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A highly accurate symmetric optical flow based high-dimensional nonlinear spatial normalization of brain images ☆

Ying Wen [a,*], Lili Hou [a], Lianghua He [b], Bradley S. Peterson [c], Dongrong Xu [d,*]

[a] Shanghai Key Laboratory of Multidimensional Information Processing & Department of Computer Science and Technology, East China Normal University, Shanghai, 200241, China
[b] Key Laboratory of Embedded System and Service Computing, Ministry of Education, Tongji University, Shanghai 200092, China
[c] Institute for the Developing Mind, Children's Hospital Los Angeles, The Keck School of Medicine at the University of Southern California, Los Angeles, CA 90027, U.S.A.
[d] MRI Unit & Epidemiology Division, Department of Psychiatry, Columbia University & New York State Psychiatric Institute, New York, 10032, U.S.A.

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ABSTRACT

Spatial normalization plays a key role in voxel-based analyses of brain images. We propose a highly accurate algorithm for high-dimensional spatial normalization of brain images based on the technique of symmetric optical flow. We first construct a three dimension optical model with the consistency assumption of intensity and consistency of the gradient of intensity under a constraint of discontinuity-preserving spatio-temporal smoothness. Then, an efficient inverse consistency optical flow is proposed with aims of higher registration accuracy, where the flow is naturally symmetric. By employing a hierarchical strategy ranging from coarse to fine scales of resolution and a method of Euler-Lagrange numerical analysis, our algorithm is capable of registering brain images data. Experiments using both simulated and real datasets demonstrated that the accuracy of our algorithm is not only better than that of those traditional optical flow algorithms, but also comparable to other registration methods used extensively in the medical imaging community. Moreover, our registration algorithm is fully automated, requiring a very limited number of parameters and no manual intervention.

1. Introduction

Many methods in image analysis have been developed to tackle diffusion tensor images (DTI) registration [1–3]. DTI registration generally falls into two categories based on setting up the correspondence between two subjects. The first involves feature-based matching, i.e. transformations that are calculated based on a number of anatomical correspondences established manually, semi-automatically, or fully automatically on a number of distinct anatomical features, including distinct landmarks [4,5] or a combination of curves and surfaces, such as sulci and gyri [6,7]. In addition, finding anatomical correspondences is a key to the success of the spatial normalization. To find anatomical correspondences, conventional methods generally first extract scalar features from each tensor individually; and then by constructing scalar maps, regional integration and other operations such as edge detection, a final set of features for correspondence matching can be constituted. For example, Timer [8] and F-Timer [9] were developed based on Hammer [10], which adopts so-called driving voxels in addition to geometric moments as the features upon which registration is based. The boundary-based registration uses the measure of the thickness of cortex in T1-weighted image [11]. Yang et al. guided their registration using information on a tensor's structural geometry and orientation [12]. Xue et al. proposed a local fast marching method for DTI registration [13]. These landmark-based methods numerically seek optimal transformations (under respective model-specific assumptions) to maximize similarity across brains.

The second category of registration methods is based on volumetric transformations between one brain image and a template image. These methods assume that the images are acquired using the same pulse sequence [14–16] and these methods therefore are generally more efficient, because they do not require the construction of a specific anatomical model using anatomic landmarks. Christensen et al. [17] proposed a viscous fluid flow model to implement registration. Unlike fluid flow, optical flow is another volumetric transformation method. Optical flow is usually posed as an energy minimization problem, with the energy function containing a data term and a smoothness term. The variational framework, together with coarse-to-fine refinement, is widely used in optical flow estimation. The technique of optical flow developed in computer vision for object tracking [18,19] is one such method. The two approaches differ with the constraints in their implementations. The former adopts viscous constraints and body

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* Corresponding authors.
E-mail addresses: ywen@cs.ecnu.edu.cn (Y. Wen), bspmd61@gmail.com (B.S. Peterson), dx2103@columbia.edu (D. Xu).

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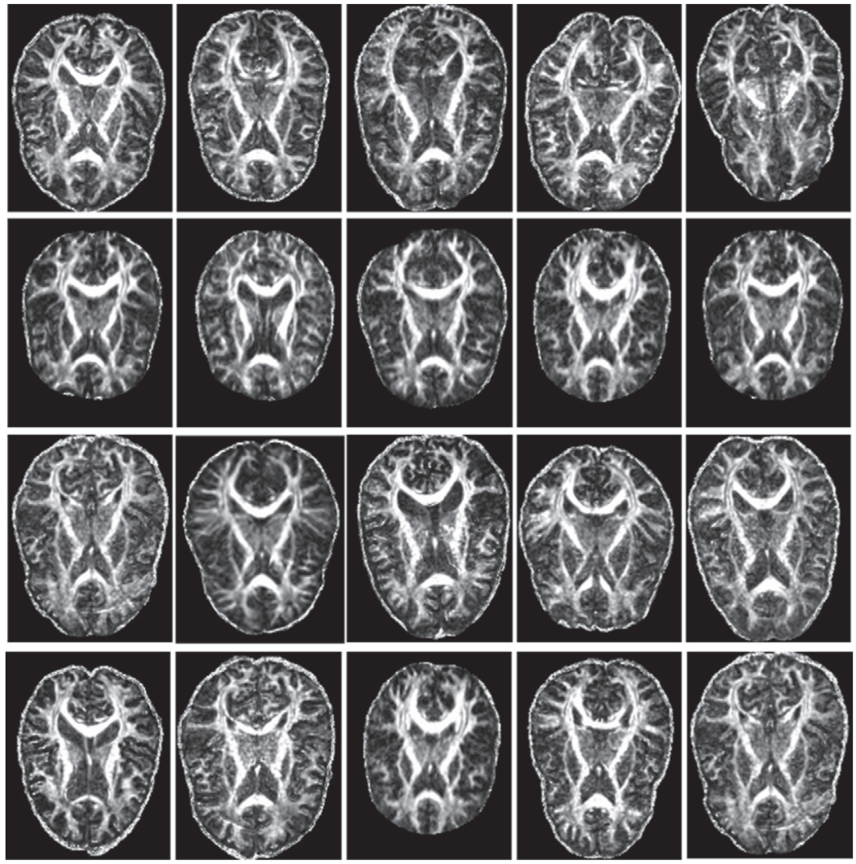

Fig. 1. Fractional anisotropy maps of the 20 randomly selected subjects from our database. The brains vary significantly in morphometry.

force while the latter adopts gradient and smooth constants. For the solution of optical flow, Xu et al. proposed an extended coarse-to-fine refinement framework which reduces the reliance of flow estimation on coarse level and corrects the optical flow in each scale [20]. Stoll et al. proposed an adaptive integration strategy for descriptor matching by selecting the positions where descriptor matching may improve the optical flow estimation [21]. Besides optical flow method, diffeomorphism methods are often used for image registration. The registration methods used extensively in the medical imaging community include symmetric diffeomorphic image registration (SyN) [22], SPM5 DARTEL [23], as well as with Thirion's Demons algorithm [24] etc. The optimization of diffeomorphism method is implemented on a space of diffeomorphic space instead of the entire space of displacement field. SyN maximizes the cross-correlation in the space of diffeomorphic maps. DARTEL is a diffeomorphic image registration for estimating inverse consistent deformations. Demons algorithm uses an approximate elastic regularizer to solve an optical flow problem.

Traditional techniques of optical flow estimation do not generally yield symmetrical solutions: the results will differ if they are applied between images f1 and f2 or between images f2 and f1. Ideally, the forward and inverse flows should be uniquely determined and should be inverses of one another. Estimating the forward and inverse flows independently very rarely results in a consistent set of transformations due to a large number of local minima. To overcome this deficiency in current optical flow, symmetrical formulations of the optical flow has been proposed in Refs. [29–31], where the solution is a constraint to being symmetric using a combination of the flow in both directions. In this work, we present a simple and effective method to recover a dense optical flow field map from two images. The idea is that it exists as a symmetric displacement between displacement vectors from f1 to f2 and f2 to f1 and to minimize an energy function of optical flow. This variational problem is then solved using the gradient flow defined by the Euler–Lagrange equations associated to the energy. This idea is introduced for DTI brain registration in this paper.

We focus on the optical flow based high-dimensional nonlinear spatial normalization of brain images. We first extend the traditional 2D optic flow to 3D form for high-dimensional nonlinear spatial normalization. Then, we propose a simple and effective symmetric variational formulation of the optical flow, where the flow is naturally symmetric for the problem of the forward and inverse flows. Finally, we incorporate the symmetric optical model into a hierarchical framework that is applied to imaging data in multiple resolution scales from coarse to fine, thereby building up a registration approach with high accuracy.

2. Materials and methods

2.1. Data acquisition

We acquired all the human Diffusion-weighted imaging (DWI) datasets from a GE 3.0 Tesla MR scanner system (General Electric, Milwaukee, Wisconsin) at New York State Psychiatry Institute, Columbia University. This unit was equipped with a high strength (50 mT/m) and high-speed gradient system (slew rate = 200 T/m/s) capable of conducting DWI. A single-shot spin echo, echo planar imaging (SE–EPI) sequence was used to acquire the DWI data, with