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Study of the Sources of Errors in Fiber Tracking using Diffusion Tensor MRI

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ABSTRACT

Diffusion tensor fiber tracking provides exciting new opportunities to study central nervous system (CNS) anatomy. In this study, simulated models are used to study the effect of anisotropy, partial voluming, and signal to noise ratio (SNR) on the quality of the tracking procedure. Effect of SNR on the tract path is also studied on real data. Results show that at low SNR values, white matter (WM) areas become more anisotropic and the angles between the eigenvectors of the tract path are over-estimated, which causes a detrimental effect on the tract length. Partial volume effects are shown to have a noticed effect on the anisotropic areas, thus affecting the tracking procedure.

Keywords: Diffusion, Partial voluming, Monte Carlo simulations.

1. INTRODUCTION

Diffusion- weighted (DW) images are magnetic resonance (MR) images with signal intensities sensitized to the random motion of molecules. From a series of DW images, it is possible to calculate an apparent diffusion coefficient (ADC) of water molecules in the direction of the diffusion sensitizing gradient [1].

Diffusion is truly a three- dimensional process. Hence, molecular mobility in tissues may not be the same in all directions. This anisotropy may result from the presence of obstacles that limit molecular movement in some directions [2].With plain diffusion MRI, diffusion is fully described using a single (scalar) parameter, the diffusion coefficient, **D.** The effect of diffusion on the MRI signal is attenuation, **A**, which depends on **D** and on the "**b** factor" which characterizes the gradient pulses (timing, amplitude, shape) used in the MRI sequence [2]:

$$A = e^{-bD} \quad . \tag{1}$$

However, in the presence of anisotropy, diffusion can no longer be characterized by a single scalar coefficient, but requires a tensor $\underline{\mathbf{D}}$, which fully describes molecular mobility along each direction [2].

$$\underline{\mathbf{D}} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix} \tag{2}$$

Several scalar indices have been proposed to characterize diffusion anisotropy. Indices are made of combinations of the terms of the diagonalized diffusion tensor, the eigenvalues $\lambda_1, \lambda_2, \lambda_3$. The most commonly used indices are the relative anisotropy (RA), the fractional anisotropy (FA), and the volume ratio (VR) [2, 3].

$$FA = \frac{\sqrt{3}\sqrt{(\lambda_1 - \lambda)^2 + (\lambda_2 - \lambda)^2 + (\lambda_3 - \lambda)^2}}{\sqrt{2}\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}, \tag{3}$$

$$\text{Where,} \quad \lambda = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3}. \qquad (4)$$

FA measures the fraction of the magnitude of $\underline{\mathbf{D}}$ that can be ascribed to anisotropic diffusion and varies between 0 and 1 [2].

Assuming that the orientation of the largest component of the diagonalized diffusion tensor represents the orientation of the dominant axonal tracts, DTI can provide a 3D vector field, in which each vector presents the fiber orientation. Currently there are several different approaches to reconstruct white matter tracts, which can be roughly divided into two types. Techniques classified in the first category are based on line propagation algorithms that use local tensor information for each step of the propagation. The second type of approach is based on global energy minimization to find the energetically most favorable path between two predetermined pixels [3, 4].

2. PROBLEM FORMULATION

Water diffusion studies using higher b- values in the rat brain and more recently in the human brain, indicate that the diffusional signal decay is no longer monoexponential, but is better described in terms of a bioexponential function, representing two water diffusion compartments at a single voxel [5-7].

$$\frac{S(b)}{S(0)} = a_1 e^{(-b\underline{D}_1)} + a_2 e^{(-b\underline{D}_2)}. \qquad (5)$$

Where $\underline{D}_1$ represents the diffusion tensor corresponding to white matter (WM) and $\underline{D}_2$ represents the diffusion tensor that corresponds to gray matter (GM) at the same voxel. a_1 and a_2 represent their respective volume fractions, which add one. S (b) represents the attenuation of the diffusion- weighted images, while S(0) represents the attenuation of the image acquired without diffusion weighting [5-7].

2.1. Study of the Partial Voluming errors in fiber tracking

In this work, we study the effect of the presence of these two compartments on the accuracy of tracking in WM areas. Monte Carlo simulations are implemented with IDL using the following algorithm:

1- Generate a sequence of GM and WM eigenvalues, where the WM pixels are distributed on the main diagonal of the slice.
2- Rotate the eigenvalues to get the tensors.
3- Compute the attenuation values using the diffusion weighting gradients.
4- Decompose the tensors and get the eigenvectors.
5- Compute FA of each pixel.
6- Change the pixels on the main diagonal so that they are WM+GM.
7- Re-estimate the attenuation values of each pixel.
8- Re-estimate the diffusion tensors using the new attenuation values, as dealing with a single- tensor problem.
9- Compute FA of the pixels, and the angles between the vectors.
10- This algorithm is repeated 1000 times with different values of the volume fractions and the mean and the standard deviation of FA and the angles are reported.

2.2. Study of the effect of noise on real data

Measurements are acquired from a horizontal slice of a volunteer on a Siemens 3T scanner using an SE/EP sequence (TE=116ms, matrix=128*128, slice thickness=5mm). 12 diffusion weighting gradients are used along with 8 b-values [200,400,600,800,1000,1200,1400,1600][2]. This results in a total number of 96 attenuation values per pixel. Signal to noise ratio (SNR) of the slice is 28 dB.

A WM area is then selected, and starting from a user- defined seed point a WM tract is generated by implementing the following algorithm using IDL:

1- Compute the tensor in each pixel using equation (1), where A is the matrix of attenuation values, and B is the B- matrix computed from the normalized diffusion weighting gradients and the b- values.
2- Decompose the tensors to get the major eigenvector of each pixel.
3- Calculate FA of all pixels.
4- Select a seed point with FA greater than threshold let it be 0.3.
5- Check the tensor slope (direction), if the difference between its x and y component is very slight then connect to the pixel on the diagonal, provided that: a- FA > 0.3. b- The angle connecting the two pixels is less than threshold let it be 45.
6- If the tensor slope is not as in step 5, check its x and y components. If the difference between its two components is large, then connect to the pixel in the x or y direction. (if the y component of the tensor slope is twice as mush as the x component then connect to the pixel in the y direction provided that this does not violate conditions a and b) , and the same goes for the x direction.
7- Noise is added to the b0 and b- weighted images, and the length of the tract is recomputed.

3. RESULTS and DISCUSSION

3.1. Partial Volume Simulations

Figure (1) shows that for the same SNR, partial volumes change the principal eigenvector orientation, thus changing the tract path. Figure (2) shows the change of FA with increasing the volume fraction that expresses the contribution of WM in the voxel. As this component increases, pixel becomes more anisotropic with higher FA value that approaches its value in case of the single tensor, i.e. before adding GM. Figure (3) shows the change of angles between the principal eigenvectors corresponding to each pixel. Small values of the partial volume of WM show large divergence in angles. As this volume is increased, angles between eigenvectors approach their original values.

3.2. Real Data

Implementing the algorithm without adding noise results in the track shown in figure (4. b). After adding noise, figure (5) shows that at low SNR values, FA values and the angles between the eigenvectors show large divergence thus terminating the tracking procedure. As SNR increases, tract length is increased.

4. CONCLUSIONS

Partial voluming has a detrimental effect on the accuracy of the tracking procedure, as it changes FA values and the orientation of the principal eigenvectors as well. At low SNR values, diffusion anisotropy values become overestimated. However, orientation of the principal eigenvectors is changed, increasing the angles between vectors, thus affecting the length of the fiber tract.

5. REFERENCES

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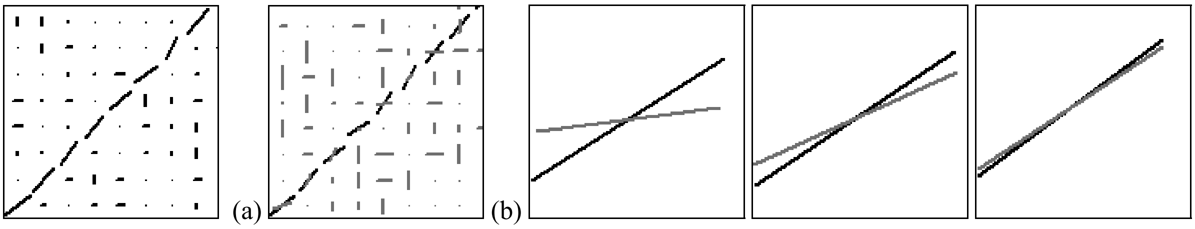


(a) (b)

(c)

Fig. (1): a- Section of the simulation results of a 32*32 slice of a single tensor. b- Results after adding the partial volumes on the main diagonal. c- Effect of partial volumes on the eigenvector orientation. 1- a_2= 0.9, 2- 0.5, 3- 0.1

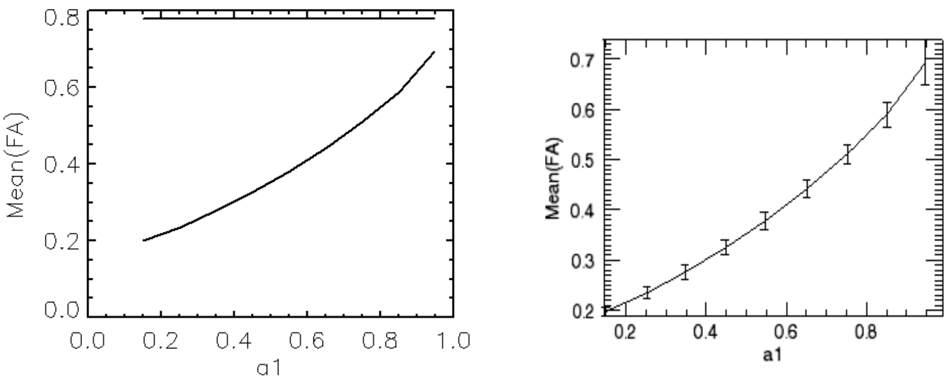


Fig. (2): effect of partial volumes on the FA of each pixel. As the a1 increases, FA value increases.

1.

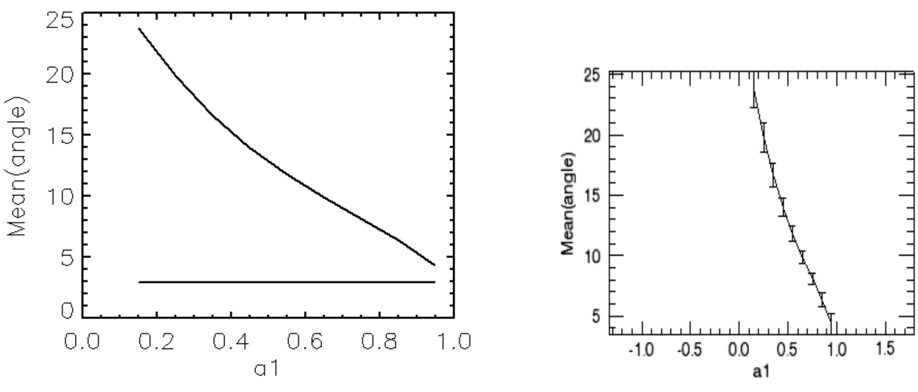
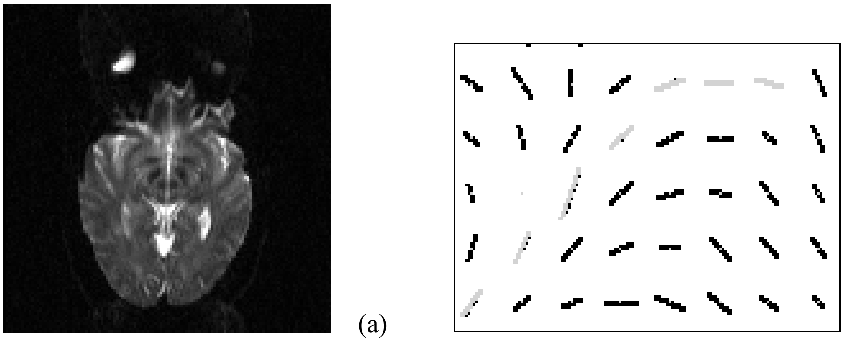


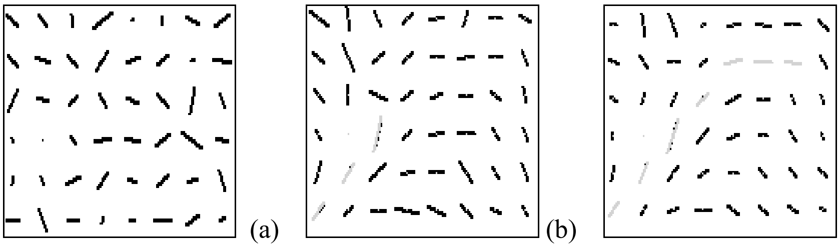
Fig.(3): effect of partial volumes on the angles between the principal eigenvectors, as a_2 increases, angles show large divergence from their values before adding the partial volumes.

2.



(a) (b)

Fig. (4): a- Slice used in the algorithm implementation. b- Section of the results of the velocity field plot of the principal eigenvectors of a WM area. A tract length of 7 pixels is displayed.



(a) (b) (c)

Fig. (5): Effect of SNR values on the tract length. a- Average tract length =zero at SNR=5. b- Average length= 2 at SNR= 10.c- Average length= 6 at SNR= 15.