Diffusion Tensor Shape and Size Encoded Colormaps Reveal Fiber Features in Human Brain Diffusion Tensor Magnetic Resonance Imaging

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INTRODUCTION

Using the principle of anisotropic water diffusion measured by magnetic resonance methods, diffusion tensor imaging (DTI) is increasingly used to assess the white matter integrity in patients with a variety of pathologies. Diffusion Tensor (DT) summarizes diffusivities measured along 6 or more directions as three eigenvalue-eigenvector pairs. In the analysis of DTI data, fractional anisotropy (FA) and the principal eigenvector ($\mathbf{v}_1$) have been widely used, with the assumption that a voxel with high FA implies white matter fibers running parallel to the principal eigenvector. This corresponds to a linear shape DT. However, since FA can also be high when fibers are crossing or being compacted (a planar shape DT), FA alone cannot fully describe the white matter features within a voxel. Several researchers have used DT shape indices for linear (cl), planar (cp) and spherical (cs) [1, 2] to allow differentiation of linear and planar DT. Recently, Ennis and Kindlmann [3] outlined an orthogonal decomposition of tensor invariants into tensor norm (TN) for the magnitude of isotropy, FA for the magnitude of anisotropy, and the tensor mode (TM) for the mode of anisotropy, where TM corresponds to a range of DT shapes ranging from linear, to orthotropic, and to planar. We describe two colormaps constructed using DT shape indices, and DT invariants. Using these color codings for DT shape and size, we compare the standard FA weighted principal eigenvector direction encoded colormaps ($\mathbf{v}_1$FA) in normal and patient, to better understand the DTI data.

METHODS

Pulse Sequence: A healthy volunteer (F, 44yrs) and a patient (F, 54yrs) with cyst provided signed statements of informed consent, and underwent diffusion-weighted imaging (TR/TE 4422/60ms and 3609/78ms, 3mm thickness with no gap, acquisition matrix 256×256; SENSE factor 2.7, FOV 23cm; b values 0 and 800s/mm^2, 15 non-collinear directions) on a Philips Intera 3T MRI system. *Image Processing:* DWI images were processed by DTI Studio (version 2.4) to derive eigenvalues and eigenvectors. These were further processed by in-house software, where shape indices $cl=\lambda_1/(\lambda_1+\lambda_2+\lambda_3)$, $cp=2(\lambda_1-\lambda_2)/(\lambda_1+\lambda_2+\lambda_3)$ and $cs=3\lambda_3/(\lambda_1+\lambda_2+\lambda_3)$, and tensor invariants $TN=\sqrt{(\lambda_1^2+\lambda_2^2+\lambda_3^2)}$, FA, and $TM=\sqrt{2}\,\mu_2^{(-3/2)}\mu_3$, where μ_n is the n^{th} central moment of the eigenvalues were derived. *Color Codings: (1)* To de-emphasize regions with low diffusivity, DT shape indices encoded and principal eigenvalue (λ_1) weighted ($clcpcs\lambda_1$) colormaps were constructed by setting the red-green-blue (RGB) values to $cl\cdot\lambda_1/RGB_{ub}$, $cp\cdot\lambda_1/RGB_{ub}$ and $cs\cdot\lambda_1/RGB_{ub}$ respectively, where RGB_{ub} is an arbitrary upper bound. *(2)* DT invariants Hue-saturation-value (HSV) coded (TNFATM) colormaps, similar to Fig. 6(a) in [3] were constructed where hue (H) ranges from red to green to blue corresponds to TM from -1 (planar, $\lambda_1=\lambda_2>>\lambda_3$), to 0 (orthotropic, $\lambda_1-\lambda_2=\lambda_2-\lambda_3$), to 1 (linear, $\lambda_1>>\lambda_2=\lambda_3$), saturation (S) reflects FA, and value (V) (or brightness) reflects TN. Since the maximum value of FA, FA_{max}, differs for different values of TM, we set $S=FA/FA_{max}(TM)$ to enhanced the visualization of planar and orthotropic DT shapes. Since TN is generally lower for linear shapes, where $\lambda_2\approx\lambda_3<<\lambda_1$, than planar shapes, where $\lambda_3<<\lambda_1\approx\lambda_2$, and spherical DT shapes, where diffusions are less restricted, a minimum brightness, V_{min}, is chosen for clearer visualization of FA and TM features when TN is low. Thus, $V=V_{min}+(1-V_{min})(TN/TN_{ub})$, where TN_{ub} is an arbitrary upper bound for TN. We set $RGB_{ub}=0.001$ mm^2/s, $V_{min}=0.5$, and TN_{ub}=upper quartile of TN.

RESULTS

Figure 1 shows images of the volunteer at the levels of the posterior limb of the internal capsule (PLIC) (Fig. 1a-f), and the decussation of the superior cerebellar peduncles (DSCP) (Fig. 1g-i). Figure 2 show images of a patient with a large arachnoid cyst. Regions specified by yellow rectangles in insets are enlarged in Fig. 1d-i and Fig. 2. In Fig. 1 and 2, columns from left to right are $\mathbf{v}_1$FA, $clcpcs\lambda_1$ and TNFATM colormaps, respectively. The $clcpcs\lambda_1$ and TNFATM colormaps demonstrate high diffusivity regions as strong blue and white, and linear DT regions as strong red and blue, respectively. At the PLIC of the volunteer, blue pixels in Fig. 1d suggests only superior-inferior diffusion, while some green sub-regions in Fig. 1e,f indicate possibility of more than one diffusion directions. At the middle region of Fig. 1g-i, the DSCP of the volunteer is red in the 1(g) suggesting lateral diffusion, while green in Fig. 1h,i suggests planar-orthotropic DT, and a red boundary in Fig. 1i also suggests more planar-like DT at the boundary than in the center of the DSCP. Although the white matter surrounding the cyst in Fig. 2a has low FA and heterogeneous diffusion directions, strong cyan color (both blue and green are strong) in Fig. 2b and light red in Fig. 2c suggest planar DT.

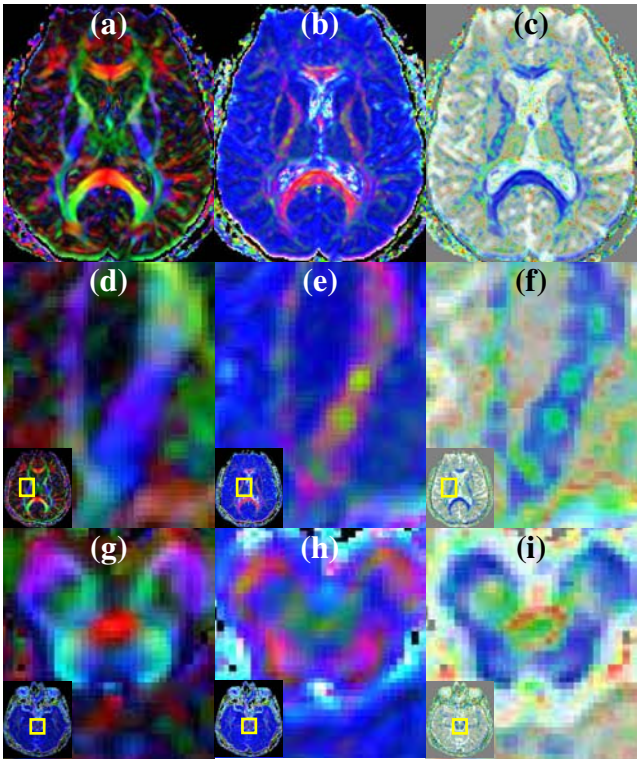

Fig. 1 $\mathbf{v}_1$FA (a,d,g), $clcpcs\lambda_1$ (b,e,h), and TNFATM (c,f,i) colormaps of the volunteer.

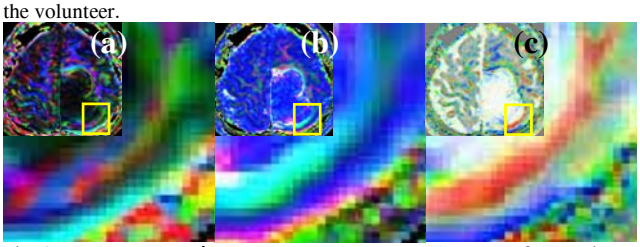

Fig. 2 $\mathbf{v}_1$FA (a), $clcpcs\lambda_1$ (b), and TNFATM (c) colormaps of the patient.

DICUSSION AND CONCLUSIONS

We describe two color encoding schemes to represent DT shape and size on a colormap. Normal anatomy of fibers (anisotropic diffusion), gray matter and ventricles (isotropic diffusion) can be recognized on these colormaps, which can be used in place of diffusivities images to complement the standard directionally encoded $\mathbf{v}_1$FA colormap. Since we do not expect crossing fibers in the PLIC, the unusual planar and orthotropic DT shape observed (Fig. 1e-f) may be due to kissing fibers that span more than 2 diffusion directions (imagine a letter x where the two halves are on non-coplanar planes). Whereas in crossing fibers at the DSCP, there is a rim of planar DT shapes surrounding the orthotropic DT shapes (Fig. 1i). Thus, TNFATM colormaps might allow the differentiation of crossing and kissing fibers. The displaced and compacted (but not invaded) fibers around a mass such as a cyst or tumor (Fig. 2b,c) can also be demonstrated. Since TN, FA and TM are DT orthogonal invariants, TNFATM colormaps contrast levels can be adjusted without affecting the color hue, by adjusting TN and FA separately to affect the brightness and color saturation respectively, and filtering TM to show only certain shape of interest. These colormaps can represent both the isotropic and anisotropic diffusion, where linear, planar, and orthotropic diffusions are distinguishable.

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