Tractography with multiple fibre directions

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Abstract
Performing fibre tracking in the brain using diffusion tensors is well established but fails in areas where the Gaussian density is a poor approximation of water molecule displacements in a voxel. We describe a new fibre tracking algorithm that uses mixtures of two Gaussian densities in these regions where the Gaussian model is poor. Results show that this algorithm allows tracking to continue through regions of fibre crossings.

Theory
Tractography is usually performed using a diffusion tensor (DT) fitted at each voxel, e.g. [1]. The algorithm follows the direction of peak diffusivity where the DTs are anisotropic. This method relies on the assumption that the displacement of water molecules is Gaussian distributed. However, this is a poor approximation where fibres cross or branch [ref] and tractography often fails in such areas. Voxels in these regions can be modelled alternatively as multiple partial volumes, each containing one structure, and with no exchange of particles between them. For example, two crossing fibres can be modelled as two partial volumes, each containing one of the fibres. We assume that the particle displacements in each partial volume follow a Gaussian distribution, and thus model the displacements in the whole voxel as a weighted sum of Gaussian densities. Each Gaussian has an associated direction of peak diffusivity, which we use as estimates of the directions of the crossing fibres. The algorithm of Alexander et al [2] tests whether the Gaussian density is an adequate approximation in each voxel. We use this algorithm and fit the diffusion tensor where it is adequate and a mixture of two Gaussian densities otherwise. The raw data contains 60 diffusion-weighted images with different gradient directions and 3 unweighted images for normalization. Each DW image has b=1000s mm^{-2}. The image arrays have size 128×128 in plane and 42 slices.

Methods
We use a simple tractography algorithm based on that of Conturo et al [1] to step along estimated fibre directions from an initial seed point. If the seed point is in a voxel containing a mixture model, we start tracking in each fibre direction. When we subsequently encounter a voxel containing a mixture model, we retrieve each fibre direction and use the direction that deviates least from the direction of the previous step along the track. We use tri-linear interpolation to obtain estimated directions at points between voxel centres. When some of the voxels used for interpolation contain the mixture model we again use the direction that deviates from the current direction least.
We tested the algorithm on both synthetic and human brain datasets. We created synthetic datasets containing crossing and branching fibres (modelled by the mixture of Gaussians), and added synthetic noise as in [2].

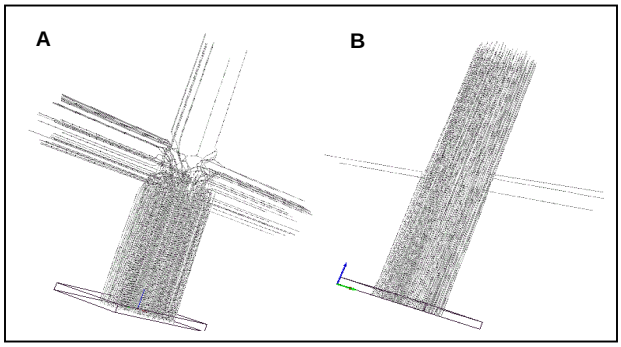
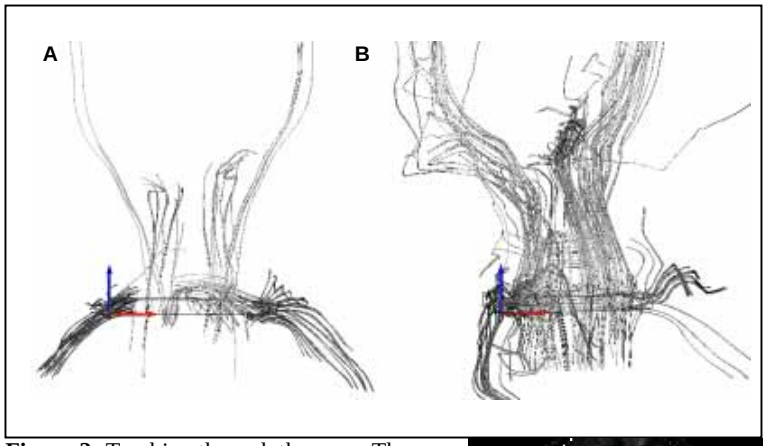


Figure 1: Tracking through a 90° fibre crossing. **A**: tractography using the diffusion tensor. **B**: tractography using the mixture model.



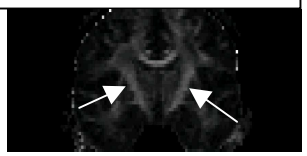


Figure 2: Tracking through the pons. The region of fibre crossing is located above the outline box in **A** and **B**. **A**: tractography using the diffusion tensor. **B**: tractography using the mixture model. **C**: coronal anisotropy map across the pons showing the pyramidal tracts (arrowed).

Results
Figure 1 shows results of tracking from a seed region in a synthetic data set containing a simulated 90° fibre-crossing. With the new algorithm that exploits the mixture model, very few tracks fail to traverse the fibre-crossing. The standard tractography algorithm based on the single diffusion tensor fails at the fibre crossing. This is also the case in regions of the brain where fibres are known to cross at roughly 90° to each other, such as the pons. Figure 2 shows results of tracking from a seed region containing the pyramidal tract, just below the pons. In the pons, the transpontine tracts intersect the pyramidal tract at approximately 90°. Many more tracks traverse the fibre-crossing in the pons with the algorithm that exploits the mixture model.

Discussion
In regions such as white-matter fibre-crossings where the Gaussian density is a poor approximation for the displacements of water molecules, tractography algorithms based on the diffusion tensor are unreliable. We use a mixture of Gaussian densities in these regions to resolve the directions of the crossing fibres. We have described a new tractography algorithm that extends a standard technique to exploit this extra information. We have tested the new algorithm on synthetic data to verify that it can follow fibres through crossings. We also show promising results on human brain data, which demonstrate an increased ability to traverse a known fibre-crossing.

References
[1] Conturo *et al, Proc. Natl. Acad. Sci. USA* 99:10422-10427 (1999).
[2] D.C. Alexander *et al, Mag. Res. Med.* 48: 331-340 (2002).