Crossing Fibers, Diffractions and Non-Homogeneous Magnetic Field: Correction of Artifacts by Bipolar Gradient Pulses

A. Bar-Shir[1], and Y. Cohen[1]
[1]School of Chemistry, Tel-Aviv University, Tel-Aviv, Israel

Introduction

In recent years diffusion tensor imaging (DTI) and its variants have been used to describe fiber orientations and q-space diffusion MR was proposed as a mean to obtain structural information on micron scale. Because of its ability to determine axonal fiber directions DTI has become one of the most important technique in neuroimaging [1], although it has some limitation for example in resolving crossing fibers [2]. In view of this, in recent years several approaches were suggested for increasing the accuracy of determining the fiber orientations, especially those of crossing fibers. These approaches include, inter alia, diffusion spectrum imaging (DSI) [3], q-ball imaging (QBI) [4], high angular diffusion imaging (HARDI) [5], and composite hindered and restricted model of diffusion (CHARMED) [6]. Therefore there is an increasing need for complex phantoms with predictable micro-characteristics to challenge different indices extracted from the different diffusion MR techniques used. Recently, such phantoms were constructed and studied on a few occasions. For example, Lin et al. have used a 50-micron phantom of crossing fibers to compare orientational uncertainty in DTI and DSI [7]. Avram et al. have used 20 and 9 micron phantoms to challenge the accuracy of the dimension extracted from q-space diffusion MR [8]. Recently Perrin et al. [9] and Poupon et al. [10] have constructed such phantoms to challenge the efficacy of the QBI approach. In the present study we describe our results on several micron-scale phantoms of increasing complexity and decreased homogeneity which demonstrate the effect of background gradients on the expected diffraction patterns and how bipolar diffusion gradients can partially cancel this type of artifacts.

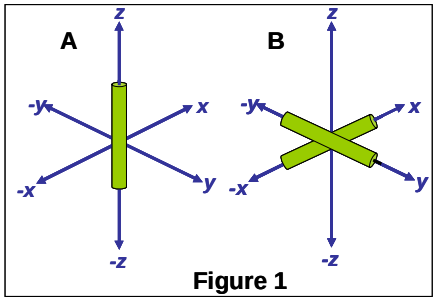

Figure 1

Methods

NMR diffusion experiments were performed on ensembles of hollow cylindrical microtubes having an inner diameter of 48µm. Microtubes of 2cm in length, filled with water, were aligned in an open 2cm-long 4mm NMR tube and arranged in two different experimental setups as shown in Figure 1. We also studied a single sleeve aligned on the x or y direction. All diffusion experiments were acquired with an 8.4T Bruker-Avance NMR spectrometer equipped with a mini-imaging (Mini5) gradient system capable of producing pulse gradients of up to 20Gcm^{-1} in each of the three directions (z, x and y on Figure 1). The diffusion experiments were performed using the pulse gradient stimulated-echo (PGSTE), the longitudinal eddy current delay (LED) and the bipolar-LED (BPLED) sequences with the following parameters: TR/TE/Δ/δ=2500/32/1000/10ms. Pulsed gradient strength (G) was incremented from 0 to 16Gcm^{-1} in 24 steps resulting in q_{max} of 681cm^{-1}. The eddy current delay time (te) between the last two 90^{o} pulses in the LED and the BPLED pulse sequences was set to 40ms.

Results

Figure 2A depicts the normalized water signal decay, on a logarithmic scale, with respect to ***q*** for both the PGSTE and BPLED experiments performed on the setup shown in Figure 1A when diffusion was measured along the x-direction (i.e. perpendicular o the long axis of the microtubes). In these experiments, from $1.22/q_{min}$ (where q_{min} is the same first minima of $E_{(\Delta,q)}$ vs. ***q***), we extracted a diameter of 45.8µm for the microtube, which is in a good agreement with the real diameter of the microtubes (48±1µm). Importantly, here the PGSTE and the BPLED sequences afforded exactly the same results.

Figure 2B presents the signal decay with respect to ***q***, for the crossing-fiber phantom (Figure 1B). This figure shows the differences in the signal decay obtained when the MR diffusion sequence was changed from PGSTE to BPLED while diffusion was measured along the x-direction, i.e., one of the main axes of the phantom (see inset in Figure 2B). Interestingly, diffraction patterns were observed only for the BPLED sequence and not for the PGSTE sequence. It should be noted that the same results were obtained for each sequence regardless whether diffusion was measured perpendicular or parallel to the x or to the y axes (data not shown). For the BPLED sequence, we found the diffraction to have a q_{min} value of 266.5cm^{-1} from which a compartment size of 45.8µm was extracted. Again, this value is in very good agreement with the expectation when diffusion is measured in 48µm microtubes with a δ of 10ms. Importantly, this value is exactly the value found for the single component phantom aligned along the z-direction described in Figures 2A. Only the BPLED sequence, which is able to cancel the effect of background gradients caused by B_0 inhomogeneity, was able to provide the expected diffraction patterns accurately and to give accurate structural information. We also found that this MR diffusion sequence showed high sensitivity to the rotational angle (data not shown). It should be noted that the LED sequence gave the same results as the PGSTE sequence in all studied phantoms.

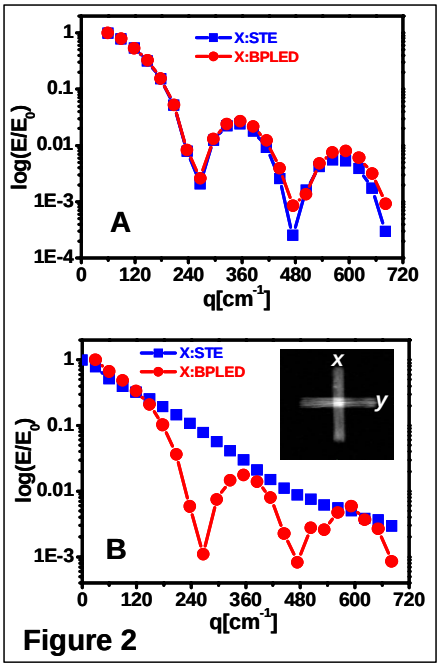

Figure 2

Conclusion

In this study we evaluated, for the first time, the effect of three different diffusion pulse sequences, i.e. PGSTE, LED (data not shown), and BPLED, on the diffraction patterns expected in micron-sized phantoms. In the most homogeneous sample however, the same results were obtained from the PGSTE and BPLED sequences. In the less homogenous sample only the BPLED afforded the expected diffractions. Since the results were similar for the PGTSE and the LED experiments and both were different from the results obtained when the BPLED sequence was used, we conclude that these observations originate from background gradients. This conclusion seems to implicate that when diffusion is measured in inhomogeneous samples with relatively weak gradient systems such as in clinical MRI scanners operating at high fields, bipolar gradient pulses may be found to be beneficial and more artifact free. Therefore it seems that one should consider implementing bipolar gradient pulses in routine DWI or DTI applications.

References

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