Single-shot Measurement and Correction of EPI Distortion Using an Oscillatory Magnetisation Pattern and Fourier-based Image Processing

A. N. Priest[1,2], E. De Vita[3], R. Ordidge[3]

[1]Department of Radiology, Universitätskrankenhaus Hamburg-Eppendorf, Hamburg, Germany, [2]Department of Medical Physics, UCL Hospitals NHS Trust, London, United Kingdom, [3]Wellcome High Field MR Laboratory, Department of Medical Physics, University College London, London, United Kingdom

Introduction

Echo-planar imaging (EPI) suffers from distortion, especially at high fields, as a result of off-resonance effects due to susceptibility gradients. Most distortion-correction methods [1–3] are based on reference data e.g. a field map, which is acquired in a separate acquisition, possibly several minutes before or after the image to be corrected in a time-course study. At high fields, the distortion field in the head can change significantly with subject position, with even very small head rotations giving frequency changes »10 Hz [4] and thus distortion changes ~1 pixel. Subject motion therefore creates a problem for the accurate distortion correction, since even after rigid-body registrations, the current distortion field may not be represented adequately by the previously measured field map. These problems are substantially worse in other body organs where physiological motion is greater, so that single-shot EPI is rarely used for non-brain applications.

We discuss an alternative which captures distortion information in the acquired image by applying a modulation pattern similar to that used in myocardial tagging. There is no time-delay between acquisition of the distortion information and the acquired image since both are acquired together, therefore distortion correction can be performed without these problems. Using the TRAIL method [5] two such images with complementary oscillations are acquired, in rapid succession, in a single shot, then combined to give a single distortion-free image without the oscillation pattern. A robust, automated distortion-correction algorithm is needed to allow rapid analysis of time-series data—the algorithm presented here uses a localised Fourier Transform (FT) to determine the local oscillation period.

Theory

The TRAIL pulse sequence [5] acquires pairs of images, both with the same contrast behaviour and modulated by sinusoidal oscillations that appear as stripes along the phase-encode (PE) direction; these images are complementary in that the stripes in one image occur halfway between the stripes on the other. In conventional TRAIL imaging, where there is no distortion, the stripes appear straight and the two image datasets can be combined to give a uniform image by interleaving half-resolution images in the spatial domain [5]. When EPI readouts are used, the stripes remain physically straight with respect to the subject, but appear distorted in the EPI images [6].

The modulated images contain the information needed to measure and correct the EPI distortion. There are two approaches to this. In the first method, each readout may be used to reconstruct two low-resolution images with different echo times: their phase difference represents a field map, corresponding to the local distortion field [6]. However this method needs a reliable way to unwrap aliasing in the phase map. A second method involves image analysis to measure the distorted positions of the stripes by local non-linear fitting and compare it with the known real stripe positions. This method is computationally demanding and provides a less localised measurement of distortion; also it requires reliable starting values to fit the complex data. We propose combing these two approaches to give a robust, localised distortion measurement without (un)wrapping problems. A localised Fourier analysis is used to determine the oscillation period from the images, avoiding iterative processing and the need to determine starting values.

In the 'image processing' analysis, the sinusoidal oscillations in images I_1 and I_2 can be described by a 'phase' $\phi(\mathbf{r})$, as

$$I_1(\mathbf{r}) = M_0(\mathbf{r})\cdot\sin\phi(\mathbf{r}); \qquad I_2(\mathbf{r}) = M_0(\mathbf{r})\cdot\cos\phi(\mathbf{r}).$$

Note that ϕ is not the same as the phase of the complex data. In the absence of distortion, $\phi(\mathbf{r})$ is a linear function of position along the *pe* direction and is defined by a wavevector $\mathbf{k}_0$ with magnitude $\pi/2d$, where d is the PE-direction pixel size:

$$\phi_0(\mathbf{r}) = \mathbf{k}_0\cdot\mathbf{r}.$$

Susceptibility-induced displacements cause local changes in $\phi(\mathbf{r})$, with the displacement given by $2d(\phi_0(\mathbf{r})-\phi(\mathbf{r}))/\pi$. Distortions change the local oscillation period and thus the wavevector $\mathbf{k}$. Determining the local oscillation period provides a good way to avoid uncertainties over 'wrapping' in the phase function. To achieve this, a masking function $g(\mathbf{r})$ (e.g. a Gaussian) is used to select the local image region, then a FT determines the local period (and phase) of the oscillation. If FT $[g(\mathbf{r})] \equiv G(\mathbf{k}')$, then assuming the wavevector to be locally constant, this gives a convolution, leading to two separate copies of $G(\mathbf{k}')$:

$$\mathrm{FT}\,[g(\mathbf{r})\cos(\mathbf{k}\cdot\mathbf{r})] = G(\mathbf{k}) \otimes (\delta(\mathbf{k}-\mathbf{k}') + \delta(\mathbf{k}+\mathbf{k}')) = G(\mathbf{k}-\mathbf{k}') + G(\mathbf{k}+\mathbf{k}')$$

Since $G(\mathbf{k}')$ has a well-defined peak, the separation of the resulting two peaks represents the local oscillation period, and hence also the local distortion. This is equivalent to the gradient of a (phase-difference) field map, and so can be used to unwrap the phase information. The shape and width of $g(\mathbf{r})$ control the accuracy and localisation of this measurement. Thus this localised FT provides detailed information on the image distortion. This process is repeated for different mask positions covering the whole image.

The local phase difference is calculated [6] and unwrapped, using the locally determined oscillation period as a predictor of the phase gradient, avoiding ambiguities where phase wrapping occurs. This unwrapped phase map corresponds to a distortion map, allowing distortion to be corrected using linear interpolation [1].

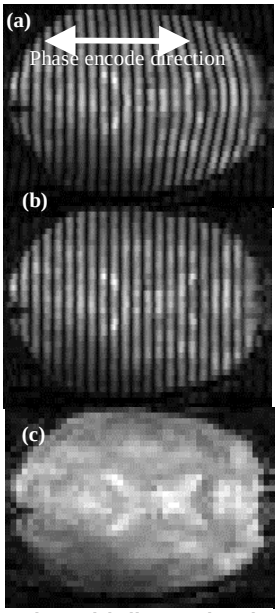

Fig. 1: (a) distorted and (b) corrected images, reconstructed to 256×64 to aid stripe visualisation. (c) Final TRAIL image.

Methods

A TRAIL-EPI sequence was implemented (as in [5,6]) on a 4.7T spectrometer (SMIS MR5000 provided by Philips). Parameters were $TE_{1/2}$ = 10.6/23.4 ms, TR = 1s, FOV = 24 cm, slice thickness 5 mm, 5 slices; during each of the two readouts (acquisition bandwidth 250kHz) 100×64 points were collected (sinusoidal readout gradients) and then interpolated to 64×64; each readout thus lasted 25.6 ms. Healthy subjects were scanned after informed consent. TRAIL-EPI images were corrected for RF inhomogeneity effects and for ghosting [7]. The distortion was measured and corrected as described above, using a gaussian g(r) of width 3 pixels.

Results

Figs. 1(a) and (b) show a modulated EPI image before and after distortion correction. The stripes become straight after the distortion correction, demonstrating its validity. Fig. 1(c) shows the corresponding final image generated by the TRAIL reconstruction (TE=10.4 ms). This method has been applied to automatically correct multi-slice and time-series data (data not shown).

Discussion and Conclusions

The proposed method allows a robust single-shot correction of EPI images, and is suitable for individually distortion correction of a series of images from a time-course study, following which only rigid-body motion correction is needed to compensate for the effects of motion. This method could allow application of EPI to abdominal or cardiac imaging, where distortions can be severe and conventional correction methods do not work because of the rapid physiological motion. The distortion measurement and correction method can readily be extended to any number of dimensions, and may also benefit from the use of wavelet-based methods.

References

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