Correlations between Diffusion Tensor Indices and Intravoxel Tissue Volume Fractions in Human Brain

W. Zhan[1], H. Gu[1], E. A. Stein[1], Y. Yang[1]

[1]Neuroimaging Research Branch, National Institute on Drug Abuse, NIH, Baltimore, MD, United States

Introduction

Diffusion tensor imaging (DTI) indices, e.g. fraction anisotropy (FA) and mean diffusivity (MD), have been widely used to assess the tissue morphology in the human brain (1). However, the histological basis for these indices has not yet been explicitly clarified. For example, the quantitative relationship between the diffusion anisotropy and the tissue components remains unclear. In addition, the relatively large voxel size used in DTI acquisitions leads to partial volume effects that may undermine the ability of DTI in providing tissue-specific results. In this study, we present a method to investigate the correlations between the diffusion tensor indices and the intravoxel tissue volume fractions, by using a DTI technique and an inversion-recovery (IR) procedure in the same brain. Significant correlations are detected between the FA / MD indices and the volume fractions of whiter matter (WM), gray matter (GM) and cerebral-spinal fluid (CSF). Moreover, the tissue fractions can be used to decompose the DTI maps into more tissue-specific components.

Methods

Fraction Estimation. Let TI_i (i = 1,2,…N_{TI}) be a series of inversion times in the IR procedure, and $T1_j$ and $T2_j$ (j = 1,2,3) the longitudinal and transverse relaxation times of WM, GM and CSF, respectively. The IR signal of tissue j at inversion time i can be written (2) as $S(i,j) = M_j[1-2e^{-TI_i/T1_j}+e^{-TR/T1_j}]e^{-TE/T2_j}$, where M_j is the equilibrium magnetization of tissue j, and TR and TE the repetition time and echo time, respectively. The total signal from a tissue-mixed voxel at time i can be given by $S_i = \sum_{j=1}^{3}\alpha_j S(i,j)$, where $(0<\alpha_j<1)$ is the volume fraction of tissue j in the voxel. Thus, with measured IR signals S_i, (i = 1,2,…N_{TI}) with $N_I > 3$, the intravoxel tissue fractions α_j (j = 1, 2, 3) can be estimated by solving the over-determined equations given above.

MRI Experiments. Both IR and DTI were performed on 6 healthy volunteers on a 3T Siemens Allegra scanner with a head volume coil. Echo-planar imaging (EPI) was used for the IR and DTI techniques at identical imaging positions. Five oblique axis slices approximately parallel to the AC-PC line were acquired with FOV = 220 mm and 64x64 in-plane matrix size (5 mm in thickness with 1 mm interval). For IR, TR/TE = 10000 / 14 ms, and the IR signals were acquired at TI = 30, 80, 130, 180, 230, 330, 430, 530, 630, 730, 830, 1030, 1230, 1530, 1830, 2230, 2730, 3230 and 3830 ms. The $T1_j$ and $T2_j$ of WM, GM and CSF (j = 1,2,3) were specified according to the literature (2). For DTI, TR/TE = 3000 / 14 ms, and the diffusion weighted spin-echo signals were acquired at 12 directions with b factor of 1000 s/mm^2. A standard DTI algorithm (1) was used to calculate the FA and MD indices in each voxel.

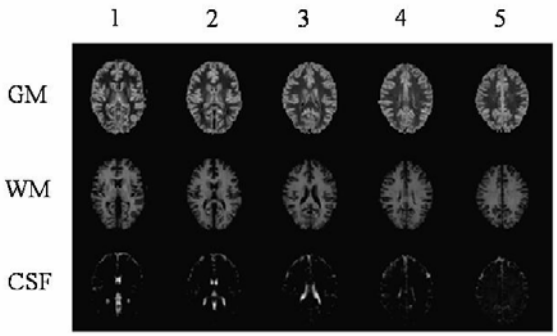


Fig.1 Tissue fraction maps of the partial brain (5 slices)

Correlation Detection. For each subject, all the image voxels inside the brain (typically n≈7000) were used to detect the correlations between the DTI indices and the intravoxel tissue fractions. The MD index was normalized into an interval of 0~1 for comparison purpose. Correlation coefficients (CC) were calculated between FA/MD and fractions α_j to estimate the correlation strength. The 1st and 2nd order polynomial regressions were performed to establish the statistical relationships between the two different measurements.

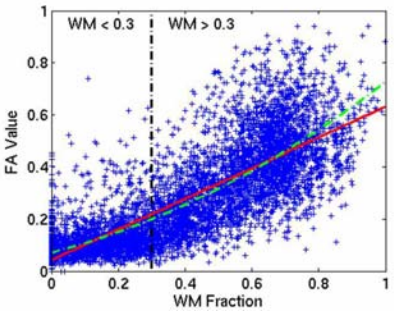
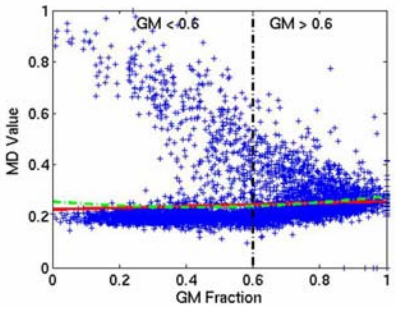


Fig.2 (a) Scatter plot of FA vs. WM



(b) Scatter plot of MD vs. GM

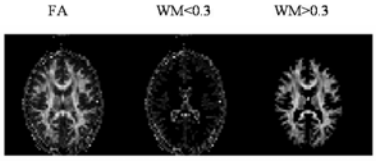
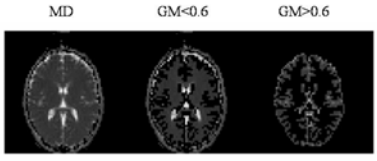


Fig.3 (a) FA map decomposition



(b) MD map decomposition

Results and Discussions

The calculated tissue fraction maps of a typical subject are shown in Fig.1. The brain regions dominated by WM, GM and CSF are clearly highlighted in the corresponding fraction maps. Unlike regular tissue segmentation techniques (3-4), the proposed method can provide quantitative intravoxel fractions (0~1) without presuming the tissue distribution in the brain. The scatter plots of FA vs. WM and MD vs. GM are shown in Fig.2 (a) and (b), respectively. Each '+' point represents an image voxel inside the brain. Significant correlations can be observed in the plots. The red and green curves represent the results of the 1st and 2nd order regression analysis, respectively. For all subjects, the linear regression between FA and WM fraction is estimated as FA = (0.587±0.08)*WM + (0.041±0.02), with a CC of R=0.808±0.02. Fig.2 (b) indicates that MD mildly increases with the increase of GM for the majority of brain voxels, while other voxels (in CSF dominant regions) show a negative correlation. Using the black vertical dashed line in Fig.2, the image voxels can be classified according to their WM or GM fractions. Thus, the DTI maps can be decomposed into components corresponding to the voxel classification. In Fig.3 (a), a slice (No.2) of original FA map is decomposed into WM <0.3 and WM>0.3 components. It is shown that the WM>0.3 component of the FA map has a higher consistency with the anatomical WM structures, whereas the WM<0.3 component includes contamination from the scalp and CSF dominant regions. Similarly, the MD map is decomposed into GM<0.6 and GM>0.6 components. The GM>0.6 component MD map has a higher consistency with the anatomical structures of brain cortex, whereas the GM<0.6 component matches the CSF dominant regions.

In summary, we have developed an IR-based technique to obtain intravoxel tissue fraction maps of WM, GM and CSF in the human brain. Significant correlations have been detected between the DTI indices and the tissue fractions. The FA and MD maps can be decomposed into components according to WM and GM fractions, providing tissue-specific DTI maps. The proposed tissue fraction method can also help analyze other MRI modalities such as functional MRI data.

References

[1] Le Bihan et al, JMRI 2001; 13:534-546. [2] Lu et al, NeuroImage 2002; 17:943-955. [3] Vinitski et al, JMRI 1999; 9:768-776. [4] Van Leemput et al, IEEE-MI 2003, 22:105-119