Mapping Relative Fiber Density with Composite Q-Ball and Diffusion Tensor Imaging

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Introduction

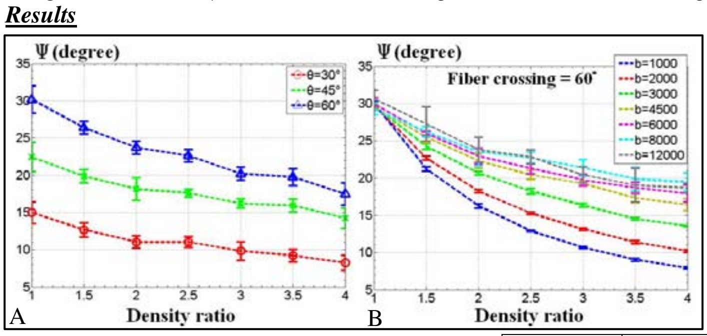
Knowledge of neuronal circuit and neuronal integrity is crucial for the comprehension of brain architecture and function. In this study, the mapping of relative fiber density for crossing fibers is demonstrated by a composite technique of q-ball imaging (QBI) [1] and diffusion tensor imaging (DTI) [2]. QBI can be used to resolve intravoxel multiple fiber directions by measuring the diffusion orientation distribution function (ODF) based on Funk-Radon transform (FRT) of the diffusion signals. The additional diffusion tensor analysis of the acquired data is suggested to calculate the principle eigenvector map, by which relative neural fiber density of crossing fibers could be quantified through angular differentiation. Both Monte Carlo simulation and MR phantom models were studied to assess the performance of the presented technique. QBI of Monte Carlo simulation showed that the angular discrimination was not altered by varying density ratios of the crossing fibers. By contrast, the principle eigenvector of DTI has a tendency toward the dominant distribution of the crossing fibers. The variation of the principle eigenvector was found to be proportional to the density ratio of the crossing fibers. Similar results were observed in 45° and 60° crossing phantom studies. In conclusion, this study proposes a method to quantify fiber distribution based on a composite technique of QBI and DTI. The potential of it could be further applied to map complex neuronal fiber orientations and to quantify fiber density distribution in biological system.

Materials and Methods

The proposed technique was evaluated by computer simulation and MR phantom models. Random walk diffusion Monte Carlo simulation model was used to simulate 3-D molecular diffusion process [3]. Two cylindrical fibers system with i.d. of 5 μm was considered in this study. The density ratios between two fibers ranging from 1:1 to 4:1 were achieved by modulating numbers of water molecules contained in each fiber. The angles between crossing fibers (θ) were set at 30°, 45°, and 60°. Diffusion signals were calculated along 162 directions with b-value = 8000 sec/mm^2. In addition, the variations of the principle eigenvector of DTI under different b-values were studied to assess the dependence of b-value selection. In MR phantom study, both 45° and 60° crossing phantoms were constructed by well arranged plastic capillary tubing with i.d./o.d. = 20/90 μm [4]. MR experiments were performed at a 9.4 T MRI system (Bruker, Germany). Diffusion weighted images were acquired by stimulated echo diffusion sequence along 162 directions, with Δ/δ = 200/3 msec, b-value = 8000 sec/mm^2, and imaging resolution = 0.625×0.625×3.6 mm^3. Data were acquired with fiber density ratios of 1:1, 2:1, and 3:1 for both 45° and 60° crossing phantoms.

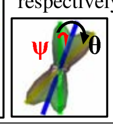
For both simulated and experimental diffusion data, FRT was applied to reconstruct the ODFs, and the angles between the primary orientations of ODFs (Φ) were calculated. Diffusion tensor analysis was subsequently performed on the acquired diffusion signals. The angle between dominant distribution of the crossing fibers and 1st eigenvector of DTI (ψ) was measured to investigate how the direction of 1st eigenvector (blue lines) varied at different density ratios among crossing fibers.

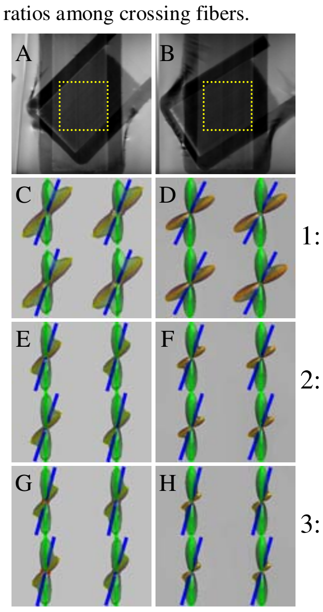
Results



▲ **Fig. 1**. The Monte Carlo simulation study. The values of ψ declined proportionally to the density ratio of crossing fibers (Fig. 1A). Several b-values were applied to assess the dependence of ψ on the b-value selection (Fig. 1B).

► **Fig. 2**. T2WI of 45° and 60° crossing phantoms (A, B). ODFs and principle eigenvectors of DTI (blue lines) are reconstructed to illustrate their changes to the density distribution of the crossing fibers. Figure (C, D), (E, F), and (G, H) are the results of fiber density ratio of 1:1, 2:1, and 3:1 of 45° and 60° crossing phantom, respectively.





► **Table 1**. Quantitative analysis of the crossing phantom model. The proposed technique can differentiate crossing fibers and estimate fiber density distribution.

	Phantom 45°		Phantom 60°	
Density ratio	Φ (QBI)	ψ (DTI)	Φ (QBI)	ψ (DTI)
1:1	44.9° ± 0.3°	21.8° ± 2.1°	59.0° ± 2.3°	29.7° ± 2.7°
2:1	43.3° ± 3.5°	16.4° ± 1.7°	57.2° ± 0.9°	22.9° ± 1.2°
3:1	43.0°± 3.8°	10.8° ± 2.5°	56.2° ± 1.9°	18.5° ± 1.7°

The results of Monte Carlo simulation were shown in Fig. 1. In Fig. 1A, the values of ψ approximated to vary linearly with the density ratios changing from 1:1 to 4:1, which meant that the principle eigenvector of DTI had a tendency toward the dominant fiber distribution among two crossing fibers. Fig. 1B showed the dependence of ψ on b-value selection. The results showed that larger deviations were produced when b-value was up to 12000 sec/mm^2, which may be caused by the noise contamination. Since QBI with lower b-value results in insufficient angular discrimination [4], thus b-values between 3000 sec/mm^2 and 8000 sec/mm^2 were suggested for the proposed technique. Fig. 2A and 2B were the high resolution T2-weighted images of 45° and 60° crossing phantoms respectively. The results of 45° and 60° crossing phantoms under density ratio of 1:1, 2:1, and 3:1 were shown in Fig. 2 (C, D), (E, F), and (G, H), respectively. The directions of local maximum vectors of ODF were not influenced by the fiber density ratio but the measured principle eigenvector of DTI was observed to approach the dominant fiber orientation. The results were correspondent with the simulation study. Further quantitative measurements of Φ and ψ were summarized in Table. 1. It demonstrated that the resolved intravoxel crossing fibers (Φ) remained consistent meanwhile the values of ψ linearly decreased as the density ratio increased.

Conclusion

A promising method that comprises QBI and DTI methodology to map relative fiber distribution is proposed in this study. Linear relationship between the fiber density ratio and the variation of principle eigenvector of DTI were observed in both simulation and phantom studies. Therefore, quantitative fiber distribution of each voxel could be estimated based on the proposed technique. The behavior of the princile eigenvector of DTI could be explained by the combination of two ADC profiles while the principle direction is predominated by the one that has higher neuronal fiber density [5].

Acknowledgements

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References

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