Entropy-based coregistration for DT-MR images using an efficient tensor shape preserving reorientation strategy

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Introduction and Purpose

Diffusion tensor magnetic resonance imaging (DT-MRI) is becoming an important diagnostic tool for various neuropathological diseases [1, 2]. It is often desirable to combine multiple DT-MRI data sets of the same patient (follow up), or even to merge intersubject information (control versus pathology). Only then, diffusion tensor abnormalities can be quantified based on a statistical analysis of these multiple data sets. Therefore, spatial normalization or image coregistration is indispensable to align the data sets in a common reference frame. In this work, we developed a three-dimensional (3D) affine (rotation, translation, scale, and skew) DT-MRI coregistration technique based on the work of Maes et al. [3] using mutual information as a similarity measure. To preserve the orientational information of the diffusion tensor **D** after affine transformation, **D** must be reoriented in order to remain consistent with the alignment of the underlying anatomical structures. Current reorientation strategies (RS) for such an affine transformation, e.g. preservation of principal direction (PPD), require calculating several rotation matrices to reorient **D** [4]. Here, a direct diffusion tensor reconstruction approach is developed without the need to calculate these rotation matrices, resulting in a lower computational cost.

Theory

Consider the diffusion weighted (DW) images $\mathbf{S}_k$ and $\mathbf{R}_k$ (here, k = 1,…,7) of two different acquisitions that need to be coregistered. Maximizing the mutual information (*MI*) of corresponding DW images according to these *k* channels allows to determine the optimal transformations $\mathbf{\Phi}_k$, i.e. $\mathbf{\Phi}_k = \arg\max_\phi \; MI\,[\phi(\mathbf{S}_k), \mathbf{R}_k]$, where ϕ represents the affine transformation. From these transformations $\mathbf{\Phi}_k$, the final registration transformation $\mathbf{\Phi}$ is estimated. The diffusion tensor shape preserving RS is based on the eigenvalue decomposition, i.e. $\mathbf{D} = \mathbf{E}\cdot\mathbf{\Lambda}\cdot\mathbf{E}^t$, where the matrix **E** defines the orthonormal eigenvectors $\mathbf{e}_i$ and the diagonal matrix $\mathbf{\Lambda}$ represents the eigenvalues λ_i. Extracting the linear transformation matrix $\mathbf{\Phi}_L$ of $\mathbf{\Phi}$, the new eigenvectors $\mathbf{n}_i$ are calculated as follows: $\mathbf{n}_1$ is defined by normalizing $\mathbf{\Phi}_L\cdot\mathbf{e}_1$, $\mathbf{n}_2$ is constructed by normalizing $[\mathbf{\Phi}_L\cdot\mathbf{e}_2 - (\mathbf{n}_1\cdot\mathbf{\Phi}_L\cdot\mathbf{e}_2)\mathbf{n}_1]$ and $\mathbf{n}_3$ is determined by $\mathbf{n}_3 = \mathbf{n}_1 \times \mathbf{n}_2$. The reoriented diffusion tensor $\mathbf{D}_\Phi$ can now be reconstructed as $\mathbf{D}_\Phi = \mathbf{N}\cdot\mathbf{\Lambda}\cdot\mathbf{N}^t$, where the matrix **N** defines the transformed eigenvectors $\mathbf{n}_i$.

Methods

First, the coregistration accuracy and the proposed RS are evaluated by means of a simulated DT-MRI phantom [5]. Next, the proposed coregistration technique is tested on experimental data. In-vivo DT-MRI on a starling brain (N=2) was performed on a 7T MR system. Sagittal slices (thickness 0.4mm) were obtained covering one hemisphere of the starling brain. DW-SE images were obtained with diffusion gradients applied in 7 non-collinear directions. The b-matrices were calculated using analytical expressions incorporating both diffusion gradients (70mT/m, δ=12ms, Δ=20ms) and image gradients [6]. Additional image parameters are FOV=25mm, TE=43ms, TR=2200ms, acquisition matrix=(256x128), 14 averages.

Results

<u>*Simulated DT-MRI phantom*</u>: Fig. 1 shows the 3D synthetic reference data set $\mathbf{D}_R$ and the source data set $\mathbf{D}_S$, with $\mathbf{D}_R=\phi(\mathbf{D}_S)$ and ϕ : {$\theta_x = \theta_y = 0$, $\theta_z = 45°$; $t_x = t_y = t_z = 0$; $s_x = 0.7$, $s_y = s_z = 0$; $g_x = 0.5$, $g_y = g_z = 0$} where θ_i, t_i, s_i, and g_i (i=x,y,z) represent the rotation angles, translations, scaling factors, and skew factors respectively (the color encoding provides directional information of the first eigenvector and the slices represent fractional anisotropy (FA) maps). Here, it is important to note that the transformation of the fiber pathways is performed prior to the simulation of the corresponding diffusion tensor data, for then, ground-truth orientational diffusion tensor information will be preserved. Fig. 2 demonstrates the coregistration solution for the slice indicated in Fig. 1, both with ($\mathbf{D}_\Phi$) and without ($\mathbf{D}_\Psi$) the RS. Notice that the similarity is significantly higher between $\mathbf{D}_\Phi$ and $\mathbf{D}_R$ than between $\mathbf{D}_\Psi$ and $\mathbf{D}_R$.

<u>*Experimental DT-MRI data*</u>: In Fig. 3, the coregistration technique is applied to the experimental DT-MRI data. As shown, a higher correspondence (quantified by the average Mean Squared Difference (MSD) of corresponding tensor components) between the registered images is obtained when the RS is taken into account.

Conclusions

A new 3D affine DT-MRI coregistration technique has been developed using a direct diffusion tensor reconstruction approach to preserve the underlying orientational information. Simulations have been performed, indicating no systematic deviations of the ground-truth registration solution. Also, an in-vivo coregistration example has been worked out, demonstrating feasibility of the proposed technique to register experimental data.

References

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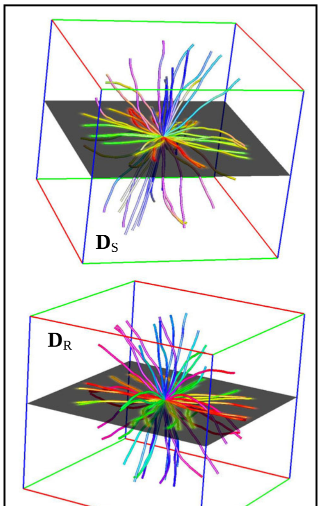

Fig. 1

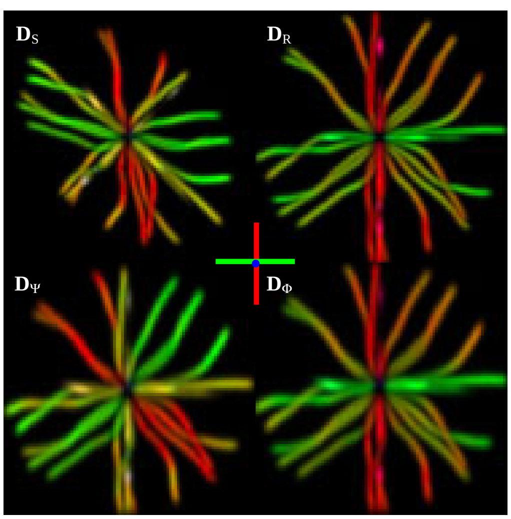

Fig. 2

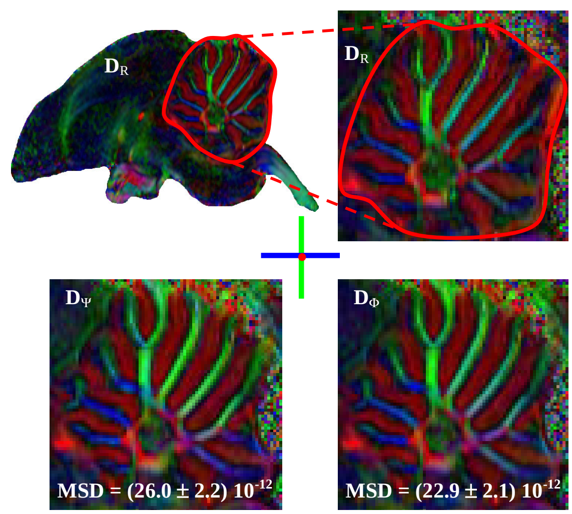

Fig. 3