Optimal Imaging Parameters for Minimum Angular Discrimination in Diffusion Spectrum Imaging

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Introduction Diffusion Spectrum MRI (DSI) can define complex oriented coherence accurately by mapping 3D probability density function (PDF) of water molecular diffusion within each MRI voxel [1, 2]. However, the optimal imaging parameters for DSI to discriminate crossing fibers have not been studied yet. In this study, Monte-Carlo simulation was used to optimize the DSI imaging parameters, such as diffusion time, duration of diffusion gradients, and b-value, for intersecting fiber mapping. We synthesized diffusion MRI measurements of two micro-structural crossing fibers both with diameter equaled to 5μm. A simple simulation model to simulate the distribution of water molecules within these two nerves in finite diffusion time was used. The results showed that DSI could map fibers intersected at a big angle, e.g. 80°, with b value of 2500 s/mm^2. To map crossing fibers at a smaller angle such as 60° with b value of 2500 s/mm^2, diffusion time >> diffusion duration is requested. Furthermore, to discriminate crossing fibers at a small intersecting angle (≤ 30°), longer diffusion time for water molecules to space the restrictive boundaries is necessary. Diffusion time >> diffusion duration is not necessary if b-value is high enough (> 7500 s/mm^2). In consideration of T2 decay and SNR effects under the clinical gradient limitation (≤ 4 Gauss/cm), how DSI discriminate fibers intersected at a small angle is highly correlated with b-value selection.

Methods A Monte-Carlo simulation model was used to simulate random molecular diffusion processes within a MR voxel in a three-dimensional space. Two dominant micro-cylindrical crossing fibers, ID = 5μm, with impermeable boundaries were studied. The molecular exchange between internal and external space was neglected due to the assumption that exchange time will be larger than diffusion time for molecular distribution within tracts [3]. The numbers of molecules entering and exiting the voxel were assumed to be the same. Only diffusion signals within the tracts were therefore calculated according to the formula: $M(\mathbf{q})/M_o = \iint \exp(i\mathbf{qR})\, P(\mathbf{R}, \Delta) d\mathbf{R}$ exp(-TE/T2) [6], where M and M_o are diffusion signal and reference signal respectively, R is the relative displacement of molecules, and P is the probability of molecular displacement **R** within diffusion time Δ. **q** = γgδ, where g is the diffusion gradient strength, and δ is the diffusion duration. T2 of white matter in human brain, 67 ms, was considered [5]. Finite δ equaled to 4 ms was studied first to find the optimal Δ. Diffusion time Δ of 40 ms was then further studied to evaluate the effect of diffusion duration δ. In consideration of clinical limitation, i.e. g_{max} = 4 Gauss/cm, Δ≒δ was studied to optimize b value for crossing fiber differentiation. Two cases were considered to simulate conventional diffusion spin echo and diffusion EPI sequence, i.e. TE = Δ+δ+2 ms and TE = Δ+δ+20 ms. SNR of >20, 15, 10, and 5 were studied to evaluate the effect of T2 decay. The reconstruction of DSI data, M(**q**), was based on the relationship between echo signal (M(**q**)) and diffusion PDF (P(**R**)) which were a Fourier pair, namely, M(**q**) =F[P(**R**)] [4]. The angle between maximum PDF orientations that is the crossing angle was calculated. To determine the minimum angular resolution (MAR), one of the intersecting PDF orientations was served as a standard. The deviation angle between this PDF orientation and the simulation fiber which was less than 5° was requested. Minimum angular resolution was then calculated from the crossing two PDF orientations.

Results With fixed diffusion duration of 4 ms, Fig. 1 showed the relationship between MAR and diffusion time under finite δ of 4 ms, with b value from 2500 to 25000 s/mm^2. With b value of 2500 and 5000 s/mm^2, minimum angular resolution is limited to respectively 58° and 37°. With b value higher than 7500 s/mm^2, minimum angular resolution of 26° can be differentiated as diffusion time increases. Angular error is minimized with diffusion time of 40 ms, which is 10-fold of diffusion duration. Fig. 2 showed the effect of diffusion duration with various b values. With the same diffusion time of 40 ms, the best angular resolution was always achieved under Δ >> δ. Fig. 3 showed the angular resolution under various b-values with gradient strength = 4 Gauss/cm. To minimize T2 decay effect, diffusion time was usually close to diffusion duration to achieve higher b value. The results showed that DSI could map 80° intersecting fibers with b-value of 2500 s/mm^2. To minimize the angular resolution, higher b-value is requested. The optimum b-value to differentiate small crossing angles under clinical gradient limitation is around 17000 s/mm^2.

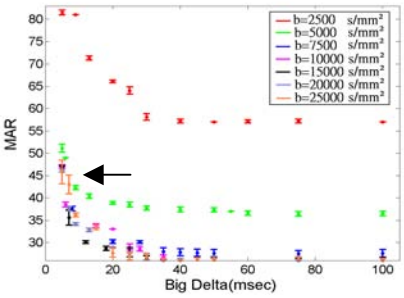

Fig. 1, With finite δ =4 ms, best MAR is achieved with b > 10000 s/mm^2 and longer Δ.

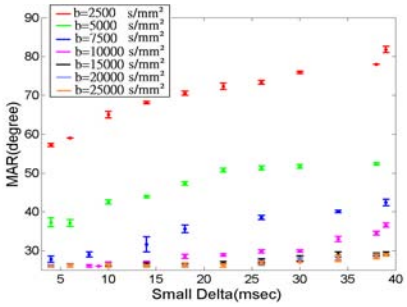

Fig. 2, With finite Δ =40 ms, distance of molecular diffusion was fixed. Ratio between δ and Δ was studied.

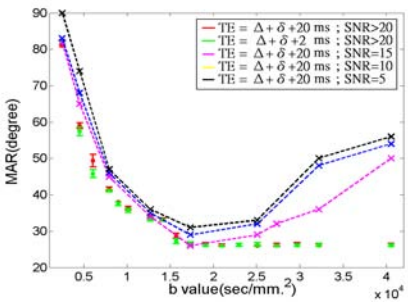

Fig. 3, With gradient =4 Gauss/cm, clinical situation was studied. MAR is highly correlated with b selection.

Discussion DSI can define complex fiber coherence accurately by the measurement of diffusion probability. To map fibers at a small crossing angle, we summarized some criteria for parameter selection: (1) Higher b-value is generally necessary to differentiate smaller intersecting fibers. (2) Diffusion time should be long enough for molecules to space the restricted boundary. Otherwise, minimum angular resolution can only achieve at about 45° while Δ≒δ even though b value was large as 25000 s/mm^2 (arrow point in Fig. 1.) (3) Diffusion time >> diffusion duration is not necessary to discriminate small crossing angle if b is large enough. On the contrary, with low b-value encoding, diffusion time >> diffusion duration is requested to improve the angular resolution. (4) Diffusion time = 10 diffusion duration is almost close to the request of diffusion time >> diffusion duration for q-space encoding. (5) Under clinical gradient limitation, mapping of fibers intersected at a small crossing angle is possible but high b-value is requested. The optimum b value is 17000 s/mm^2 in consideration of T2 decay and SNR.

We have discussed that diffusion time >> diffusion duration is not necessary for fibril orientation mapping using DSI method [2]. To map fibers at small intersecting angle, higher b-value is suggested. Another factor might affect the minimum angular resolution of DSI is the number of encoding points. In this study, 515 points with the radius of 5 in q-space sphere within a 3D Cartesian lattice was encoded. The angular resolution of this encoding number can be estimated to be 2 arctan (1/5) = 22.6°, which is close to our results of 26° in this study. To improve the angular resolution, more encoding points might be necessary but the acquisition time will dramatically increase. In conclusion, this study has optimized the DSI encoding parameters under the consideration of mapping small angular crossing. Some criteria have been concluded for the selection of encoding parameters. Under clinical gradient limitation, DSI is capable of mapping fiber orientation accurately with optimum parameters selection. This study also provides a criterion for further tracking algorithm development.

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