, mapping of the static magnetic field B_0 or the point spread function for all voxels. Yet these techniques require additional reference scans and in some cases extensive computational time. Moreover, only static field inhomogeneities can be corrected, because the correction is based on a static reference scan. We present an approach which allows for simultaneous acquisition and distortion correction of a functional image without a reference scan. The technique is based on a modified multi-echo EPI data acquisition scheme using a phase-encoding (PE) gradient with alternating polarity. The images exhibit opposite distortions due to the inverted PE gradient. After adjusting the contrast of the images acquired at different echo times, this information is used for the distortion correction. We present the theory, implementation, and applications of this single-shot distortion correction. Significant reduction in geometric distortion is shown both for phantom images and human fMRI data. Moreover, sensitivity to the blood oxygen level-dependent (BOLD) effect is increased by weighted summation of the undistorted images.

Keywords: Distortion correction; Echo-planar imaging; EPI; Functional magnetic resonance imaging, fMRI; Real-time; Single-shot; BOLD; Sensitivity; Multi-echo; Multi-image

Introduction

Echo-planar imaging (EPI) is widely used for functional magnetic resonance imaging (fMRI) of the human brain. This single-shot imaging technique offers a high temporal resolution and is relatively insensitive to motion and physiological artifacts, because a single slice is encoded in under 100 ms. It even allows for imaging of human brain function in real time (e.g., Posse et al., 2001) and neurofeedback of fMRI signals (deCharms et al., 2004; Posse et al., 2003a; Weiskopf et al., 2003, 2004; Yoo and Jolesz, 2002). In addition to fast data acquisition and processing, real-time fMRI applications such as functional localizers (Goodyear et al., 1997; Weiskopf et al., 2004) or neurofeedback demand high image quality and superior functional contrast-to-noise ratio (CNR) in order to increase sensitivity to brain activations. Single-shot multi-echo EPI (also referred to as single-shot multi-image EPI) acquires additional images as compared to conventional EPI and increases CNR (Posse et al., 1999; Speck and Hennig, 1998). Moreover, this technique can be implemented for real-time fMRI (Posse et al., 1999, 2001).

Both conventional EPI and multi-echo EPI suffer from geometric distortions, if there are local differences in the resonance frequency. Distortions are most prominent along the phase-encoding (PE) direction, because it is encoded with a low effective spectral bandwidth. Distortions along other directions might occur as well but are much smaller and were disregarded in this study (Morgan et al., 2004; Munger et al., 2000). The differences in the resonance frequency, that is, frequency offsets, might result from imperfections in the magnetic field gradients used for imaging, for example, those caused by eddy currents, and gradients in the concomitant fields (Jezzard and Clare, 1999). More importantly, frequency offsets are caused by inhomogeneities of the static magnetic field which are mainly due to differences in the magnetic susceptibilities of the imaged object, for example, different susceptibility of air, bone, and brain tissue (Jezzard and Clare, 1999). Frequency offsets caused by susceptibility differences increase with the strength of the static magnetic field of the magnetic resonance (MR) scanner. Therefore,

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geometric distortions are more prominent at high-field systems (≥3 T), using the same readout as at low fields. These systems, however, provide an improved signal-to-noise ratio (SNR) and increased sensitivity to the blood oxygen level-dependent (BOLD) effect used in fMRI (Krasnow et al., 2003). Thus, they are used more and more frequently.

Since the localization of brain activity is based on EPI data in fMRI experiments, geometric distortions lead to mislocalizations and make it difficult to assign activations to their respective anatomical location (Studholme et al., 2000). Even worse, effects such as respiration (Glover et al., 2000) and head motion (Jezzard and Clare, 1999; Ward et al., 2002) may cause dynamic changes in this mislocalization during the experiment.

We aimed at the development of a real-time distortion correction which accounts for dynamic changes in the distortions. Ideally, such a distortion correction technique should be fast and robust, and it should retain or even increase BOLD CNR. Optimization of the technical CNR is crucial for fMRI, since it is the chief determinant of sensitivity to functional activations and the statistical power of the procedure.

Besides advanced shimming techniques which improve *global* field homogeneity (Morrell and Spielman, 1997; Ward et al., 2002), several techniques to suppress *local* distortions in EPI have been reported. In general, these standard approaches require an additional reference scan, for example, anatomical scans for image-based methods (Kybic et al., 2000; Studholme et al., 2000), field maps (Jezzard and Balaban, 1995) or point spread function (PSF) maps (Zaitsev et al., 2004; Zeng and Constable, 2002). Additional scan time demands range from seconds in EPI-based field map approaches (Hutton et al., 2002; Reber et al., 1998) to several minutes in multi-echo reference acquisitions (Chen and Wyrwicz, 2001) or PSF mapping (Zeng and Constable, 2002) procedures. Moreover, computational time for the distortion correction can exceed several minutes for field mapping procedures or at least half an hour for some image-based approaches (Andersson et al., 2001; Studholme et al., 2000). The increase in acquisition and computational time makes it difficult or impossible to use the techniques for real-time applications.

Here, we present a technique which corrects distortions along the PE direction in a single shot. It combines multi-echo EPI data acquisition with alternating PE gradients. This allows for simultaneous acquisition and distortion correction of the images. No additional reference scans are required and computation is efficient. We discuss the theory, implementation, and applications of this single-shot distortion correction. The reduction in geometric distortions is assessed in phantom MRI and human fMRI. Effects on SNR and BOLD sensitivity in fMRI are investigated.

Theory and procedure

Theoretical background

The presented undistortion technique combines the distortion correction method using PE gradients with alternating polarity (Bowtell et al., 1994; Chang and Fitzpatrick, 1992; Morgan et al., 2004) with a single-shot multi-echo EPI acquisition scheme (Mathiak et al., 2002).

The multi-echo EPI sequence acquires three images at successive echo times with alternating polarity of the PE gradient blips (see PE gradient G_{PE} in Fig. 1a). Hence, the second image will exhibit distortions of opposite direction but equal magnitude as compared to the first and third images (see *original images* in Fig. 1b; Bowtell et al., 1994; Chang and Fitzpatrick, 1992; Morgan et al., 2004). Therefore, we consider the first and second images only, and the results for the first image apply to the third image as well. Depending on the polarity of the PE gradient blip (G_{PE}), an object at the position x with field offset ΔB will be projected to the positions x_1 and x_2 in the first and second images, respectively:

$$x_1 = F_1(x) = x + \delta x, \tag{1}$$

$$x_2 = F_2(x) = x - \delta x \tag{2}$$

with

$$\delta x = \frac{\Delta B \Delta t}{\int_{t_0}^{t_0+\Delta t} G_{\mathrm{PE}}(t)dt} \tag{3}$$

and Δt being the echo spacing within the EPI readout echo train and t_0 being the beginning of the first PE gradient blip. If the correspondence of the positions x_1 and x_2 is known, it is straightforward to determine the local shift δx and the true position x of the object. Thus, calculation of this relationship for each x_1 and x_2 determines the undistortion transformations F_1^{-1} and F_2^{-1}. Moreover, distortions modify image intensities. The true intensity ρ is estimated from the two image intensities ρ_1 and ρ_2 of the two images using the Jacobian of the transformation:

$$\rho(x) = \rho_1(x_1)\frac{dx_1}{dx} = \rho_2(x_2)\frac{dx_2}{dx}. \tag{4}$$

Chang and Fitzpatrick (1992) have shown that F_1 and F_2 are monotonic functions, if the gradient in the field inhomogeneity is smaller than the applied effective gradient, that is, for distortions in the PE direction:

$$\left|\frac{d(\Delta B)}{dx}\right| < \left|\int_{t_0}^{t_0+\Delta t} G_{\mathrm{PE}}(t)dt\right| \Big/ \Delta t \tag{5}$$

In the present study, the effective gradient amplitude in the PE direction was about 270 μT/m. Based on previous studies, maximal gradients in field inhomogeneities may be expected to be of a comparable size at 3 T (compare Deichmann et al., 2003) but restricted to rather small brain areas.

Assuming monotonicity of F_1 and F_2, the correspondence between x_1 and x_2 can be found by integrating the signal intensities of the two images ρ_1, ρ_2 along the PE direction:

$$\int_{-\infty}^{x_1=F_1(x)} \rho_1(F_1(\xi))d\xi = \int_{-\infty}^{x_2=F_2(x)} \rho_2(F_2(\xi))d\xi. \tag{6}$$

This derivation holds true for images acquired with the same parameters except for the polarity of the PE gradient. For instance, it could be applied to sequential acquisitions of EPI (Bowtell et al., 1994; Morgan et al., 2004). In multi-echo EPI, images are acquired in a single-shot at different echo times and exhibit different contrasts. Therefore, the signal intensity of the images should be adjusted. To that end, a virtual image is constructed with the same distortions as the first and third images and contrast properties similar to the second image acquired at TE_2.

Assuming a mono-exponential decay of the MR signal across the three images, the intensity $\bar{\mathrm{I}}_2$ of the virtual image can be