Comparison between Q-Ball Reconstructions Using Radial Basis Function and Spherical Harmonic Basis

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Introduction

Q-ball imaging (QBI) estimates the orientation distribution function (ODF) by applying Funk-Radon transform on high angular resolution diffusion imaging (HARDI) data and can map cerebral white matter integrity [1]. To improve the accuracy of QBI in estimating fiber orientations, Hess *et al.* reformulated *q*-ball reconstruction using the spherical harmonics basis functions (SHB QBI) [2]. In this study, we systematically compared the accuracy in resolving fiber crossing between the conventional QBI and SHB QBI using a crossing phantom with a separation angle of 45°. The results showed that SHB QBI can increase the percentage success rate in resolving fiber crossing, while it may underestimate the separation angle using an insufficient b-value.

Methods

The crossing phantom model with a separation angle of 45° was built by water-filled plastic capillaries with internal and external diameters of 20 μm and 90 μm respectively [3]. Diffusion-weighted (DW) images were acquired at a 9.4 Tesla MRI system (Bruker, Germany) using a stimulated echo pulsed gradient sequence with the following parameters: voxel dimensions = 0.78 × 0.78 × 3.6 mm^3, TR = 3,000 ms, TE = 13.8 ms, diffusion gradient duration δ = 3 ms, and diffusion time Δ = 100 ms. The diffusion time of 100 ms gives a root-mean-square diffusion distance equal to the internal diameter of the capillary and thus is sufficient to generate anisotropic diffusion. Four datasets were acquired with b-values = 3,000, 4,000, 5,000, and 6,000 s/mm^2. In each dataset, DW images were encoded with 162 sampling points (4-fold tessellated icosahedrons) in *q*-space, yielding an angular resolution of 17°. To reduce the cross-term effect, geometric averaging was performed on the DW images acquired with the opposite polarity diffusion gradients prior to ODF reconstruction [4].

The conventional QBI was applied to reconstruct the ODFs using spherical radial basis function (sRBF) [1]. The width of interpolation kernel was calculated to minimize the condition number of the RBF interpolation matrix. The number of points on the equator was set to be 48. For SHB QBI, the reconstruction was based on the matrix implementation [2]. The harmonic order was varied from 4 to 16. All the ODFs were reconstructed with 2,562 points (16-fold tessellated icosahedrons), giving an angular sampling resolution of 4°. The primary orientations of ODF were defined as the fiber orientations.

Results

The results of the success rate for resolving crossing fibers are summarized in Table 1. For both RBF QBI and SHB QBI, increasing the b-value was helpful to improve the success rate in discriminating crossing fibers. At a relatively low b-value of 3,000 s/mm^2, SHB QBI with a higher harmonic order ($L \geqq 12$) was better than RBF QBI. Across all b-values, the success rates were reduced using low harmonic orders (L = 4, 6, and 8) in SHB QBI.

Table 2 shows the results of accuracy in revolving a crossing angle of 45° through the separation angle. Under a particular b-value, there were no significant differences in separation angles between RBF QBI and SHB QBI with L from 8 to 14. However, the crossing angle was further underestimated when a relatively low ($L \leqq 6$) or high ($L \geqq 16$) harmonic order was used in SHB QBI.

Fig. 1 shows the results of ODFs together with their main fiber orientations reconstructed using RBF QBI and SHB QBI (L = 14). For both methods, sharper ODFs, which indicate crossing fibers can be resolved easier, were obtained through applying a higher b-value.

Discussion

This study shows that RBF QBI and SHB QBI are capable of resolving fiber orientations accurately, while SHB QBI using various harmonic orders is more flexible for data analysis. In addition, the efficiency in calculating the reconstruction matrix is remarkably higher in SHB QBI than that in RBF QBI. The ODF reconstruction using SHB method with L = 16 took 1 % of the computing time using RBF method in this study.

The results in Table 2 imply that the harmonics order between 8 and 14 may be better for SHB QBI regarding to the angular accuracy. However, both RBF and SHB QBI can lead to underestimation of the crossing angle if an insufficient b-value is used. According to the results in this study, such error can be reduced through an adequate b-value selection in the considerations of the angular resolution and the SNR of DW images [3, 5]. Therefore, we conclude that b-value is the predominant factor to determine the intrinsic angular resolution in QBI.

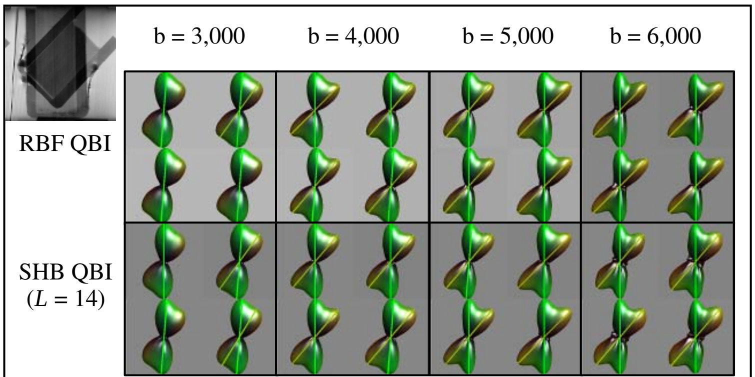

Fig.1 The ODFs overlaid by the main fiber orientations for RBF QBI and SHB QBI (L = 14). Phantom data were acquired at b-values of 3,000, 4,000, 5,000, and 6,000 s/mm^2.

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	RBF	L = 4	L = 6	L = 8	L = 10	L = 12	L = 14	L = 16
b = 3,000 s/mm^2	27.3	0	0	9.1	24.2	30.3	39.4	97.0
b = 4,000 s/mm^2	100	0	24.2	97.0	100	100	100	100
b = 5,000 s/mm^2	100	0	72.7	100	100	100	100	100
b = 6,000 s/mm^2	100	0	90.9	100	100	100	100	100

Table 1. The successful rate (%) for resolving fiber crossing using RBF QBI and SHB QBI.

References

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	RBF	L = 4	L = 6	L = 8	L = 10	L = 12	L = 14	L = 16
b = 3,000 s/mm^2	32.5° ± 2.0°	X	X	31.5° ± 0.0°	32.1° ± 1.6°	32.0° ± 2.6°	31.2° ± 2.9°	32.2° ± 2.4°
b = 4,000 s/mm^2	40.1° ± 2.7°	X	32.1° ± 1.6°	39.6° ± 2.4°	40.2° ± 2.5°	40.7° ± 2.2°	39.8° ± 2.1°	35.9° ± 1.5°
b = 5,000 s/mm^2	43.6° ± 2.3°	X	35.8° ± 2.1°	43.2° ± 2.2°	43.7° ± 2.3°	43.9° ± 1.9°	42.1° ± 2.9°	38.7° ±2.6°
b = 6,000 s/mm^2	44.3° ± 1.5°	X	38.1° ± 4.1°	44.5° ± 1.5°	44.1° ± 1.9°	44.5° ± 1.4°	44.6° ± 1.7°	39.9° ± 2.3°

Table 2. Separation angles for RBF QBI and SHB QBI with different harmonic orders. Separation angles are represented in the form of mean ± standard deviation. “X” means that the method failed in identifying two primary directions in every voxels.