Proceedings of the 2006 WSEAS Int. Conf. on Cellular & Molecular Biology, Biophysics & Bioengineering, Athens, Greece, July 14-16, 2006 (pp131-134)

DIFFUSION TENSOR MAGNETIC RESONANCE IMAGING

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Abstract: - During the last decade the development of Magnetic Resonance Imaging (MRI) has led to the design of numerous imaging techniques. One of these is Diffusion tensor MRI, which measures the motion of hydrogen atoms within water molecules in all three dimensions. In tissues containing a large number of fibers, like skeletal muscle or white brain matter, water tends to diffuse only along the direction of the fibers. The development of Diffusion Tensor MRI has raised hopes in the neural science community for *in vivo* methods to track fiber paths in the white matter. A number of approaches have been presented, but there are still several essential problems that need to be solved. The technique may also be used to understand the functional connectivity between the different regions of the brain. Diffusion tensor tractography is being used to study the areas of complex anatomy (such as the language areas), the connections of which were poorly understood before. These techniques may go a long way in both clinical neurological and neurosurgical practice, as well as in furthering our understanding about this complex organ.

Keywords: - Brownian motion, Isotropic and anisotropic diffusion, Diffusion tensor tractography,Eigen values and eigen vectors.

1 Introduction/Background:

Within biological tissues, water molecules constantly undergo random motion as a result of their thermal energy. This random motion is referred to as Brownian motion. If molecules are free to diffuse in all directions with equal probability, as in pure water, diffusion is described as isotropic and a single diffusion coefficient, D, is sufficient to describe the expected diffusion behavior.

However, in biological tissues, the mobility of water molecules is affected by the local cellular micro-architecture. For example, neural tissue – especially white matter contains organized bundles of neurons, which act as barriers for free diffusion. These biological barriers permit free diffusion only along the direction of the white matter fibers. When the freedom of mobility is different depending on the direction of molecular motion, diffusion is described as anisotropic, and a different diffusion coefficient may be measured along each direction. Hence, diffusion is a three-dimensional process, which can be modeled by a second rank tensor. This tensor is represented by one 3×3 matrix, which is symmetric, positive and real:

$$[D]=\begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{pmatrix} \qquad (1)$$

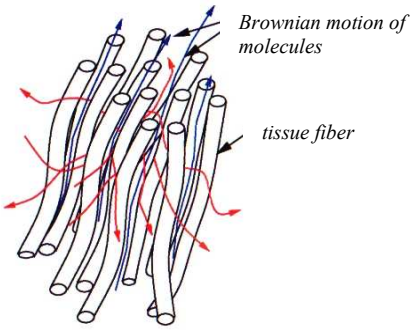

Fig 1:Artistic representation of what happens to water molecules inside white matter.

2) Measuring Diffusion with MRI:

Random motion of water molecules (diffusion) in the presence of a strong magnetic gradient results in MR signal loss as a result of the dephasing of spin Coherence. The application of a pair of strong gradients to elicit differences in the diffusivity of water molecules among various biologic tissues is known as Diffusion sensitization or Diffusion weighting.The degree of diffusion weighting is described by the ***b*** value, a parameter that is determined by the type of sensitizing gradient scheme implemented in the MR experiment. For the Stejskal-Tanner spin-echo scheme a pulsed pair of approximately rectangular gradients around a 180° radiofrequency pulse that is most commonly implemented on clinical MR scanners.

The "b "value is determined by the duration (d) and strength (G) of the sensitizing pulsed gradients, and the time interval between the two pulsed gradients (D)

$$\text{"b "value} = \gamma^2 G^2 (D - \gamma / 3) \qquad (2)$$

Where "γ"is the gyro magnetic ratio. Thus, the b value **(diffusion sensitization)** can be increased by using stronger (*G*) and longer (γ) pulsed gradients or by lengthening the time between the pulsed gradients (D).

Adding diffusion-sensitizing gradients to an imaging sequence (spatial encoding) constitutes the basis for Diffusion-weighted MR imaging.The signal intensity (S) in every voxel of a diffusion-weighted MR image is influenced by the choice of" b "value and pulse sequence TE and by two parameters intrinsic to biologic tissues:

2.1) Apparent diffusion coefficient

(ADC), a coefficient that reflects molecular diffusivity in the presence of restrictions, such as viscosity and spatial barriers;

2.2) Spin–Spin relaxation time (T2).

The following formula describes the relationship between signal intensity in a diffusion-weighted MR image and the different parameters:

$$S = S_0 e^{-b\,(ADC)} \qquad (3)$$

Where S_0 is the signal intensity at a b value of 0; or the natural logarithm

$$L_n (S / S_0) = -b\,(ADC). \qquad (4)$$

Acquiring diffusion-weighted images with at least two different b values while keeping the TE fixed allows the determination of the ADC value for each image voxel.

3) DiffusionTensor Imaging:

3.1) Diffusion Tensor:

The diffusion tensor formalism was first applied in multi dimensional mag netic resonance imaging (MRI) in order to simplify analysis of anisotropic diffusion data.

In this model, diffusion at each voxel is described by a symmetric 3 * 3 matrix of diffusivities, D, known as the diffusion tensor, where the bold face is used to indicate that D is a matrix. The diagonal elements of this matrix, Dxx, Dyy, and Dzz, correspond to the diffusion coefficients estimated with gradients applied along the principal axes of the reference frame, i.e., the scanner frame. The off-diagonal elements, Dxy, Dyx, Dxz, Dzx, Dyz, and Dzy, represent correlations between random motions along the respective paired axes of the reference frame. The matrix is symmetric, i.e., Dxy = Dyx, Dxz = Dzx, and Dyz =Dzy.

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

Fig 2: The Tensor Matrix

3.2) Data Acquisition:

In anisotropic diffusion**,** diffusion is directionally dependent and correlations in diffusion between the axes of the reference frame are possible, such that the tensor may contain all nonzero values. In diffusion tensor analysis, the tensor is diagonalized, i.e., rotated mathematically onto another set of axes that eliminate the off-diagonal correlations, known as the principal axes of diffusion. Once this has-been accomplished, the diagonal elements of the rotated matrix, known as the eigenvalues, represent the diffusion coefficients along the principal axes formed by the corresponding eigenvectors. The largest eigenvalue is known as the major Eigen value, and the corresponding major eigenvector represents the "preferred" direction of diffusion at each voxel.

The eigenvalues and eigenvectors can be graphically represented by an ellipsoid the major axis of the ellipsoid is parallel to the major eigenvector and the minor axes parallel to the minor eigenvectors, with the size of the ellipsoid along each axis related to the corresponding eigenvalue. The eccentricity of the ellipsoid thus graphically reflects the anisotropy of diffu sion. In the case of isotropic diffusion, the ellipsoid reduces to a sphere.

Diffusion tensor elements Dij (i, j , x, y, z) can be obtained on a pixel-by pixel basis by solving the system of linear equations according to the diffusion-weighted signal equation,

$$I = M_0 \exp(-\sum\sum b_{ij} D_{ij}), \quad (5)$$

Where *I* is image intensity, *Mo* is the diffusion-independent magnetization, and *bij* is the diffusion weighting factor corresponding to the tensor element *Dij*. The diffusion tensor then diagonalized to its eigenvalues and eigenvectors.

As D has 6 independent variables instead of nine, obtaining a unique solution requires diffusion to be measured along at least 6 non-coplanar encoding directions. Therefore, the *minimum* DT-MRI dataset would consist of 7 MRI acquisitions, including 1 un-weighted image, and 1 diffusion-weighted image in each of the 6 encoding directions denoted by. A typical set of gradient combinations along each direction is as follows.

$g = (gx, gy, gz)\mathrm{T}\,\gamma$ {(2 , 2 , 0), (2 , 0, 2), (0, 2 , 2), (2 , – 2 , 0), (2 , 0, – 2), (0, 2 , – 2)}.

Because of the signal attenuation, the image noise will affect the measurement diffusion tensor. Practically more than 6 encoding directions and multiple encoding levels in each direction are performed in the experiments.

Clinical Significance: - Fiber Tractography

Diffusion tensor imaging and fiber tractography have opened up research possibilities in areas that hitherto relied largely on postmortem studies. The quantitative indices that are calculated from the diffusion tensor data can be used to non-invasively delineate the white matter tracts within the brain. This technique may find application in presurgical imaging for delineating the relation of structural lesions to the white matter tracts.Evidence of white matter tract edema,infiltration,displacement and disruption in infiltrative brain tumours may also be observed.DTI identification of white matter tracts can be incorporated to intraoperative neuro navigational systems used during brain tumour resections.Diffusion tensor imaging can be useful to realize some studies about the development of cerebral white matter according to the age. But the most promising application remains the clinical diagnostic of pathologies and disorders of the cerebral white matter.

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