Determining optimum b maximum values for diffusion spectrum imaging and q-ball imaging in clinical MRI system

L-W. Kuo[1], V. J. Wedeen[2], C. Mishra[3], T. G. Reese[2], J-H. Chen[1], and W-Y. I. Tseng[4,5]

[1]Interdisciplinary MRI/MRS Lab, Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, [2]MGH Martinos Center for Biomedical Imaging, Harvard Medical School, Charlestown, MA, United States, [3]School of Medical Science and Technology, Indian Institute of Technology, Kharagpur, West Bengal, India, [4]Center for Optoelectronic Biomedicine, National Taiwan University College of Medicine, Taipei, Taiwan, [5]Department of Medical Imaging, National Taiwan University Hospital, Taipei, Taiwan

Introduction

In clinical MRI systems, both diffusion spectrum imaging (DSI) and q-ball imaging (QBI) were validated to provide better accuracy in defining complex neural fiber structures than reconstruction methods based on Gaussian model [1-5]. With fixed diffusion encoding gradient numbers, the accuracy to resolve complex orientations highly depends on the maximum b-value (bmax) and signal-to-noise ratio (SNR) of the diffusion dataset. However, to acquire DSI and QBI datasets with different bmax from a single subject is difficult due to exceedingly long scan time. The purpose of this study is to use a systematic method to determine the optimum bmax of both DSI and QBI with fixed gradient numbers using a simulated approach. The accuracy was quantified as the deviation angle and the optimum bmax can be determined from the comparison.

Materials and Methods

Diffusion data were obtained from five healthy volunteers on a 3T MRI system (Trio, Siemens, Erlangen, Germany). To reduce the eddy current effect, twice-refocused balanced echo diffusion EPI sequence was used to acquire MR diffusion images. A highly sampled diffusion data with bmax of 9000 s/mm^2 and 925 diffusion gradients were acquired to fill the grid points over the 3D q-space [6]. Isotropic voxels were obtained by setting in-plane resolution and slice thickness to be 2.9 mm. Fifteen slices were acquired and the total scan time was less than one hour (TR/TE = 2900/150 ms). The analysis was separated into three main procedures: sub-sampling, reconstruction and comparison. In the first step, both DSI and QBI datasets were interpolated from the original diffusion data. For DSI, two fixed gradient numbers, 203 and 515, were used as the sub-sampled data sets with bmax = 1000, 2000, 3000, 4000, 5000, 6000 and 7000 s/mm^2. To obtain comparable QBI datasets, 253 and 493 gradient numbers were sub-sampled using a QBI shell encoding method with bmax equaled to those in DSI, except an additional bmax of 500 s/mm^2. DSI analysis was based on the relationship that the echo signal $S(\mathbf{q})$ and the diffusion probability density function $P(\mathbf{r})$ (PDF) were a Fourier pair, i.e., $S(\mathbf{q}) = FT\{P(\mathbf{r})\}$ [2;7]. The integration of $P(r)\, r^2$ along each radial direction was used to calculate the orientation distribution function (ODF). QBI reconstruction was based on the Funk-Randon transform and the ODF was obtained directly by this procedure [4]. To compare each DSI or QBI dataset, a gold standard DSI data set of 691 gradient points and bmax of 7250 s/mm^2 was used. This ensured better SNR and enough sampling rate. Deviation angle comparison between each DSI or QBI sub-sampled data set and the gold standard was performed to quantify the accuracy. A threshold of the numbers of the main orientations from the gold standard DSI data was used to divide the voxels into single-fiber and crossing-fiber groups. In the single-fiber group, only the maximum vector in the gold standard was used for comparison. For the crossing-fiber group, the first and second vectors were studied and compared.

Results

All five subjects showed consistent results of simulation. As shown in figure 1a, the color-coded vectors represent the main orientations within each voxel of the gold standard DSI, showing well-organized structures in the white matter. The reconstruction results of DSI and QBI of single slice were shown in figure 1b and the corresponding bmax and gradient numbers were listed to summarize the sub-sampling schemes. The results of the deviation angle and bmax of each DSI or QBI method were shown in Table 1. Among the single-fiber groups, DSI of 515 gradients has the lowest deviation angle (7.72°) and the highest bmax of 6400 s/mm^2. With DSI of 203 gradients, a lower optimum bmax, 3800 s/mm^2, was obtained to achieve deviation angle of 9.99°. For QBI, both 253 and 493 gradients had the angle deviation of around 12° with the optimum bmax around 1500 s/mm^2. For the crossing-fiber groups, the deviation angles were in the range of 23° to 31°, with DSI being a little bit better than QBI. The optimum bmax for DSI was 3000 s/mm^2 for 203 gradients and 6000 s/mm^2 for 515 gradients, while QBI was 1800 s/mm^2 for both 253 and 493 gradient directions.

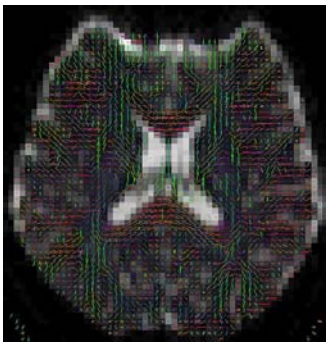

Figure 1a. Color-coded DSI map of the gold standard (red: transverse; green: anteroposterior; blue: axial)

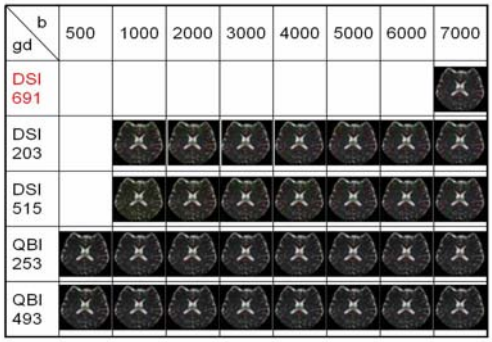

Figure 1b. DSI and QBI reconstruction of each gradient number with different bmax.

Methods	DSI203	DSI515	QBI253	QBI493
Deviation angle of single-fiber group	9.99°	7.72°	12.43°	12.35°
bmax of single-fiber group (s/mm^2)	3800	6400	1400	1600
Deviation angle of crossing-fiber group (fiber-ratio >= 0.7)	26.70°	22.50°	31.27°	31.38°
bmax of crossing-fiber group (s/mm^2)	3000	6000	1800	1800

Table 1. Comparisons of average deviation angle and optimum bmax of each DSI or QBI method with fixed gradient numbers. Results were classified into single-fiber and crossing-fiber groups.

Discussion and Conclusion

In this study, the optimum bmax of DSI and QBI with different gradients for our 3T system were determined. In QBI, the optimum bmax for single-fiber estimation is slightly higher than what has been used for diffusion tensor imaging. For crossing-fiber estimation, however, the optimum bmax is lower than the empirical values and requires experimental verification. In DSI, the optimum bmax for both single and crossing fibers are comparable. The more the gradients numbers, the higher the optimum b values are. In conclusion, both DSI and QBI have trade-offs in clinical applications. For QBI, the scan time and gradient performance are relatively feasible in the clinical setting. Although DSI requires longer sampling time and higher gradient performance, it is more accurate and the measured PDF can be further utilized to derive relevant indices such as diffusion coefficients.

Reference

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