CSF partial volume reduction in hydrocephalus using a variational framework

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Introduction

Hydrocephalus is a disease in which cerebral spinal fluid (CSF) accumulates abnormally in the ventricles, causing high pressure on surrounding brain tissue. Subsequently, white matter tracts are diverted and compressed depending on the severity of the condition. Diffusion tensor imaging (DTI) and tractography of fiber bundles that surrounds the ventricles often result in partial volume contamination [1], especially in cases of extensive enlargement of the ventricles where the white matter fibers are pressed to a thin layer surrounding the ventricles. Although pressed white matter can be characterized by increased fractional anisotropy (FA) [2], the fibers that surround the ventricles will show reduced FA due to the partial volume effect. In such cases fiber tracking will provide incomplete result. Here we reduce the partial volume contamination by fitting DTI data to a dual compartment model: a tensor compartment and an isotropic compartment with high ADC. We use a modification to the multiple tensor variational (MTV) framework [3,4] in order to perform a regularized fitting to a multiple compartment model with continues white matter tracts.

The fitting procedure

The MTV framework was initially used to resolve partial volume effect concerning multiple fiber orientations residing in the same voxel [3,4]. Here we modified MTV to perform a fitting to a bi-exponential diffusion model for the attenuation signal in gradient direction $\mathbf{q_k}$, shown in equation (1). The model has one tensor and one isotropic compartment with high ADC [1]. $\mathbf{D_1}$ is the diffusion tensor of the first compartment and $\mathbf{D_2}$ is the diffusion coefficient of the isotropic compartment having relative volume of $\mathbf{f_1}$ and $\mathbf{(1\text{-}f_1)}$. $\mathbf{D_1}$ is spectrally decomposed to three eigenvalues ($\boldsymbol{\lambda_i}$) and eigenvectors ($\mathbf{U_i}$) leading to the functional given in equation (2).

$$E(q_k) = f_1 \exp(-bq_k^T D_1 q_k) + (1 - f_1)\exp(-bD_2) \quad (1)$$

$$S(D_1, D_2) = \int_\Omega (\alpha \sum_k (\hat{E}(q_k) - E(q_k))^2 + \phi(|\nabla U_1|) d\Omega \quad (2)$$

The first term of the functional is the fitting term. This term aims to equate the measured signal decay, $\hat{\mathbf{E}}$, to the modeled signal decay, $\mathbf{E}$. The second term of the functional is the regularization term controlled by the function ϕ. We assume that the change in tensor orientation over neighboring voxels is smooth; therefore we regularize only the principle eigenvector of each D_1. The relative weight of each functional is controlled by the parameter $\boldsymbol{\alpha}$. The minimization of this cost functional via the Euler-Lagrange Partial Differential Equations (PDEs) and the gradient descent procedure, leads to finding $\mathbf{D_1}$ and $\mathbf{D_2}$ which best describe the data while preserving continuity of fiber orientations. During the minimization the eigenvalues of $\mathbf{D_1}$ were restricted to be positive and smaller than 2.5, while $\mathbf{D_2}$ was restricted to be larger than 2.5.

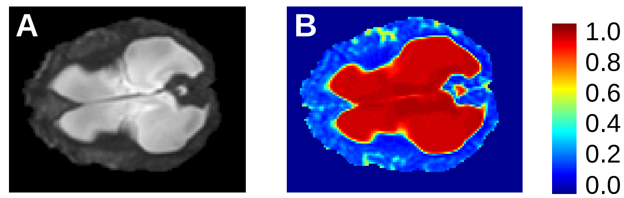

Figure 1: (A) T2 image of one slice of a patient with hydrocephalus showing large ventricles. (B) The volume of the isotropic compartment ($1\text{-}f_1$) which is significant in all brain pixels.

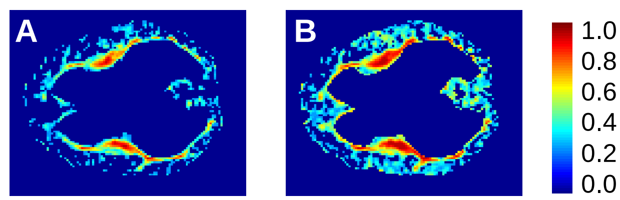

Figure 2: (A) FA map from conventional DTI with threshold of FA>0.25. (B) FA map of the tensor component from MTV fitting with threshold of f_1>0.4 and FA>0.25.

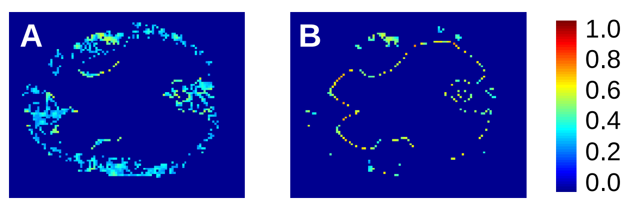

Figure 3: (A) FA map of the pixels added by MTV. Most pixels were added in the cortical areas, but some were added in deep white matter areas. (B) Pixels with significant partial volume ($0.4<f_1<0.6$ and FA>0.25).

Methods

Six patients with acute hydrocephalus were scanned in order to investigate the effect of mechanical pressure on white matter fibers. MRI was performed on a 1.5T MRI scanner (GE, Milwaukee). DTI experiments were performed using a diffusion-weighted spin-echo echo-planar-imaging (DWI-EPI) pulse sequence. The experimental parameters were as follows: TR/TE=10000/98ms, Δ/δ=31/25ms, b=1000 s/mm^2 with six diffusion gradient directions. 48 slices with thickness of 3mm and no gap were acquired covering the whole brain with FOV of 240mm^2 and matrix of 128x128. Number of averages was 4, and the total experimental time was about 6 minutes. Head movement and image distortions were corrected using a mutual information based registration algorithm [5]. The corrected DWIs were fitted to the model via the MTV framework with $\phi(s) = (1+s^2/k^2)^{0.5}$, then the large isotropic compartment was omitted. FA was calculated for the remaining tensor for which FA higher than 0.25 was considered as white matter. We compared these results to single component DTI with no regularization.

Results and Discussion

Figure 1 shows example of a hydrocephalus patient (F/13y) and the MTV predicted isotropic fast diffusing component. The effect of partial volume is significant all over the brain with high weighting in proximity to the ventricles. The bi-exponential fitting via the MTV framework shows two main effects: The first, the number of anisotropic pixels was increased compared to DTI (Figure 2B vs. 2A, and Figure 3A), especially in proximity to the enlarged ventricles and near the scalp. The second, the overall FA values increased since the isotropic compartment was removed. This effect was found in all pixels but with different magnitudes. The most striking effect was in pixels that are adjacent to the ventricles (Figure 3B). In pixels where significant partial volume was found the FA increased from 0.21±0.05 for DTI to 0.50±0.03 for MTV with relative weight of 0.52±0.03. After removal of CSF these pixels can be referred to as white matter pixels having high anisotropy. In conclusion, we show that bi-exponential fitting for CSF reduction is beneficial, especially for hydrocephalus cases. Using this fitting we were able to identify larger quantity of white matter, which was hidden by partial volume effects using conventional DTI.

References

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