Evaluation of a Novel Continuously Distributed Diffusion Model in Normal Human Brain

H. Wang[1], Y. Zhang[1], and G. Cao[1]
[1]Global Applied Science Laboratory, GE Healthcare, Shanghai, Shanghai, China, People's Republic of

Introduction: Quantitative modeling of diffusion in biological tissues has remained a challenge. Le Bihan et. al. proposed a bi-exponential model assuming a combination of a slow and a fast component to separate molecular diffusion and microcirculation or blood perfusion [1]. The bi-exponential model shows superiority to the previous mono-exponential model because the diffusion-weighted signal decay in normal and tumorous tissues shows a multi-exponential characteristic. However, the bi-exponential model lacks the capability to describe a larger number of pools with more diffusion components. Further studies of animal and human brain tissues revealed that the simple categorization of fast and slow elements being extra- and intracellular water pools could be barely supported by empirical results [2]. In this study, a novel continuously distributed exponential model based on the regularized nonnegative least square (NNLS) algorithm [3] was explored to preclude the assumption about the number of diffusion components. We investigated the behavior of the continuously distributed diffusion coefficients in cerebral white matter from a healthy volunteer considering the different diffusion rates between the longitudinal and axial directions along the fiber tracts. Gray matter and CSF were also evaluated for comparison.

Materials and Methods: A continuously distributed exponential model can be mathematically described as follows: $S(b)/S(0) = \int A(D)\exp(-b\times D)dD$, where S is signal intensity and A(D) is the proportion of tissues with specific diffusion coefficient D. The regularized NNLS was performed to get A(D) in continuous distribution. An in-house software program implementing the above algorithm was developed in the Pascal programming language to process the acquired diffusion-weighted images with different b-values. All studies were performed on a GE 3.0-T Signa MR scanner (GE Healthcare, Milwaukee, WI) with an eight-channel phased-array head coil. Diffusion-weighted images were acquired using the following parameters: 16 axial slices, FOV 240 x 240 mm, matrix 128 x 128, thickness/gap 5/1.5 mm, TE/TR 100/4000 ms. Twenty-one b-values included 0, 10, 20, 50, 100, 200, 300, 400, 600, 800, 1000, 1200, 1500, 1800, 2100, 2400, 2700, 3000, 3300, 3600, 4000 s/mm^2 measured with three mutually orthogonal diffusion encoded directions plus 3 averages. For the purpose of region of interest (ROI) selection, a diffusion tensor dataset was also acquired to provide the information about the orientation of underlying cerebral white matter fiber tracts. Figure 1 shows the ROIs manually placed on three mutually orthogonal white matter fiber tracts calculated from the DTI dataset (1: Superior-Inferior, 2: Left-Right, 3: Anterior-Posterior). ROIs located in the gray matter and cerebrospinal fluid (CSF) regions were selected from a T1-weighted image acquired during the same exam (Fig. 2). The T1-weighted, diffusion-weighted and diffusion tensor images were co-registered together before ROI selection.

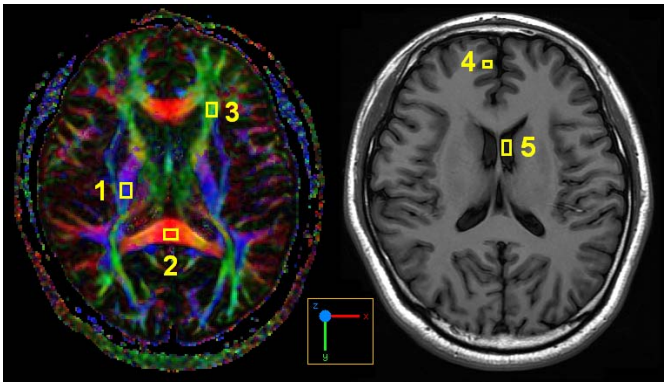

Fig. 1 ROIs selected on a DTI colormap (left) and T1-weighted image (right), ROIs 1-3 from white matter fiber tracts with mutually orthogonal orientation, ROIs 4 and 5 from gray matter and CSF.

Results: Figure 2 shows the raw diffusion-weighted signal intensity versus different b-values and fit curves from the white matter fiber tract oriented at the superior-inferior direction (Fig. 2a, ROI 1), gray matter (Fig. 2b) and CSF (Fig. 2c) along different diffusion encoded directions. The distribution of diffusion coefficients from the fiber tracts oriented at the other two directions (ROIs 2 and 3) shows a quite similar pattern as compared to ROI 1 (data not shown). The peak positions are located at 1.03, 0.99, 1.78 um^2/ms along the L-R, A-P and S-I directions respectively within the superior-inferior fiber tract (Fig. 2d). For gray matter and CSF, the peak positions of the diffusion coefficients are consistent in all three orientations (Fig. 2e and 2f). CSF has a higher peak value at 3.32 um2/ms than gray matter at 0.83 um^2/ms.

Discussion: In this preliminary study, the regularized NNLS provided a good fit to the signal decay in the volunteer diffusion experiment. White matter showed different diffusion rates among three orthogonal orientations as contrast to CSF and gray matter with similar diffusion rates in all directions. More widely dispersed diffusion distribution in white matter benefits from the application of the continuously distributed exponential model. This technique may be used to characterize diffusion heterogeneity in different types of tumors in further investigation.

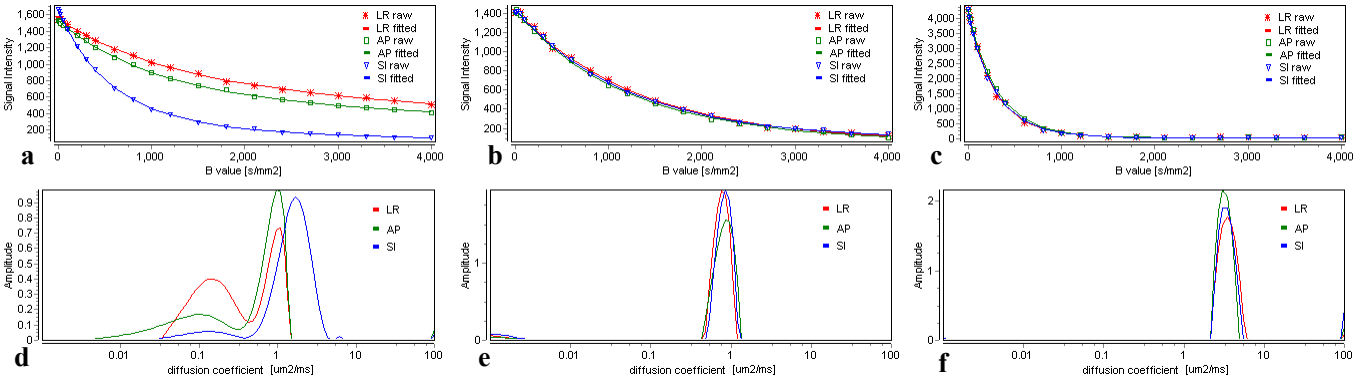

Fig. 2 Raw diffusion-weighted signal intensity along with fit curves (a-c) and calculated diffusion coefficient distribution (d-f). The diffusion encoded directions were LR (red), AP (green), and SI (red).

Reference: [1] Lee JH, et al., Radiology. 1988;168(2):497-505. [2] Lee JH and Springer CS, Magn Reson Med. 2003;49(3):450-458. [3] Lawson CL and Hanson RJ, Solving Least Square Problems. Prentice-Hall, Englewood Cliffs. NJ, 1974.