Nonlinear Image Registration with Voxel Adaptive Regularization to Correct for EPI-induced Geometric Distortions

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Introduction: Echo planar imaging (EPI) is commonly used in functional MRI and diffusion tensor imaging. However, EPI images produce significant geometric distortions that need to be corrected for accurate registration of EPI images to anatomical scans such as fast-spin echo (FSE) for accurate interpretation of the data. Existing distortion corrections techniques are not very satisfactory. The Demon's algorithm is improved here to restore the distortions induced in EPI with elastic constraint driven by the local correlation map. Consistent registration is enforced with an improved bijectivity strategy.

Theory: This intensity-based algorithm uses the sum of squared differences (SSD) as a similarity measure between the source (*J*) and target (*I*) images, and adjusts the transformation, *T*, until the SSD is minimized [1]. *T* is represented by the displacement field *U(p)* for each voxel, *p,* of the target image such that *T(p) = p + U(p)*. Therefore, a voxel *p* with intensity *I(p)* in the target image corresponds to a point *T(p)* with intensity *J(p+U(p)). J(p+U(p))* is denoted by $(J \circ U)(p)$. The combined cost function is given by:

$$E = SSD(I, J \circ U) + \beta \sum_{\alpha \in \{x,y,z\}} \int [1 - k(x,y,z)] \left\| \nabla \frac{\partial U_\alpha}{\partial t} \right\| + \gamma \sum_{\alpha \in \{x,y,z\}} \int [d(x,y,z)] \left\| \nabla U_\alpha \right\|$$

where the first term is associated with SSD and the second and the third are regularization terms for imposing viscous and elastic constraints. *k(x,y,z)* and *d(x,y,z)* denote the viscous and elastic strengths, respectively. The constants β and γ control the balance for each constraint. These regularization terms are minimized through a diffusion process that can be solved efficiently by the Additive Operator Scheme [2]. The elastic constraint $d(x, y, z)$ is determined at each voxel by using the local correlation value calculated from the target image and updated source image. Thus the elastic constraint can be spatially variable according to the distortion. To improve computational efficiency, the local correlation ratio is calculated using a Gaussian window instead of a hard block [3].

To preserve the topology of brain during the deformation, the transform must be consistent (or bijective) to guarantee invertibility. Minimizing of the SSD term usually relies on gradient descent with a very small step size. However, this approach makes it difficult to guarantee the invertibility of the transform, which is essential for guaranteeing the integrity of brain structures. Therefore, we employ an improved bijectivity strategy to achieve consistent registration. The inverse transformation of forward and reverse deformation are calculated explicitly by Christensen' method [4]; the consistent registration is enforced by adjusting the residual of the forward and inverse deformation to zero at the grid points of the target image, and vice-versa on the grid point of source image [5]. This bijectivity strategy is therefore more numerically robust.

Result: The above method was applied to register EPI to fast spin echo (FSE) brain images, acquired on normal volunteers on a 3T Philips scanner. The results of the registration are shown in Fig. 1. The quality of registration (or distortion correction) is visually evaluated by superimposing the contours of FSE image (shown in red) on the EPI images before and after correction. As can be seen from these images, the corrected EPI images appear virtually identical to the FSE images. The invertibility of our algorithm (bijectivity) is also demonstrated by inverse transforming the corrected image (D). As can be seen from this figure, the EPI image and inverse deformation of the deformed EPI image are identical.

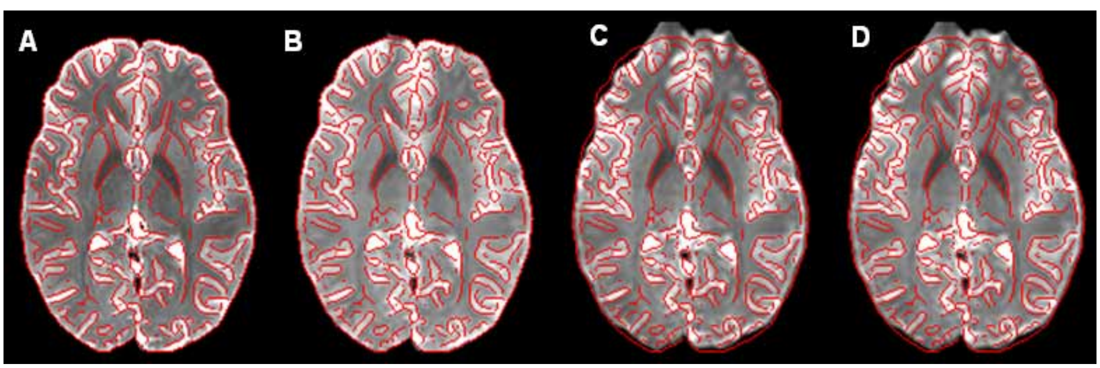

Fig. 1. **Sample images at the level of the frontal lobes: (A) FSE image, (B) corrected EPI image (C) original EPI image, (D) inverse deformation of the deformed EPI image**

Conclusions: An improved nonlinear registration method for correcting geometric distortions in EPI images is presented that features a spatially-varying elastic constraint, and an improved bijectivity strategy. The algorithm was implemented to register EPI to FSE images. The registration was found to be quite effective, even at slice locations with significant distortions, such as the frontal lobes.

References.

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