Improved Unwarping of EPI Volumes using Regularised B_0 Maps

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Introduction

Echo Planar Imaging (EPI) images suffer from geometric distortions. These distortions originate from intrinsic magnetic field inhomogeneities (in B_0) that are particularly large near air/tissue and bone/tissue boundaries. In fMRI these distortions impair the registration accuracy of functional EPI images to structural images. This is important since it leads to errors in the localisation of activations with respect to individual anatomy and standard coordinates.

This poster compares several different unwarping methods in conjunction with different regularisation methods for the acquired field maps, in order to assess which approach is the most accurate for EPI unwarping. The unwarped images are assessed by registration to an image acquired using a non-distorting sequence with the optimised cost function (as provided by the registration method) giving a quantification of the success of the unwarping.

Theory

The MR signal measured in the presence of an inhomogeneous B_0 field is given by:

$$S(k_x, k_y) = \int \rho(x,y) \;\; \exp(-j2\pi(k_x x + k_y y)) \\ \exp(-jt_k B_i(x,y))\, dx\, dy \qquad (1)$$

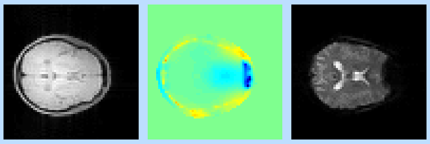
where $B_i(x,y)$ is the inhomogeneity ($B_0(x,y)$ less the constant B_0 component), $\rho(x,y)$ is the density of the sample, and t_k is the time at which the measurement at (k_x, k_y) in k-space is made.

Using the approximation that for EPI sequences t_k depends only on the phase encode k value (i.e. $t_k = 2\pi\alpha k_y + t_0$ taking the y direction as phase encode), and then taking the (continuous) inverse Fourier Transform gives the corresponding image as:

$$I_w(x,y) = \frac{\rho(x,s)\exp(-jt_0 B_i(x,s))}{|1 + 2\pi\alpha B_i'(x,s)|} \qquad (2)$$

where $s + 2\pi B_i(x,s) = y$ and $B_i' = dB_i/dy$.

Examples of typical fieldmaps and EPI images are shown in figure 1. Note how the frontal lobe is pushed posteriorly in the EPI with respect to the Structural Image, at the point where the local B_0 field (shown in the field map) is low.



Structural Image | Field Map | EPI

Figure 1: Some typical images illustrating the effects of B_0 inhomogeneities.

In addition, z gradients in B_i also create distortions in EPI, warping the slice selection and introducing additional dephasing across the slice, which is ignored in the above equations. This dephasing manifests itself particularly in EPI, due to the long echo times, as additional blurring and signal attenuation in image space.

Unwarping Methods

If $B_i(x,y)$ is known then this image can be simply unwarped by applying the inverse transformation:

$$I_u(x,y) = |1 + 2\pi\alpha B_i'(x,y)| . |I_w(x,q)| = |\rho(x,y)| \qquad (3)$$

where $y + 2\pi B_i(x,y) = q$.

The B_0 map can be measured using the difference in the unwrapped phase of two spin-echo images (each having negligible geometric distortion, and the second having a slightly asymmetric echo time).

Several methods exist for unwarping discrete images, including the reverse voxel shift [2] (discrete approximation of equation 3), conjugate phase, Weisskoff and conjugate gradient methods (the last three are all detailed in [3]). Note that in [3] the warping process is modelled as a discrete matrix equation relating the warping and unwarping images. However, this discrete form is only an approximation to the continuous form given in equation 1.

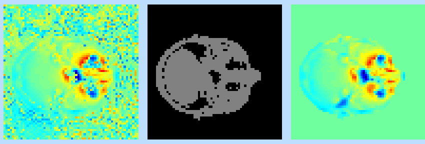
The three unwarping methods considered here are:

1. Voxel Shift Method;
2. Voxel Shift Method with Intensity Correction;
3. Phase Conjugate Method.

Measurement and Regularisation of the B_0 Field

The B_0 map can be measured using the difference in the unwrapped phase of two spin-echo images (each having negligible geometric distortion, and the second having a slightly asymmetric echo time). However, areas with very low signal-to-noise (SNR) produce very poor phase estimates and this leaves hole-like areas in the B_0 map where the estimates are very noisy (see figure 2). In order to reduce this noise, which can have a significant effect on the unwarped images, some method of regularisation is required.

The initial stage of regularisation employed here is to create a mask that is zero for areas where the SNR is low. This is done by thresholding the absolute spin-echo images. After the mask is applied to the B_0 map, the gaps in the estimates (where the mask=0) are filled in by linear interpolation of the values on either side, in the phase encode direction only. This interpolation makes the voxel shifting linear in that region and continuous with the boundaries on either side of the gap.



Before Regularisation | Estimated SNR Mask | After Regularisation

Figure 2: A typical Field Map before and after Regularisation

Following the initial stage, there are several methods of regularisation which have been implemented for evaluation. They are:

- 2D de-spiking filter
- 2D median filtering
- 2D Gaussian smoothing (σ of 0.5, 1.0 and 2.0 voxels)
- 3D Gaussian smoothing (σ of 0.5, 1.0 and 2.0 voxels)
- Polynomial fitting (order 3)
- Sinusoidal fitting (order 3).

Testing

As it is the *registration* of the EPI to non-distorted images that is of interest, the testing applied here looks directly at how similar the unwarped EPI is to a structural image. The skull-stripped symmetric spin-echo image, since it contains minimal geometric distortion, is used here as the structural image (as shown in figure 1).

For each combination of unwarping and regularisation method the following steps are performed:

1. the field map is regularised;
2. the EPI is linearly registered (using 6 DOF FLIRT [1]) with a warped version (using forward pixel shift) of the absolute spin-echo image — this aligns the EPI and field map coordinates;
3. the unwarping is applied to the registered EPI;
4. the unwarped EPI is registered to the structural image;
5. a multi-modal cost function (Correlation Ratio) is used to measure the similarity between the unwarped EPI and the (non-distorted) structural.

Results

The median cost results are shown in figure 3 using 6 different subjects, 3 unwarping methods (Shift, Shift plus Intensity Correction, Phase Conjugate) and 11 regularisation methods: None, DeSpiking (DS), Median (M), 2D Gaussian with $\sigma = 0.5, 1.0, 2.0$ (g0.5, g1, g2), 3D Gaussian with $\sigma = 0.5, 1.0, 2.0$ (G0.5, G1, G2), Third order Polynomial fitting (P3) and Third order Fourier fitting (F3).

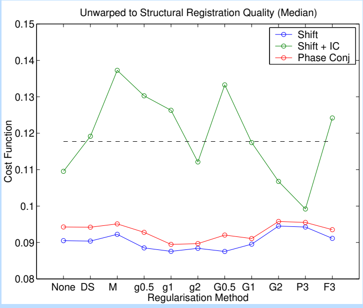
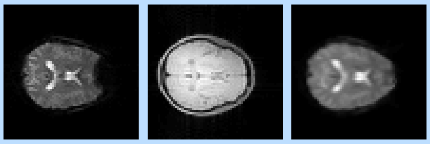


Figure 3: Cost Function Results. Note that the dotted line represents the cost function for the registration of the original warped EPI to the structural.

The lowest cost (best similarity) occurred for the 2D Gaussian smoothing methods. Although the difference in cost appears small between the various regularisation methods, these differences are equivalent to changes induced by noticeable rotations. For example the difference between: the 2D Gaussian methods $\approx \Delta C = 0.001 \approx 1°$; the Median and 2D Gaussian methods $\approx \Delta C = 0.01 \approx 5°$; and the original EPI and unwarped EPI $\approx \Delta C = 0.03 \approx 10°$.

Some typical images are shown below in figure 4 for the optimal regularisation (2D Gaussian smoothing with $\sigma = 1.0$) and unwarping method (Shift Method). For comparison, the difference of two unwarped images (after registration) using the best and worst regularisation, is shown in figure 5. Note that Shift unwarping was used for both images.



Original EPI | Structural Image | Unwarped EPI

Figure 4: A Typical Unwarping Result

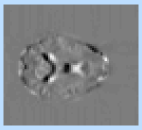


Figure 5: Difference between two unwarped EPIs.

Summary

It has been shown that unwarping methods can significantly improve registration between EPI and structural images. To do this well a measured field should be regularised.

Applying the Shift plus Intensity Correction unwarping method gave very poor results — often worse than the original, warped case. This is likely to be caused by the estimate of the derivative of B_0, which will be more noisy than B_0 itself, thus causing degradation of image quality. Of the regularisation methods tested (with either Shift or Phase Conjugate methods), 2D Gaussian smoothing gave the best results, with all methods peforming better than when no unwarping was used. However, for low order Polynomial and Fourier fitting and Median filtering, the results were worse than using no additional regularisation beyond the initial SNR masking and gap-filling. Therefore, it is best not to use the intensity correction term or heavy smoothing regularisations in practice.

A C++ implementation of these methods, *FUGUE*, is freely available from `www.fmrib.ox.ac.uk/fsl`

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References

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