Nonlinear Registration of Diffusion Tensor Images Using Directional Information

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Introduction

In Diffusion Tensor (DT) MRI [1], local diffusion properties are described via a 3x3 symmetric diffusion tensor. From the DT and the T_2-weighted amplitude parameters several diffusion related quantities can be derived. E.g.: eigenvectors and eigenvalues of the DT, trace, diffusion anisotropy, etc. Thus, when registering (spatially aligning) DT images one has several potential choices of parameters to use to measure image similarity during registration. Previous work [2] has shown the advantages of using multiple DT parameters simultaneously during image registration, though the parameters used in that work were rotationally invariant. In this work we compare the use of channel configurations that include rotationally invariant scalar quantities derived from the DT model against channel configurations that include directional information, such as the DT elements.

$$I(\mathbf{S},\mathbf{T}) = \frac{1}{2}\log\left(\frac{|\Sigma_\mathbf{S}||\Sigma_\mathbf{T}|}{|\Sigma|}\right) \quad (1)$$

Methods

The multi-channel image registration problem is defined as an optimization problem where the goal is to find spatial transformation $f:\mathbf{x}\rightarrow\Re^3$ that maximizes some multi-variate image similarity measure $I(\cdot,\cdot)$ between a source multi-channel image $\mathbf{S}(\mathbf{x})$ and a target image $\mathbf{T}(\mathbf{x})$. Image similarity is measured using the multivariate measure defined in equation (1), where $\Sigma_\mathbf{T}$ and $\Sigma_\mathbf{S}$ represent the covariance matrix of the images and Σ represents their joint covariance matrix. As shown in [2], this similarity measure compares favorably against more standard ones such as the average linear correlation coefficient between all image channels. The adaptive bases algorithm [3] is used to optimize the nonlinear (elastic) transformation *f*, defined in eq. (2). We used this multi-channel registration methodology to compare the performance of two channel configurations in registering images: $\mathbf{S}(\mathbf{x}) = \{Trace(\mathbf{x}), Aniso(\mathbf{x})\}$ and $\mathbf{S}(\mathbf{x}) = \{Amp(\mathbf{x}), D_{xx}(\mathbf{x}), D_{xy}(\mathbf{x}), D_{xz}(\mathbf{x}), D_{yy}(\mathbf{x}), D_{yz}(\mathbf{x}), D_{zz}(\mathbf{x})\}$, where *Trace* is the trace of DT, *Aniso* is the fractional anisotropy, *Amp* is the amplitude term of the DT model, and $D_{xx}(\mathbf{x}), D_{xy}(\mathbf{x}),...$ are the individual DT elements.

$$f(\mathbf{x}) = A\mathbf{x} + \mathbf{t} + \sum_i \mathbf{c}_i \Phi_i \quad (2)$$

We compared the accuracy of the registrations based on different channel configuration with three types of experiments: simulation experiments, intra-subject registrations, and inter-subject registrations. In our simulation experiments we generated 10 deformation fields randomly and applied them to a 3D template DT image. Registrations using both channel configurations were then used to recover the known deformation fields. In addition, registration of DT images of a single subject acquired at different time points in the cardiac cycle were also performed using both methods in order to reduce cardiac related brain pulsation. Finally, nonlinear registration of 6 3D DT images of unrelated subjects to a 7th one was also performed using both channel configurations.

Results and Discussion

In the simulation experiments, registration based on the DT channel configuration produced an average voxel error of 0.483 voxels, whereas the error produced by the {trace, anisotropy} channel configuration was 0.699. In the cardiac gated experiments the mean standard deviation of the anisotropy and trace channels were 0.0159 and 117.3, respectively. After nonlinear registration using the {trace, anisotropy} configuration, the errors were reduced to 0.0138 and 88.9. After nonlinear registration using the DT elements, the errors were further reduced to 0.0131 and 82.8. Figure 1 displays an axial slice of the coefficient of variation of the trace of the diffusion of cardiac gated DT images before (left), and after nonlinear registrations with the {trace, anisotropy} configuration (middle), and after registration with the DT elements (left). The reduction in variability is most visible in the areas of interface between gray matter and cerebro-spinal fluid.

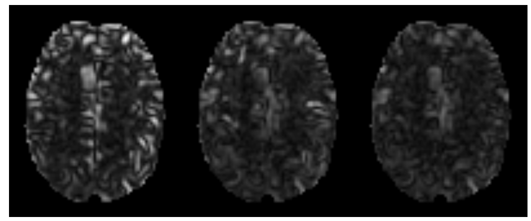

Fig 1. Coefficient of variation of the trace of the diffusion tensor in cardiac gated experiments. Left: before any registration; middle: after registration using scalar quantities; right: after registration using DT components.

The results of the nonlinear inter-patient registration experiments were visually inspected and, in general, we found that the registration using the tensor channel combination failed to produce results that were significantly more accurate than the results obtained using the {trace, anisotropy} channel combination. This can be seen in figure 2, which shows axial, saggital, and coronal reconstructions of average anisotropy, column-wise from left to right, maps before any registration, after rigid body registration using the trace and anisotropy channels, after nonlinear registration using the trace and anisotropy channels, and after registration using the DT elements.

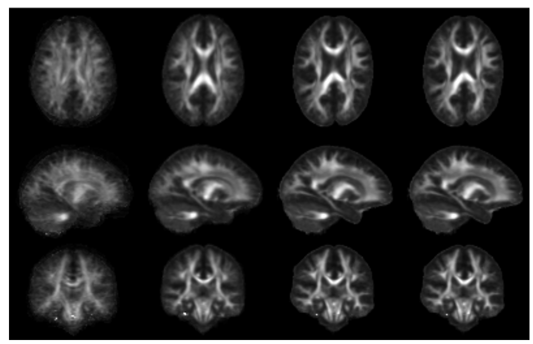

Fig 2. Average anisotropy maps, column-wise from left to right, before registration, after rigid body registration, after nonlinear registration using scalar quantities and after nonlinear registration using DT elements.

One region of the brain where tensor-based registration seems to have outperformed scalar based registration is in the area of the pons. This is shown by the slight increase in the sharpness of the average color images produced by the tensor-based registration as compared to scalar based registration (figure 3). The images shown in figure 3 are color representations of the direction vector associated with greatest diffusivity, weighted by an anisotropy index [4].

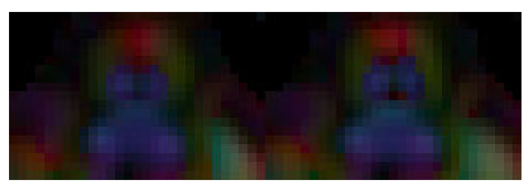

Fig 3. Average color representation of diffusion direction profiles after scalar (left) and tensor elements (right) nonlinear registration.

Conclusions

We compared channels that contain rotationally invariant scalar quantities against channels that contain the DT elements themselves for registering DT-MRI datasets. Experiments performed with real and simulated data suggest that the use of the directional information present in the DT elements can, in some instances, significantly improve the accuracy of registration results. We expect that the methods shown here should be useful in characterization and removal of artifacts, e.g., arising from cardiac pulsation, in comparing data obtained from longitudinal and multi-site DTI studies, in co-registering raw DWIs in DTI and in other high angular resolution methods, and in atlas construction from DTI data.

References

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