Correction of Spatial and Intensity Distortions in Functional Magnetic Resonance Imaging

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Introduction

Images acquired using echo planar imaging (EPI) are prone to local field inhomogeneities, induced for example by local magnetic susceptibility variations, which distort the image in the phase encode direction[1]. Generally, images appear stretched in one and compressed in the other direction (Fig. 1a). Alterations in signal intensity occur as well. In functional imaging, these phenomena affect activation maps, since distorted voxels cannot be directly compared with voxels which are less affected, and problems with alignment to anatomical images arise. We propose a solution to these problems by applying the reversed gradient method for the correction of field inhomogeneity induced distortions to functional imaging and present a sequence that does not elongate scan time. We found that most in-plane voxel displacements, e.g. near air-tissue boundaries in the skull, could be corrected, yielding a good match with anatomical images. Additionally, voxel intensities reflected the tissue properties (and thus the BOLD signal) better, yielding increased activation significances. The latter point was confirmed in particular for functional imaging in the cerebellum.

Theory

In the reversed gradient method[2,3], two images with the phase encode gradient in opposite direction are acquired. In the first image, for each point on the frequency encode axis, x_0, magnetic field induced displacements $\Delta y(x_0) = \Delta B(y(x_0))/|G_y|$ show up mainly in the phase encode direction (along y), and in the second image along $-y$, where $\Delta B(y(x_0))$ is the magnetic field inhomogeneity and G_y is the gradient in y direction. For each x_0, this procedure yields one image with intensity $I_-(y_-)$ with voxels at position $y_- = y-\Delta y$ (Fig 1a), and another image with intensity $I_+(y_+)$ with voxels at position $y_+ = y+\Delta y$ (Fig. 1b). These displacements are corrected by the following principle[4,5]: For each value of x_0, one defines isopoints, y_+ and y_-, which have the same value on the two image cumulative distribution functions (which are the image intensity integrals from zero to y, for fixed x_0). Two isopoints correspond to the same Δy. Each isopoint of I_+ refers to the would-be position in I_-, and vice versa. The two images are then merged by shifting voxels to $y = (y_+ + y_-)/2$ (*). Intensity distortions arise as a consequence of spatial distortions and can be corrected in the following way: From the cumulative distribution function $\int_0^{y} I(y)\,dy = \int_0^{y_-} I_-(y_-)\,dy_- = \int_0^{y_+} I_+(y_+)\,dy_+ = \int_0^{y} I_+(y_+(y))\,\partial y_+(y)/\partial y\,dy$ and its I_- counterpart follows $I(y) = I_+(y_+)\partial y_+/\partial y = I_-(y_-)\,\partial y_-/\partial y$ (**), and from (*) one gets $\partial y_+/\partial y = 2 - \partial y_-/\partial y$. Insertion into (**) finally yields the corrected intensity, $I(y) = 2I_+(y_+)I_-(y_-)/(I_+(y_+) + I_-(y_-))$, for each x_0.

Methods

Images were acquired using a GE 3T scanner with 50 mT/m gradients. The reversed gradient method was implemented in a modified way by rotating the acquisition frame in *k*-space by 180 degrees in the slice plane, leading to a reversal of both the frequency and phase encoding gradients. The functional imaging sequence (GE EPI, TE/TR = 40 ms/2s) applied this rotation at every other repetition. Five block-design paradigms (rhyming, picture naming, and three motor paradigms) were tested on one subject. Tasks were performed three times during 3.7 min of scanning time, and the voxel intensity deviations were correlated to a rectangular ideal function. The images were corrected using a sliding window across each two consecutive images, keeping the scan time unchanged. Activation maps were computed using afni[6].

Results

The application of the reversed gradient method to a phantom with a grid (Figs. 1a-c) showed that the corrected image has straight grid lines and much better intensity homogeneity than the two EPI acquisitions. The application to the human brain showed that severe distortions in EPI scans (Figs. 1d,e) could be corrected almost completely (Fig. 1f), yielding good coincidence with an anatomical scan (Fig. 1g). For the proposed functional imaging sequence, we found that (i) the shape of the brain was a close approximation to the true anatomical shape, (ii) the intensities were corrected, yielding a much more homogenous signal, (iii) the activations seemed to be less scattered and more pronounced in four of the five paradigms. In the fifth paradigm activations were weak in both cases. As an example, Fig. 2 shows ipsilateral[7] cerebellar activation for a right-handed finger tapping opposition task (thumb touches each other fingertip in quick succession) which were observed at this slice location only with the new sequence (Fig. 2b).

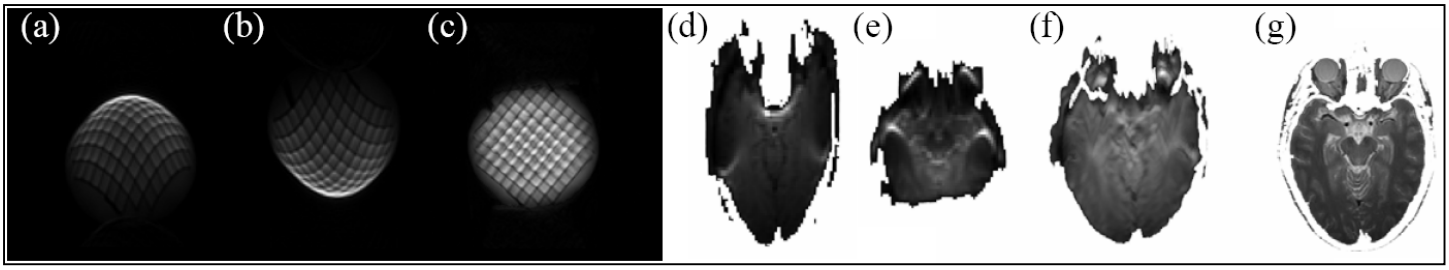

Figure 1: Illustration of the reversed gradient method. Two phantom images, I_- with (a) and I_+ without (b) rotated gradients, and the corrected image (c). Axial EPI brain slice with (d) and without rotated gradients (e), the corrected image (f), and an anatomical T2 weighted image (g) with four times the resolution. In (d) to (g), the background has been removed to enhance the shape of the brain, and the corrected image has been interpolated to the resolution of the anatomical image.

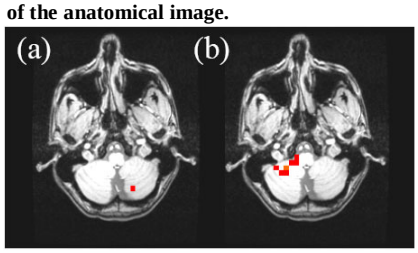

Figure 2 (color): Example of the functional sequence. Correlation map for a right-handed finger tapping task (a) and the corrected map using the new functional sequence (b). For the shown slice, only with the new sequence the expected ipsilateral cerebellar activations were observed, and spurious activations have disappeared. Colored voxels denote correlation coefficients larger than 0.7.

Discussion

The proposed functional sequence does not alter scan time and can readily replace methods without reversed gradients after adding another post-processing step to correct for the spatial and intensity distortions. We expect the functional imaging sequence to be useful in particular where EPI images are degraded by magnetic susceptibility differences across air-tissue boundaries whose magnitude are within the limits[3] of the method. The induced slight smoothing in time, due to the windowing procedure, and the fact that the small BOLD induced intensity fluctuations were transferred into spatial transformations by the correction method turned out to be insignificant.

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