Application of Independent Component Analysis for Resolving Multiple Fibre Orientations in DT-MRI data

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Introduction: The use of standard diffusion tensor (DT) models in the brain is based on the fundamental assumption that the diffusion of water molecules is governed by a Gaussian probability density function [1]. This results in a straigthforward estimation of white matter fiber orientations as the eigenvector, which corresponds to the largest eigenvalue of the DT. However, in cases where the fibers cross within a voxel, this assumption does not hold and the fiber orientation will be estimated erroneously [2-5]. As a result, several methods have been developed recently for resolving multiple intravoxel fiber orientations [2-5]. In this study, a method based on independent component analysis (ICA) is proposed and its efficiency to estimate the orientations of the two fibre populations is evaluated in simulations.

Theory: We assume N measured DW signals S_i, corresponding to different DW gradient directions g_i (i=1,2,...,N) and the same b-value b.

ICA analysis: ICA is applied to the Nx3 matrix $X = S_i.g_i$ [6]. ICA is based on the information-theoretic principle and uses mutual information minimisation (infomax) to find independent signals in the data. It assumes that each fiber population present has independently contributed to the measured DW signal. The ICA algorithm used in this study is a neural network approach [7]. The aim is to estimate an unmixing matrix W which will decompose X to three independent signals with maximally non-gaussian distributions. The columns of W represent spatial directions along which the higher order (>2) moments of X are maximum; the magnitude of each column of W reflects this maximum. Therefore by sorting the columns of W according to their magnitude, we can determine the directions that correspond to local extrema of the DW signal magnitude. These directions are then taken as the directions of the constituent fibers. Since X is Nx3, the method can determine at most 3 constituent fibers. In this preliminary study, we have considered mixtures of two fibres, and therefore the two columns of W with the largest magnitude were used as an estimate of the directions of the two fibers. W was estimated iteratively and the ICA algorithm stopped when the rate of change in W has reached a small pre-defined value.

Method: Simulations were developed for two crossing cylindrical fibers of identical shape and diffusivities: 1.9, 0.1, 0.1 (x10^{-3} mm^2/s); they both contributed equally to the baseline (b=0) signal using the methods described in [6]. The separation angle ang_o between the two fibers ranged from 40° to 90°. Four different sets of uniformly distributed DW gradient orientations were investigated (N = 72, 48, 24 and 12, at b-value = 1.2). The absolute value of the angular difference between the fibre directions retrieved by ICA and the original ones was computed and it was used to evaluate the efficiency of ICA in resolving the fibre orientations.

Results and Discussion: Figure 1 plots the error in the fibre orientations estimated by ICA as a function of the original separation angle of the two fibres for different sets of DW gradient directions N.

Overall, ICA is able to retrieve the fiber orientations with errors smaller than 5 degrees, when at least N=24 DW gradient directions are used. The plot for N=12 reveals that a small number N of DW directions (N<24) and a small angular separation between the fibres (ang_o<50°) will render the ICA unstable and the results unreliable, since the ICA error shows wild oscillations.

Although preliminary, this investigation shows that data driven techniques such as ICA may be used to resolve fibre orientations without an assumption about the fibre shape (cf the spherical deconvolution method [5]). Furthermore, the additional information contained in the unmixing matrix W (namely, the magnitude of its columns) may be used to obtain estimates of the relative weight of the two fibres in the baseline (b=0) signal, using a back-projection method.

This study is ongoing, and several issues need to be investigated in order to assess fully the merits of the method. Such issues include its noise sensitivity, and its performance when fibers with different shape and baseline (b=0) signal contributions are mixed. In addition, given that in theory the maximum number of fibres that the method can resolve is three fibers at most, its performance in a three-fibre signal mixture could also be assessed.

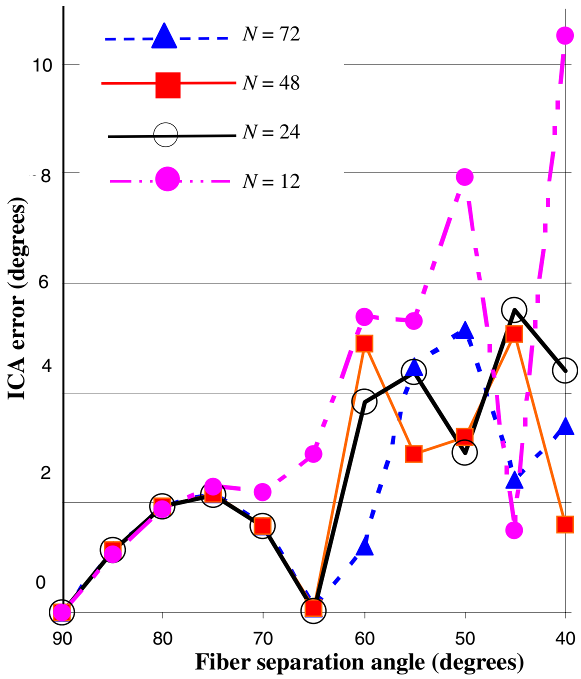

Figure 1: Plots of ICA degree error (y axis) as a function of the fiber separation angle (x axis) and the number of gradient directions (color coded).

Conclusion: A new method for resolving multiple fibre orientations was developed based on ICA. The method was successfully applied in simulated two-fibre DW signals. Its robustness with respect to varying fiber separation angles as well as number of gradient orientations was also demonstrated. Further investigations are necessary to fully assess the noise sensitivity of the method.

References: [1] Basser PJ NMR Biomed. 8 333-44 (1995) [2] Tuch DS *et al.* MRM 48:577 (2002). [3] Frank LR MRM 47:1083 (2002). [4] Alexander DC *et al.* MRM 48:331 (2002). [5] Tournier J-D *et al.* NeuroImage 23 1176:1185 (2004). [6] Papadakis NG *et al.* Phys. Med. Biol. 48 N343:N350 (2003). [7] Lee T-W Sejnowski TJ 4th Joint Symp. Neural Computation 7 132:139 (1997).

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