EPI Distortion Correction with ORACLE

Wei Lin1, Feng Huang2, Enrico Simonotto1, and Randy Duensing3
1In vivo Corporation, Philips Healthcare, Gainesville, Florida, United States

Introduction

Echo-planar imaging (EPI) is the gold-standard acquisition method in important applications such as functional MRI [1] and diffusion imaging [2], due to its capability to traverse k-space rapidly. A major hindrance to wider applicability of the EPI technique, however, is image distortion due to main field ($B_0$) inhomogeneity. During an EPI acquisition window (up to tens of milliseconds), each voxel accumulates an additional $B_0$-induced linear phase term along the phase-encode direction, which translates into a spatial-dependent shift up to tens of pixels. Existing methods for EPI distortion correction involves estimation of either a field map or a distortion map in the image domain [3-5], which is error-prone at pixel locations with low signal intensities [6]. In this work, an off-resonance artifacts correction technique with convolution in k-space (ORACLE) is proposed for EPI distortion correction. In ORACLE, both the field map estimation and the actual correction are performed directly in the k-space. In vivo results demonstrated that ORACLE achieves excellent EPI distortion correction in diffusion-weighted imaging (DWI).

Theory

In EPI, the phase-encode value $k$ has a linear relationship with the acquisition time $t$:

$$k = t / \alpha, \quad \alpha = T_{\text{aq}} / 2k_{\text{max}}.$$  

In the presence of $B_0$ inhomogeneity $\Delta \omega(r)$, the acquired EPI signal is

$$f(k) = \int \rho(r) \exp\{-i k \cdot [r + \alpha \Delta \omega(r)]\} \, dr.$$  

Let’s define a $B_0$-induced EPI distortion map $R = r + \alpha \Delta \omega(r) = r + \alpha \Delta \omega(t)$.

Assuming that the distortion map varies slowly across the space, then $dr = dR$. The acquired k-space signal corresponds to a distorted image $\rho'(R)$:

$$f(k) = \int \rho'(R) \exp(-i k \cdot R) \, dR.$$  

Since a multiplication in the image-space is equivalent to a convolution in the k-space, a phase-encode line $k_j$ acquired at time $t_j$ can be corrected by applying a convolution kernel $K_j$, which is the Fourier Transform of an off-resonance phase correcting term:

$$K_j = FT\{\exp[i \Delta \omega(R) \Delta t]\}; \quad \tilde{f}_j(k) = \tilde{f}(k) \otimes K_j,$$

where $\tilde{f}(k) = \int \rho(r) \exp(-i k \cdot r) \, dr$ [1].

The $B_0$ map $\Delta \omega(r)$ is determined by data fitting in k-space using two EPI datasets $f_1$ and $f_2$ acquired at slightly different echo time $t$ and $t+\Delta t$, similar to the calibration procedure of a k-space-based parallel imaging methods such as GRAPPA:

$$f_j(k) = f_j(k) \otimes K_0; \quad K_0 = FT\{\exp[i \Delta \omega(r) \Delta t]\},$$  

$$\Delta \omega = \arg[FT^{-1}(K_0)] / \Delta t$$  

[2]

Methods

The procedure to apply ORACLE to EPI datasets is shown in Fig. 1. A basis convolution kernel $K_0$ is first determined by fitting two EPI data sets with slightly different echo time (Fig. 1a). The $B_0$ map is then computed according to Eqn. [2]. To apply the ORACLE correction, different convolution kernels are applied for different phase-encode lines (Fig. 1b).

Single-shot DWI EPI images were acquired from a healthy volunteer on a 3.0T clinical scanner (Achieva, Philips, Best, Netherlands). Scan parameters: FOV 230×230 mm, slice thickness 5mm, TR/TE = 2250/100 ms, b = 0 and 1000 s/mm². For the calibration of ORACLE kernels, a separate b = 0 dataset was acquired with an echo time shift of 0.5 ms. A distortion-free reference image was also acquired using a turbo spin-echo (TSE) sequence with similar parameters except following modifications: 7 shots, each shot with 16 echoes. The ORACLE basis kernel size was 8 × 8.

Results and Discussions

Figure 2 shows ORACLE correction results from the in vivo DWI experiment. The $B_0$ map (Fig. 2c) shows a strong off-resonance shift of ~200Hz at the frontal lobe of the brain. For two EPI datasets without and with diffusion weighting, the same set of ORACLE correction kernels compensates for both geometric distortion and the global image shift, resulting in an excellent correspondence of the boundary of brain tissues between the EPI and the reference TSE image (Fig. 2e). The computation time for ORACLE is about 5 seconds for each slice.

In conclusion, ORACLE is a robust EPI distortion correction method that avoids direct field map estimation in the image domain. The other advantage for ORACLE is that the same set of convolution kernels can be applied to images acquired with the same sequence but different contrasts, as long as they share the same $B_0$ map.

References