Diffusion Tensor Imaging in Patients with Glioblastoma Multiforme using the Supertoroidal Model

Choukri Mekkaoui[1], Fabricio Pereira[2], William J Kostis[3], and Marcel P Jackowski[4]

[1]Harvard Medical School - Massachussetts General Hospital, Boston, MA, United States, [2]CHU Nîmes, France, [3]Harvard Medical School-Massachusetts General Hospital, Boston, MA, United States, [4]University of São Paulo, São Paulo, Brazil

Target Audience: Scientists/clinicians interested in the structural characterization of cerebral lesions.

Purpose: Diffusion Tensor Imaging (DTI) has lead to improvements in the diagnosis and prognosis of cerebral lesions and neurosurgical guidance for tumor resection.[1] Traditional tensor modeling,[2] however, has difficulties in differentiating tumor-infiltrated regions and peritumoral edema.[3] In this work, we employ the supertoroidal model of the diffusion tensor and a diffusivity metric, the toroidal volume (TV), in the characterization of Glioblastoma multiforme (GBM).[4] We hypothesized that the supertoroidal model is better suited to identifying the heterogeneity of structure in GBMs and that TV can enhance the differentiation of gliomas from surrounding edema and normal brain parenchyma.

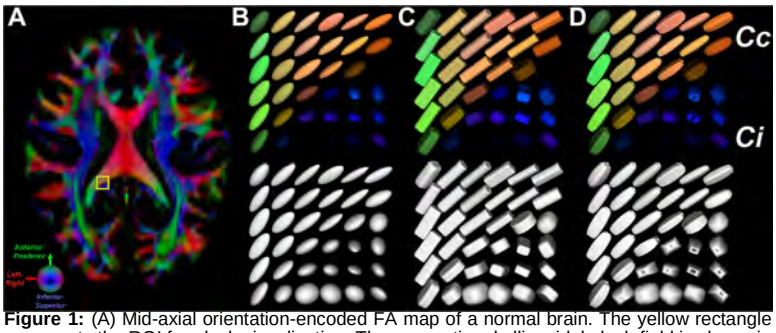


Figure 1: (A) Mid-axial orientation-encoded FA map of a normal brain. The yellow rectangle represents the ROI for glyph visualization. The conventional ellipsoidal glyph field is shown in (B), the superquadric glyph field in (C), and the supertoroidal glyph field in (D), with and without orientation encoding. The location of the Cingulum (Ci) and Corpus callosum (Cc) tracts are labeled. Supertoroids facilitate the visual identification of Cc and Ci tracts even in the absence of the color-based orientation coding.

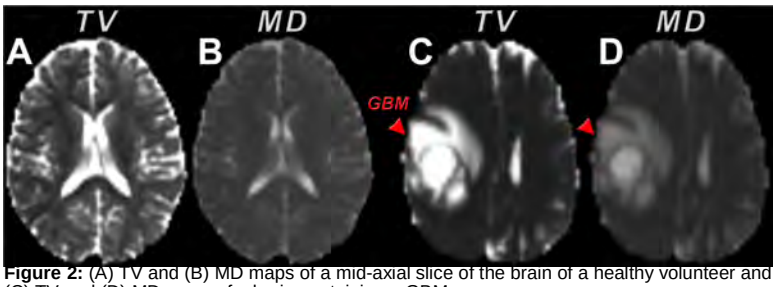
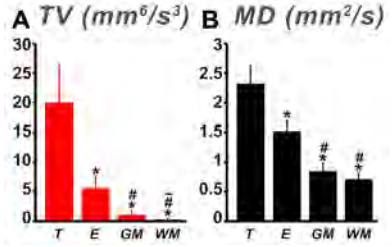


Figure 2: (A) TV and (B) MD maps of a mid-axial slice of the brain of a healthy volunteer and (C) TV and (D) MD maps of a brain containing a GBM.

Methods: Six individuals with GBM and 6 normal subjects agreed to participate and provided written informed consents. DTI brain datasets were obtained using a 3T scanner (Siemens). We used a diffusion-weighted single-shot EPI sequence with 32 gradient directions, two b-values (0 and 800 s/mm^2), FOV=320x320 mm, matrix size=128x128, resolution=2.5x2.5x3.3 mm^3, 40 slices, TE/TR=76/4700 ms, and 3 averages. The supertoroidal glyph is a function of the geometric shape metrics $C_L=(\lambda_1-\lambda_2)/(\lambda_1+\lambda_2+\lambda_3)$, $C_P=2(\lambda_2-\lambda_3)/(\lambda_1+\lambda_2+\lambda_3)$, and $C_S=3\lambda_3/(\lambda_1+\lambda_2+\lambda_3)$ [Westins]. The parameters $\eta_1=(1-C_P)^{\wedge}\gamma 1$ and $\eta_2=(1-C_S)^{\wedge}\gamma 2$ produce a smooth transition between supertoroidal shapes. The toroidal volume, defined as $TV=(\pi/3)\lambda_1(\lambda_2\lambda_3+\lambda_3^2)$ mm^6/s^3, is compared with mean diffusivity (MD) in the characterization of GBM. Regions of interest (ROIs) were selected inside the tumor (T), within the surrounding edema (E), as well as on the contralateral side to the lesion, within the white matter (WM) and gray matter (GM). The presence of variation in TV and MD across ROIs was assessed non-parametrically using the Friedman test.

Results: Figure 1A-D depict the ellipsoidal, superquadric, and supertoroidal representations in two major white matter (WM) tracts within an ROI near the splenium: the cingulum (Ci) and the corpus callosum (CC). TV and MD maps (Fig. 2A-B) were computed for a normal brain dataset, demonstrating the enhanced contrast when using TV as compared to MD, due to the nonlinearity of TV. Both TV and MD display high intensities in the tumor, with lower values in the surrounding edema, which in turn are higher than those of unaffected brain parenchyma (Figure 2C-D). The Friedman test revealed marked contrast using both MD ($p<0.001$) and TV ($p<0.001$) (Figure 3A-B). Both MD and TV were able to distinguish tumor from edema, however MD was not able to differentiate GM from WM ($p=0.06$), whereas TV was ($p<0.05$). Structural differences are easily perceived between tumor, peritumoral edema, and normal brain tissue when using the supertoroidal representation (Figure 4).



Discussion: The supertoroidal glyphs facilitate visual perception of the principal orientation of local diffusion, regardless of the scene orientation, and the nonlinear response of TV enhances the boundaries between neoplasm and surrounding structures. The concomitant use of TV and MD enable accurate tissue characterization between tumor, edema, and normal brain parenchyma. As a consequence, these subcortical landmarks may be useful for surgical planning and intraoperative image guidance during brain tumor surgery in eloquent areas.

Conclusion: The supertoroidal model enhances understanding of the underlying tissue structure properties and may provide meaningful information in terms of diagnosis, prognosis, and therapeutic management of brain lesions.

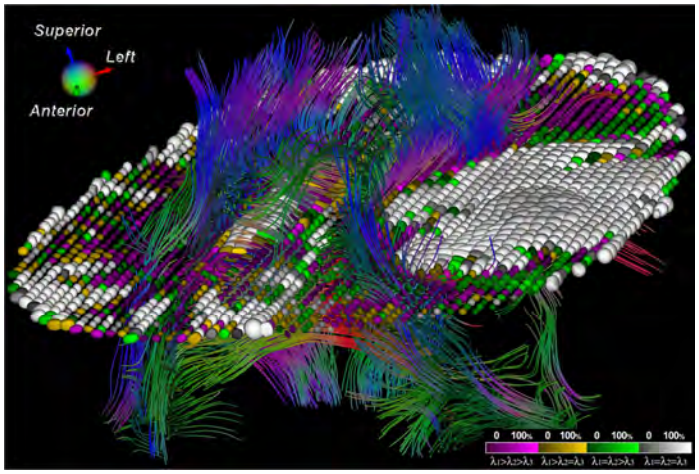


Figure 4: (A) Supertoroidal glyph field exhibiting a GBM in a mid-axial brain slice location, color-coded with eigenvalue configuration. Tumor and surrounding edema can be differentiated based on eigenvalue configurations. Surrounding WM tracts are pushed away from their normal trajectories as a result of tumor growth.

References:

1) Lerner A, et. al., World Neurosurgery, 2014; 2) Schultz T and Kindlmann GL, IEEE Trans Vis Comput Graph 2010;
3) Hoefnagels FW, *et al.*, J Neurooncol, 2014; 4)Mekkaoui, et al., ISMRM 2012.