Fuzzy partial volume correction of spinal cord DTI parameters

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Introduction

We present a novel correction method for partial volume effects on the estimation of parameters derived from diffusion tensor imaging (DTI) in the cervical spinal cord. DTI measures have become increasingly important as imaging biomarkers in studying numerous spinal cord diseases [1,2]. However, due to the small size of the cord and the limited spatial resolution, a large proportion of voxels are affected by partial volume averaging (PVA) from surrounding cerebro-spinal fluid (CSF). Water molecules in CSF are less hindered than in nervous tissue, resulting in increased diffusivity measures and decreased anisotropy in PVA voxels [3,4]. This can lead to biased average measurements over specific regions of interest (ROIs) and over the whole cord volume and potentially conceal subtle disease effects. Existing correction methods like [5] are often not applicable due to the low signal-to-noise ratio in spinal cord diffusion images. Therefore in common practice, CSF affected voxels are excluded from analysis with a subjective and manual editing of the outlined ROIs. However, objectively deciding which voxels to exclude while retaining information can be problematic, particularly when the cord area is small and only few unaffected voxels exist, e.g., in patients with spinal cord atrophy. We introduce a robust partial volume correction method for average DTI parameters that avoids the manual exclusion of PVA affected voxels, and reduces their contribution depending on their distance to the interface between spinal cord voxels and CSF. We investigate the accuracy of our approach in healthy volunteers and demonstrate that our method significantly reduces PVA effects on DTI indices.

Methods

Data acquisition and DTI analysis: We acquired diffusion-weighted images of 14 healthy volunteers (13 male, age=35±11). In each subject cardiac gated DTI of the cervical cord was performed (acquisition matrix=96x96, sinc interpolated in image space to 192x192, FOV=144x144mm^2, slice thickness=5mm, 20 slices, TE=88ms, TR≈4000ms) with a total of 100 b=1000s/mm^2 diffusion weighted volumes (20 unique diffusion directions repeated 5 times) and 5 non-diffusion weighted volumes. In each voxel the diffusion tensor was fitted to the data using camino (www.camino.org.uk) [6] and maps of fractional anisotropy (FA) and mean diffusivity (MD), axial diffusivity (AD) and radial diffusivity (RD) were generated.

PVA method: We semi-automatically delineate the cervical cord between levels C1/2 and C4/5 using the active surface segmentation [7] available in Jim6 (www.xinapse.com), performed on the computed FA maps [8]. A 2D distance transformation is applied to the binary segmentation masks, i.e., determining the distance d of each masked voxel to the border of the mask. Assuming that only voxels close to CSF are affected by PVA, the fuzzy partial volume correction factor w is then computed as $w=d/max(d)$ if $d<c$ and $w=1$ if $d\geq c$ where c is a cutoff distance determined on the basis of the DTI parameter values (see Figure 1). This approach ensures that for larger spinal cord areas, the border voxels are weighted less than in the case of small cord areas. The weighted average using the weighting factors w is computed for all DTI parameters over the whole segmented spinal cord area. We determine the optimal cutoff voxel distance c' in our dataset so that for $c\geq c'$ the average DTI parameters over the cord area reach a stable plateau, i.e., assuming that CSF contribution effects are minimized. In our data, DTI parameters reach the desired plateau for $c\geq 2$voxels (see Figure 2) and are in agreement with previously reported values in the healthy cord [8,9]. Thus the cutoff value $c=2$ is chosen for further analysis. A two-tailed paired t-test is performed to compare significance of differences between uncorrected and corrected measurements among all subjects.

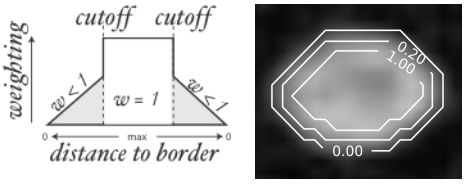

Figure 1: *(A) 1D illustration of computed weighting factors. (B) Isolines of weighting factors overlayed on FA map in one subject.*

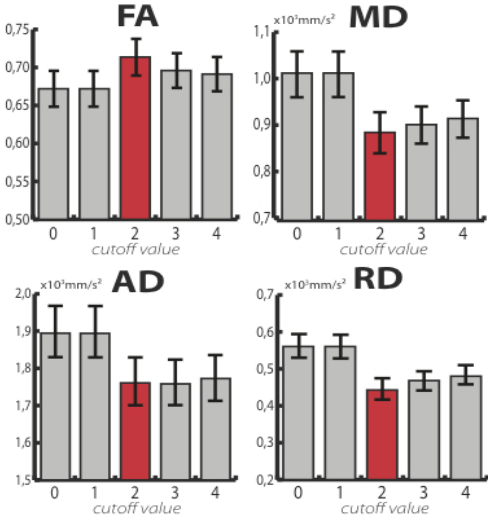

Figure 2: *Weighted average and standard deviation among all subjects for DTI parameters computed with different cutoff values. Columns corresponding to the chosen cutoff value of 2 are colored red.*

Results and discussion:

Table 1 shows lower standard deviation of diffusivity parameters among subjects when using our PVA correction method, suggesting lower inter-subject variability compared to the uncorrected measurements. Furthermore, the largest reduction of DTI values is observed in the RD ($p<0.0001$). We also find moderate decrease in the AD and MD and increase in FA (all $p<0.0001$). These results can be explained by CSF contribution to average measurements in uncorrected values and are in agreement with similar findings in simulations [3] and in the brain [4].

Conclusion and future work:

In this study we propose a novel fuzzy partial volume correction method that removes CSF contribution effects in measurements of DTI parameters over the whole spinal cord volume. We avoid fully excluding all potentially CSF contaminated voxels, and introduce a weighting factor that is dependent on the size of the cord and therefore accounts for the variability in number of white matter voxels. This allows more reliable measurements, particularly in patients who might suffer from white matter atrophy. Our method can be easily extended to other analysis methods such as histogram analysis and other quantitative modalities such as magnetization transfer imaging.

	Average change in mean (%)	Average change in std (%)
FA	+6.2* ± 0.7	+2.1
MD	-12.2* ± 1.3	-10.6
AD	-7.0* ± 1.0	-6.6
RD	-21.0* ± 2.1	-9.8

* Significance $p<0.001$ (confidence interval 99%)

Table 1: *Averaged relative change of mean and standard deviation between uncorrected and PVA corrected DTI measurements over all subjects.*

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