Optimization of b-Factor in Diffusion Circular Spectrum Mapping for Identifying Intravoxel Fiber Crossings

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Synopsis

A study is present to optimize the b-factor for the recent developed diffusion circular spectrum mapping (DCSM) technique, which is able to identify fiber crossings in the human brain. The 4th-order DCSM maps were calculated on a digital phantom with different b-factors at various SNR levels. The contrast-to-noise ratio (CNR) between fiber-crossing area and planar area was used to specify the effectiveness of the 4th-order map. Results indicated that a higher SNR leads to a higher CNR of the 4th-order map. For a fixed SNR, the maximum CNR can be obtained when an optimized b-factor (2000-2500 s/mm^2) is applied.

Introduction

The primary advantage of the diffusion circular spectrum mapping (DCSM) [1] over regular diffusion tensor imaging (DTI) [2] is the ability to identify intravoxel fiber crossings [1]. However, this ability is weakened by the relatively high sensitivity to noise in the 4th-order DCSM map. Generally, a higher b-factor is favorable for the 4th-order map to identify fiber crossings in a noise-free environment [1], but the relationship is much complicated for in vivo diffusion measurements. The aim of this study is to tackle this problem by choosing an optimized b-factor in the high-angular resolution diffusion MRI experiment with respect to different SNR levels. A digital phantom was constructed to simulate various diffusion patterns, and the contrast-to-noise ratio (CNR) of the 4th-order map in the fiber-crossing area was calculated to characterize its ability of identifying fiber-crossings. A CNR "surface" with respect to b-factor and SNR was obtained, and an optimized b-factor can be determined by the CNR surface according to SNR levels. Experiments on human brain were also performed to validate the simulation results.

Methods

A digital phantom (Fig.1) was used to simulate various objects with different diffusion patterns. Spherical objects (I and II) had isotropic and planar diffusion patterns, with eigenvalue ratios of 1:0.95:0.9 and 1:0.95:0.1 respectively. Cylinder objects (III, IV, V, and VI) had linear diffusion pattern with eigenvalue ratio 1:0.1:0.1, and the major eigenvector was placed parallel to the cylindrical axis. The axis of object VI was perpendicular to the imaging slice. Fiber intersection (A)(B)(D) and fiber dispersion (kissing) (C) were simulated in the areas where objects across each other.

The diffusion MRI experiment was simulated on 90 diffusion-encoding orientations equally spaced on a sphere, generating the corresponding 90 diffusion weighted (with a b-factor) images and a non-diffusion reference image. Gaussian distributed noises were deliberately added onto these images at a SNR with respect to the reference image. The 4th-order circular spectrum map was calculated according to the procedures described in [1]. The CNR was estimated by the averaged intensity difference between fiber-crossing area (A) and the planar object II divided by standard deviation of noise in object II. For SNR values at 40, 50, 60, 70, 80, 90, 100, 110, 120, and b-factor at 1500, 1750, 2000, 2250, 2500, 2750, 3000, 3250, 3500 s/mm^2 , this procedure was repeated to calculate the CNR for each (SNR, b-factor) pair.

MRI experiments were performed on normal subjects on a 3T Siemens Allegra scanner, with the same 90 diffusion-encoding orientations as in the simulation. Five coronal slices approximately parallel to the extension of the brain stem were chosen. A diffusion weighted spin-echo EPI sequence was used for acquiring data with TR/TE = 1300/134ms, matrix size = 128x128, NEX = 10, and b-factor at 1750, 2250, 2750, 3250 s/mm^2. CNR values for the in vivo data were calculated similar to the simulation study.

Results

The 4th-order maps of the digital phantom were illustrated in Fig.2 (a)(b) with b factor of 2500 and SNR of 50 and 100 respectively. It is shown that the 4th-order map is able to exclusively identify the fiber-crossing areas (A)(B)(C) and (D). However, with decrease of the SNR, the difference between the fiber-crossing area (A) and the planar object III is getting less significant, indicating the sensitivity to noise of the 4th-order map.

The CNR surface with respect to the array of b-factors and SNR values is plotted in Fig.3. It can be observed that, for a given b-factor, a higher SNR leads to a higher CNR value with an approximately linear relationship. On the other hand, the CNR surface for a given SNR generally has a curve pattern that reaches its maximum at a certain b-factor between 1500 and 3500. Therefore, an optimized choice for b-factor can be obtained at the maximum CNR for a given SNR level. It can be also observed that the optimized b-factor becomes higher with increasing of the SNR. The SNR of the in vivo data with 10 averages were 85-90, and the CNR of their 4th-order maps at different b-factors matched the simulation results well.

Discussions

The pattern of CNR surface over various SNR and b-values can be explanined by following two counteracting facts. First, the 4th-order component of the circular spectrum is propotional to the b-factor in the noise-free orthogonal fiber-crossing mode [1], so a higher b-factor can lead to a higher CNR of the 4th-order map when SNR is sufficiently high. Second, image intensity attenuates more with higher b-factor, resulting in a poorer SNR in the diffusion weighted images and leading to a lower CRN of the 4th-order map. An optimized b-factor can be selected, by compromizing the two competing factors, to improve the sensitivity of the diffusion circular spectrum technique for identifying fiber crossings in the brain.

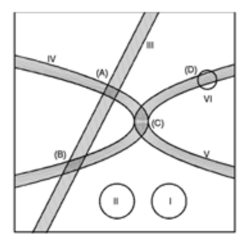
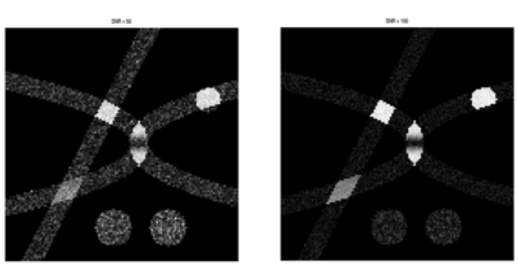


Fig.1: The structure of the digita phantom containing diffusion objects

References

[1] Zhan W, et al, MRM 2003; 49:1077-1083.
[1] Basser PJ et al, MRM 2000; 44: 625-632.



(a) (b)

Fig.2: The 4th order Diffusion Circular Spectrum Map (DCSP) of the digital phantom simulated under differen noise levels. (a): SNR = 50 and (b): SNR = 100.

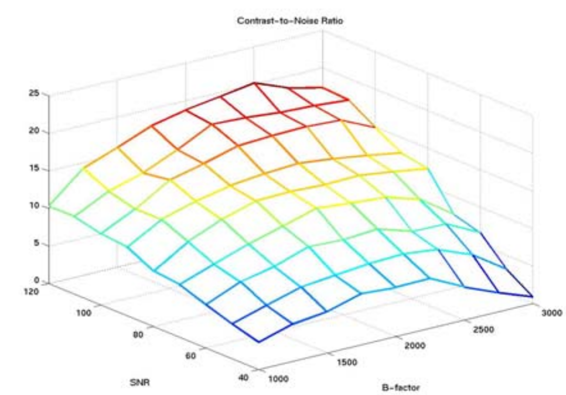


Fig.3: The calculated CNR surface over different b factors (1000 - 3000) and SNR values (40 - 120).