EPI Distortion Correction with ORACLE

Wei Lin[1], Feng Huang[1], Enrico Simonotto[1], and Randy Duensing[1]
[1] *Invivo 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 capacity 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:

$$k = t/\alpha, \qquad \alpha = T_{acq}/2k_{\max}.$$

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

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

Let's define a B_0-induced EPI distortion map $R = r + \alpha\Delta\omega(r) = r + \alpha\Delta\omega'(R)$. Assuming that the distortion map varies slowly across the space, then $dr \approx dR$. The acquired k-space signal corresponds to a distorted image ρ':

$$f(k) = \int \rho'(R)\exp(-ikR)dR, \qquad \rho'(R) = \rho(r) = \rho[R - \alpha\Delta\omega'(R)]$$

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:

$$K_j = FT\{\exp[i\Delta\omega'(R)t_j]\},$$

$$\hat{f}_0(k_j) = [f(k)\otimes K_j]\big|_{k=k_j} = \int \rho(r)\exp(-ik_j r)dr \qquad [1]$$

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 in a k-space-based parallel imaging methods such as GRAPPA:

$$f_2(k) = f_1(k)\otimes K_0, \qquad K_0 = FT\{\exp[i\Delta\omega(r)\Delta t]\}$$

$$\Delta\omega = \arg[FT^{-1}(K_0)]/\Delta t \qquad [2]$$

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/mm^2. 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.

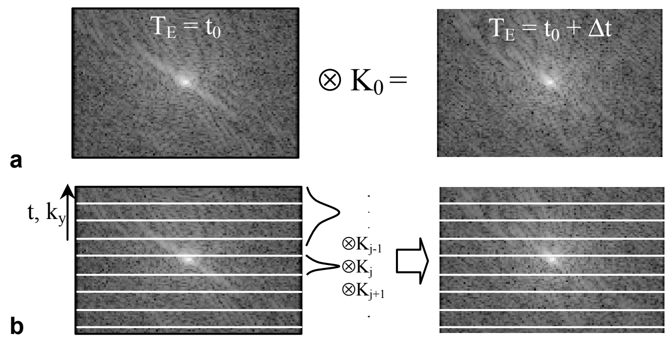

Figure 1 EPI distortion correction with ORACLE. **(a)** The B_0 map is computed from the inverse FT of a basis kernel K_0, which is determined from a data fitting process using two EPI datasets with slightly different echo times. **(b)** EPI distortion is corrected directly in the k-space by applying different convolution kernels for different phase-encode lines.

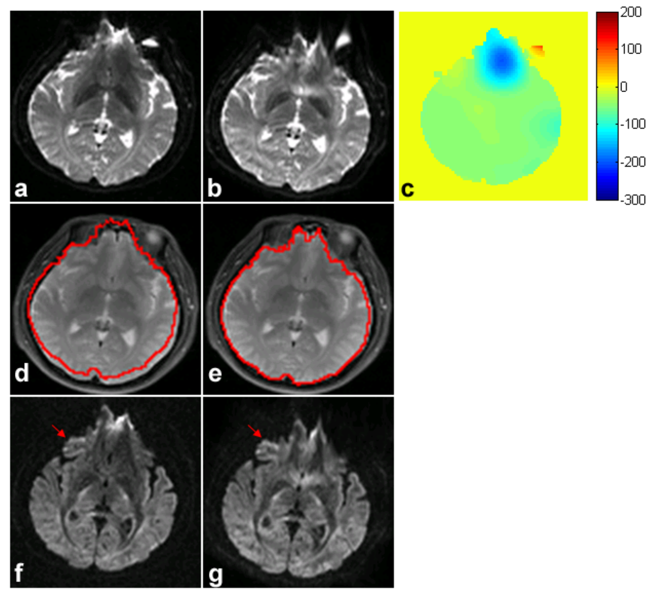

Figure 2 ORACLE correction results for DWI. **(a) - (b)** EPI images without diffusion weighting before (a) and (b) after ORACLE correction. **(c)** The B_0 map (in Hz) computed from the calibration of basis kernel. **(d) - (e)** The boundary of brain tissue of (a) and (b) overlaid over a reference TSE image. **(f) - (g)** DWI EPI images (b= 1000 s/mm^2) before and after ORACLE correction. The arrow indicates a region where distortion is particularly severe.

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

[1] Hennig J et al. *J Magn Reson Imag* 2003;18: 1-15.
[2] Le Bihan D et al. *J Magn Reson Imag* 2006;24: 478-488.
[3] Reber P, et al. *Magn Reson Med* 1998;39:328-330.
[4] Xiang QS et al. *Magn Reson Med* 2007;57:731-741.
[5] Holland D, et al. *NeuroImage* 2010;50:175-183.
[6] Funai A, et al. *IEEE Trans Med Imaging*; 2008;27:1484-1494.