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A hybrid strategy for correcting geometric distortion in echo-planar images

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ABSTRACT

A hybrid strategy for geometric distortion correction of echo-planar images is demonstrated. This procedure utilizes standard field mapping for signal displacement correction and the so-called reverse gradient acquisition for signal intensity correction. (The term reverse gradient refers to an acquisition of two sets of echo-planar images with phase encoding gradients of opposite polarity.) The hybrid strategy is applied to human brain echo-planar images acquired with and without diffusion-weighting. A comparison of the hybrid distortion corrected images to those corrected with standard field mapping only demonstrates much better performance of the hybrid method. A variant of the hybrid method is also demonstrated which requires the acquisition of only one pair of opposite polarity images within a set of images.

1. Introduction

Geometric distortion is a well-known problem in echo-planar imaging (EPI). Spatial variation of the static magnetic field causes both displacement along the phase encoding direction and intensity alteration of voxel signals. The influence on signal intensity comes about because voxels are either “compressed” or “stretched” due to the local magnetic field variation. Various methods of correcting images for this distortion have been proposed.

The standard field mapping method [1] is, perhaps, the most common method of distortion correction. This involves the creation of magnetic field/frequency maps from changes in signal phase between at least two images acquired with different gradient echo times. Signal intensity correction is based on determining the spatial rate of change of frequency at a given voxel position along the phase encode direction, typically considering nearest neighboring voxels [1]. The additional time for phase mapping with gradient echo imaging is often small compared to the total protocol time especially if, for example, a set of diffusion-weighted (DW) images is acquired. An important strength of this method is that it is relatively straight forward to apply. However, its performance may be inadequate in regions where the spatial rate of change of the magnetic field is rapid and near object edges [2,3]. One might expect that correction of the signal intensity is the most serious concern for performance because it involves calculating a local spatial rate of change of frequency (i.e., a spatial first derivative).

The so-called reverse gradient methods [4–7] of distortion correction have been reported to provide better performance than the field mapping method [2,6]. These methods require the acquisition of two sets of echo-planar images with phase encoding gradients of opposite polarity. A few different post processing techniques have been developed to provide a distortion corrected image from these acquired images. One post-processing strategy [4,5] involves a procedure in which the displacement for each voxel is determined by integrating the signal from a common anatomical feature (e.g., an edge) in each of the two acquired images. This requires recognition of such features either manually or via additional processing. However, after the displacement values are determined a simple formula is applied for intensity correction [4,5]. A more recent reverse gradient post-processing method [6] involves the determination of the displacement (and intensity correction) for each voxel via a non-linear optimization process. This procedure [6] applied to one image pair in a set of echo-planar images (e.g., $b = 0$ image pair in a DW image set) provides a distortion field that can be applied to remaining images in the set (e.g., other b values) acquired with only one polarity. However, this non-linear optimization procedure is somewhat complex involving the simultaneous optimization of all voxel positions along the phase encode direction and includes empirically determined regularization terms. Initially the optimization is performed on spatially filtered images followed by its application to images with progressively less filtering and ultimately to the images with the acquired resolution.

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Here we report on a “hybrid” distortion correction strategy which combines field mapping with the reverse gradient acquisition. Like the field mapping method this hybrid strategy is straightforward to apply, but shows greatly improved performance for intensity correction compared to the field mapping method. The approach requires a field map to determine voxel displacement corrections which are applied to a pair of echo planar images. These displacement corrected images are then combined with the simple formula previously determined [4] to correct signal intensity. In this report, the performance of this hybrid strategy applied to brain imaging, with and without diffusion-weighting, is compared to that of the standard field mapping method alone, which we refer to here as the field mapping only method. A variant of the hybrid method is also demonstrated which requires (as in ref. [6]) the acquisition of only one pair of opposite polarity images (e.g., b = 0 images of DW imaging set).

2. Background equations

In echo planar imaging, spatial variation of the static magnetic field leads to both signal displacement along the phase encoding direction and signal intensity alteration. The displacement at position $\underline{r}$ is given by: $\Delta y(\underline{r}) = f_{in}(\underline{r})/(BW_y)$, where $\Delta y(\underline{r})$ is the displacement divided by the pixel width, $f_{in}(\underline{r})$ is the frequency offset at the (correct) position of the signal due to the magnetic field variation (inhomogeneity) and BW_y is the imaging bandwidth per pixel along the phase encoding direction. This bandwidth is given by $BW_y = 1/(N_\text{p} \times \text{echo spacing})$, where N_p is the matrix size along the phase encoding direction. The signal intensity in the acquired image ($I(\underline{r})$) is altered from its true intensity ($I_\text{true}(\underline{r})$) due to local stretching or compression. This alteration can be expressed as [1],

$$I_\text{true}(\underline{r}) = I(\underline{r}) \times (1 \pm R(\underline{r})), \tag{1}$$

where $R = \Delta f_{in}(\underline{r})/(BW_y)$, and $\Delta f_{in}(\underline{r})$ is the difference in f_{in} across one voxel centered at true position $\underline{r}$. The + or – in Eq. (1) depends on the direction of the phase encoding gradient. Suppose that two echo-planar images with phase encoding gradients of opposite polarity are acquired and denoted by $I_+(\underline{r})$ and $I_-(\underline{r})$. They will each be related to $I_\text{true}(\underline{r})$ as in Eq. (1), but with opposite sign (e.g., $I_\text{true}(\underline{r}) = I_+(\underline{r}) \times (1 + R(\underline{r}))$). Given these two equations, it can be shown that [4,5]

$$I_\text{true}(\underline{r}) = \frac{2I_+(\underline{r}) \times I_-(\underline{r})}{I_+(\underline{r}) + I_-(\underline{r})}, \tag{2}$$

3. Methods

3.1. Acquisition

MRI was performed using a 3 T system (Biograph mMR; Siemens Medical Systems, Erlangen, Germany) and a 16 element head/neck coil. Human images were acquired under the approval of our institutional research ethics board, and written informed consent was obtained. Transverse slices were positioned within the brain such that the lowest slice was immediately superior to the nasal cavity. All image sets had 10 slices of 4 mm thickness, 2 mm gap, 128 × 128 matrix and 250 mm × 250 mm FOV.

Field mapping was performed using a gradient echo (GE) acquisition with 12 echo times set to have water and fat in-phase (multiples of 2.46 ms). Other GE parameters included TR = 350 ms, tip-angle = 45°, bandwidth/pixel = 1953 Hz/pixel and acquisition time = 46 s.

Four sets of DW images were acquired using single shot EPI with an echo spacing of 0.75 ms, TE = 85 ms, TR = 4000 ms, bandwidth/pixel = 1502 Hz/pixel, 6/8 partial Fourier and SPAIR fat suppression. Each DW image set refers to the acquisition of 10 slices with three b-values (0, 400, 800 s/mm^2) and three directions. As indicated in Table 1, the four DW image sets (DW1AP, DW1PA, DW2AP, DW2PA) differed only in the number of signal averages and the direction of the phase encoding gradient (anterior to posterior (AP) or posterior to anterior (PA)). The acquisition time for the DW image sets with 4 signal averages was 1 min 56 s. Three scan diffusion trace-weighted images [8,9] were obtained from the scanner for post processing. Conventional spin-echo images were also acquired for anatomical reference (TE/TI/TR = 85/220/2000 ms, 6/8 partial Fourier, total acquisition time = 3 min 16 s).

3.2. Image processing

Distortion correction was performed using two strategies referred to here as (1) field mapping only distortion correction and (2) hybrid distortion correction. As indicated in Table 1, both strategies utilized the same method of signal displacement correction (based on a field map), but differed in the method of signal intensity correction as described in more detail below. Field mapping only distortion correction was applied to each of DW image sets DW1AP and DW1PA. Hybrid distortion correction involved combining DW image sets DW2AP and DW2PA (total of 8 signal averages after combination). All image post-processing was performed using Matlab version 2013a (The MathWorks, Inc., MathWorks, Natick, MA).

Correction of signal displacement was performed as follows: signal phase values were unwrapped, voxel-by-voxel, along the time (TE) dimension and then fit to a linear function of time to determine the frequency. Linear fits were weighted by the signal magnitudes. Frequency maps were divided by the bandwidth per pixel and then applied to all acquired echo planar images to correct the signal displacement. (Echo planar images were interpolated by a factor of 17 along the phase encoding direction to allow for shifts having a non integer number of voxels.)

Signal intensity correction was performed after signal displacement correction. For the hybrid strategy Eq. (2) was applied for intensity correction, where $I_+(\underline{r})$ and $I_-(\underline{r})$ correspond to the image sets DW2AP and DW2PA (Table 1). For the phase mapping only strategy, intensity correction was applied as previously described [1]. Briefly, maps of quantity $R(\underline{r})$ [see Eq. (1)] were created from the frequency maps using local three point linear fits involving each pixel and its nearest neighbors along the phase encoding direction (i.e., to determine the local rate of change of f_{in} per pixel). Following

Table 1
Direction of the phase encoding gradients, number of signal averages and image processing schemes for the four DW image sets acquired.

DW image set	Direction of phase encoding gradient	Number of signal averages	Signal displacement correction using	Signal intensity correction using	Overall distortion correction method
DW1AP	AP	8	Field map	Field map	Field mapping only
DW1PA	PA	8	Field map	Field map	Field mapping only
DW2AP	AP	4	Field map	Combine AP and PA	Hybrid correction
DW2PA	PA	4	Field map		