# Anomalous Diffusion Tensor Imaging

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## Introduction

The observation of non-monoexponential decay of diffusion-weighted MR signals with b-value has been widely reported [1]. Using the theory of anomalous diffusion, several groups have derived a stretched-exponential form for this signal decay (e.g. [2][3]) which parameterises the signal in terms of a distributed diffusivity $\alpha$ (measuring the overall rate of diffusion) and an anomalous exponent $\gamma$ which is a measure of the complexity of the environment and controls the degree of deviation of the signal from mono-exponential decay. Studies based on fitting the stretched-exponential form [2][3] have reported contrast between tissue types in images weighted by both parameters. In this study we extend the formalism of [3] to include directional anisotropy. The resulting technique, anomalous diffusion tensor imaging (aDTI), provides a tensor-based description of both parameters in the stretched-exponential form. This technique estimates a distributed diffusivity tensor, A, and an anomalous exponent tensor, Γ, in each image voxel. As both tensors are symmetric and positive definite the same analysis methods may be applied as those routinely used in regular diffusion tensor imaging [4]. In particular, we examine the eigenvalues, Trace and FA of the tensors describing the distributed diffusivity and anomalous exponent as well as their principal eigenvector orientations. We find that both tensors provide estimates of principal fibre directions that are sufficient for tractographical reconstruction of the corpus callosum in a healthy subject.

## Methods

Diffusion-weighted images were acquired on a 3T Siemens Trio MRI system using the same parameters as [3]. We fit the stretched-exponential form $S = S_0 \exp\left(-\alpha b^{\gamma}\right)$ predicted by [3] to diffusion-weighted acquisitions along radial lines in 12 different directions in q-space using a Levenberg-Marquardt algorithm. Each fitted form provides an estimate of $\alpha$ and $\gamma$ in each direction. Free diffusion corresponds to $\gamma = 1$, with disorder in the environment leading to a decreased values $\alpha \in [0,1)$. The fitted parameters in the 12 directions are then treated as samples to which Gaussian ellipsoids are fitted using the general linear model to provide two tensors (one for each parameter) in each voxel. For each tensor the eigenvalues and eigenvectors are computed and Trace and FA determined. Eigenvectors were coloured using the absolute value directional encoded colour (DEC) scheme to visualise their orientation [5].

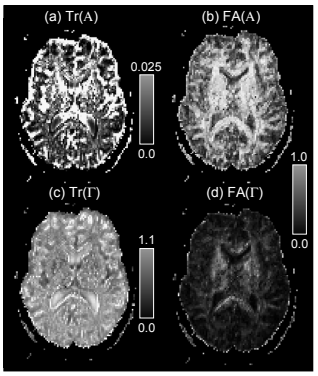


**Figure 1:** Maps of (a) Trace(A), (b) FA(A), (c)Trace(Γ), and (d) FA(Γ).

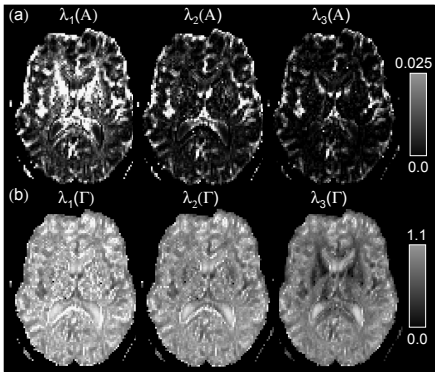


**Figure 2:** Eigenvalues of (a) Distributed diffusivity tensor (A) and (b) Anomalous exponent tensor (Γ).

## Results

Both tensors show tissue contrast in Trace and FA images (Fig-1). In both tensors FA is higher in white matter than in grey matter or CSF although this is greater in the distributed diffusivity tensors. Fig-2 also shows tissue contrast in eigenvalues of both tensors. However, for the distributed diffusion tensor $\lambda_1$ shows the greatest contrast between grey and white matter whereas for the anomalous exponent tensor it is $\lambda_3$. In particular Fig-3 shows that the principal diffusion directions corresponding to $\lambda_1(A)$ and $\lambda_3(\Gamma)$ are parallel to the expected orientation of white matter axonal structure as reported for regular DTI [6]. Fig-4 illustrates results obtained by performing deterministic tractography through the corpus callosum by following $v_1(A)$ and $v_3(\Gamma)$, with termination criteria of FA < 0.5 and FA < 0.1, respectively. It is apparent that the structure of the corpus callosum is reconstructed in both cases.

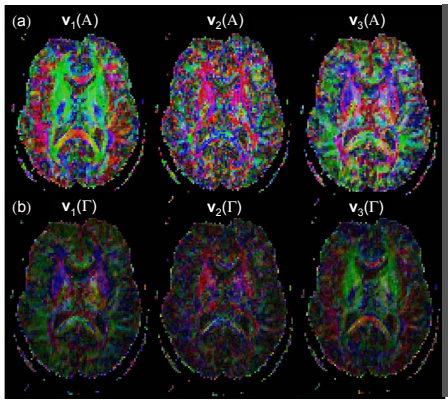


**Figure 3:** DEC maps modulated by FA intensity for (a) eigenvectors of A, (b) eigenvectors of Γ.

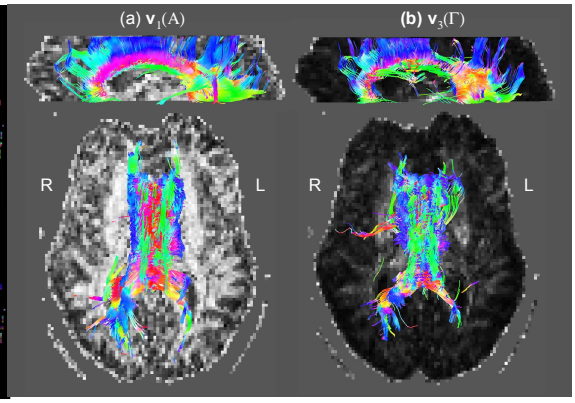


**Figure 4:** Deterministic tractography of the corpus callosum obtained by following principal diffusion directions (a) $v_1(A)$ and (b)

## Discussion & Conclusions

Both tensors show directional anisotropy and contain important information about the diffusion environment. The distributed diffusion tensor exhibits similar behaviour to the regular diffusion tensor with high FA in white matter and principal eigenvectors aligned with dominant white matter fibre directions. However, the anomalous exponent tensor exhibits disc-like shapes oriented normal to the dominant white matter fibre direction with the smallest eigenvalue exhibiting greatest tissue contrast and oriented along the dominant fibre direction. Previous investigations of directional anisotropy in the anomalous exponent tensor did not report anisotropy [6], but this may be due to the tensor model not being applied. A lack of application of a rotationally invariant model causes anisotropy to be underestimated, possibly leading to observations of moderate anisotropy values being overlooked. The origin of the disc-like shape of the exponent tensors is unclear, but is suggestive of diffusion restriction along the dominant orientation of white matter fibres. Recent work comparing models of diffusion to ex vivo animal data suggests that there is significant restriction in the parallel direction [7]. Further work will include comparison of our findings with histological sections of white matter to determine whether restricting structures are present along axons and to identify their length scales. In conclusion, this work provides a new vector of information from which to infer white matter microstructure. Both parameters are sensitive to changes in tissue microstructure and may lead to new biomarkers for pathologies which alter microstructure such as MS or aid classification of lesions or tumours, reducing the need for biopsy.

## References

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