New invariant indexes to quantify water anomalous diffusion in brain

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Introduction

Conventional DTI methods are based on the Stejskal-Tanner analysis which predicts for water signal a mono-exponential decay, namely S(b)=S(0)exp(-Db), as function of b-values. The evidence of a non-monoexponential trend which is largely reported in brain, both in animal models and in humans brain [1,2], prompted the search for alternative approaches which take into account the deviation from the Gaussian diffusion conditions. A new method was recently proposed [3,4] which attempted to relate the diffusion decay to the different degrees of structural complexity found in different brain regions. This method is based on the stretched-exponential model, namely $S(b)=S(0)\exp(-Db^{\gamma})$. The stretching parameter has been used as a source of contrast revealing the capability to discriminate among cerebrospinal fluid (CSF), white matter (WM) and grey matter (GM). An anisotropy parameter has been also proposed. Even though it showed moderate sensitivity to structure degrees of orientation, Mean γ as defined in ref. [4], cannot be considered a good marker because it is not defined as a scalar invariant (i.e. it is not derived from a tensor) and thus depends on the relative orientation between the structures and the applied encoding gradients. We propose an alternative description which considers the behaviour along each of the three principal diffusive directions as a simple stretched exponential, thus defining three main exponents. The diffusion along a generic direction contains instead a combination of these three exponents.
The goals of the present work were: 1) to realize an algorithm for image reconstruction based on the three main exponents mean value and on its anisotropy, in analogy to the conventional DTI analysis and 2) to investigate the potential role of non-Gaussian diffusion parametric maps in discriminating among the different cerebral tissues and in detecting differences into selected ROIs, characterized by a known MR parameters such as mean diffusivity (MD) or fractional anisotropy (FA). Additionally, we aimed at drawing a comparison between the stretching exponent as defined in previous literature and our derived new indexes (Mean γ, Mγ and γ Anisotropy, γA) based on the three principal stretching exponents.

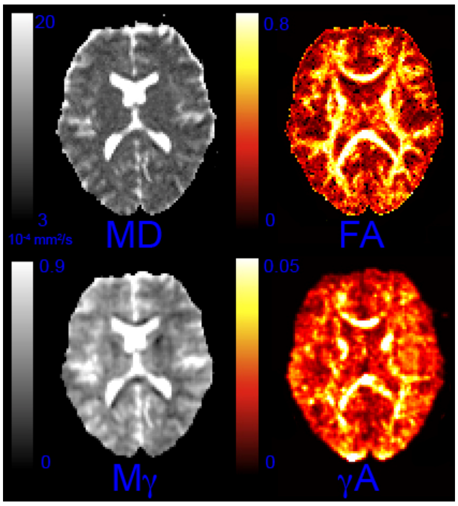

Fig. 1 Parametric maps of conventional MD and FA (top). Mean γ and γ anisotropy maps (bottom)

Methods

Ten young healthy subjects (mean age 24±3 years) underwent a MRI examination on a 3T scanner (Siemens Allegra) including: dual-echo turbo spin echo (TSE, TR = 6400ms, TE = 12/109 ms); DTI protocol using diffusion weighted SE EPI (TR= 6400ms, TE=107 ms, bandwidth 1860 Hz/px, slice thickness 3mm, in plane resolution 1.8mm^2) acquired in 6 non collinear directions at 16 different b-values: (0, 100, 200, 300, 400, 500, 700, 800, 1000, 1200, 2000, 2400, 3000, 4000, 5000) s/mm^2. Forty contiguous axial slices were collected with NS=2. An algorithm was realized in Matlab to perform a multidimensional fit of the diffusion signal decay in each pixel across the applied gradient directions. The principal directions have been obtained in the conventional DTI framework. The fit generates as output the three main exponents. Parametric maps representative of the Mγ values and maps of the anisotropy displacement of γ (γA) values are then realized and displayed. ROIs have been drawn based on anatomical criteria on selected WM (Thalamus, Pericallosal areas and Corpus Callosum) and GM (Putamen and Head of the Caudate Nucleus) regions and the obtained values have been averaged across all the subjects. Moreover, on the same ROIs also conventional MD and FA, as well as the mean exponent and its anisotropy as previously proposed [4], were obtained.

Results and Discussion

In fig.1, typical parametric maps obtained with conventional DTI reconstruction and with non-Gaussian innovative method are reported. The two results are characterized by a different kind of contrast as expected. In fig.2 the mean values of conventional MD and FA, Mγ and γA, as well as Mγ and γA calculated as ref.[4] are reported for different tissue structures: the WM of the CC, the WM of the Thalamus and Pericallosal areas, the GM of the Putamen and Head of the Caudate Nucleus. Preliminary statistical analysis confirmed that Mγ and γA offer a different kind of contrast when compared to conventional analysis. The non-Gaussian parameters as proposed in literature [4] do not offer a specific trend or differences among different tissues. Vice-versa, our new indexes can better discriminate among different microstructural features of brain tissues. Indeed, GM is characterized by a lower Mγ and a higher γA as compared to WM Mγ and γA. This may reflect a different degree of complexity of the two media which is reversed as compared to conventional analysis. WM is, in fact, the highest structured tissue since it contains bundles of nerve fibres where the diffusion is strongly anisotropic, but it can be considered also an ordered media. Conversely, GM is characterized by a lower level of fiber tracts coherency, i.e. it is a less oriented but disordered structure [5].

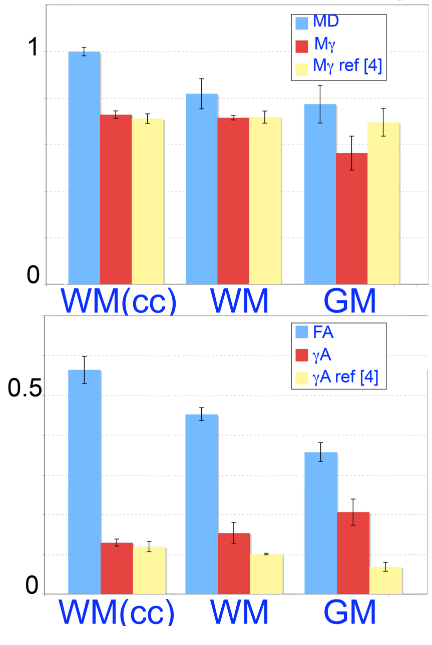

Fig. 2 Mean values and standard devations of MD, Mγ and Mγ of ref.[4] (top) calculated in CC, WM and GM ROIs. MD is calculated as % of maximum value. Same results for FA, γA and γA of ref.[4] (bottom)

Conclusion

We propose a new procedure to detect the non-monoexponential decay of the water diffusion signal which is recorded in brain. The quantification of the stretching exponent along the three principal directions can offer important information about the degree of complexity associated to each tissue structure and may be exploited as a new source of contrast. Preliminary results on healthy human brain demonstrated that this new analysis provide a different kind of contrast when compared to conventional MD and FA. We can speculate that the investigation of subtle changes in the diffusive motion by means of non-Gaussian parameters may offer more specificity and a chance for an earlier diagnosis in diseases associated to tissue disruption.

References

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