Evaluation of Angular Uncertainties of q-space Diffusion MRI Under Finite Gradient Pulse Widths : A Phantom Study

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Introduction

Q-space diffusion-weighted (DW) MR imaging is a valuable technique to evaluate the physiological state and the geometry of tissues. However, in clinical DW imaging protocols, the essential requirement of a short pulse gradient (SPG) is not achievable due to the limited gradient intensity of current MR systems. According to previous studies, finite diffusion gradient pulse widths are generally considered as a deficiency for *q*-space measures of tissue compartmentation [1-3]. Nevertheless, for fibre orientation estimation, prolonging diffusion pulse duration (δ) has been found to be beneficial, as the spin displacement of the averaged propagator is decreased in a restricted tissue environment, such as the transverse directions of axonal fibres [4]. Therefore using a long δ can enhance the overall signal-to-noise ratio (SNR) and the angular contrast of DW signal. However, under practical conditions, a longer δ also leads to a longer echo time (TE), which needs to be taken into account for setting the optimal diffusion imaging parameters. Therefore, in this study we compare the DW signal acquired using various δ with the corresponding minimum TE from a unidirectional DW phantom model. In addition, we performed q-ball imaging (QBI) [5] using the same parameters on a fibre-crossing phantom to compare the angular uncertainties between each condition.

Methods

Experimental data were acquired from a unidirectional and a 45º fibre-crossing phantom constructed using plastic capillaries immersed in water with inner and outer diameters of 20 μm and 90 μm [6]. For both phantoms, DW datasets were acquired using a 2-D FT stimulated echo sequence on a 9.4 T MRI scanner (Bruker, Germany). DW images were acquired using δ = 2, 12, and 36 ms, which results in minimum TE = 12, 32, and 81 ms respectively. A fixed TR = 2,300 ms and an effective diffusion time Δ_{eff} (= Δ – δ/3) = 100 ms were used. For the unidirectional phantom, 40 DW gradient directions were applied at 9º intervals in the plane of the fibres using *b* = 1,000 and 4,000 s/mm^2 (NEX = 5). While for the fibre-crossing phantom, a DW gradient scheme of 160 directions was applied at *b* = 4,000 s/mm^2 (NEX = 4).

For the unidirectional phantom model, the SNR measured on the null DW image (i.e. *b* = 0) of δ/TE = 2/12, 12/32, and 36/81 ms were 10.6, 9.9, and 9.0 respectively. The DW signal of each δ is displayed as a function of the diffusion gradient orientation using polar plots. For the fibre-crossing phantom model, the orientation distribution function (ODF) was reconstructed using *q*-ball imaging (QBI) method for each dataset. The local maximum vector of ODF was regarded as the fibre direction in this study. The angular uncertainties were measured considering the success rate of estimating two distinct fibre directions and the separation angle between these two directions.

Results

Fig. 1 shows the result obtained from the unidirectional phantom. At *b* = 1,000 s/mm^2, the DW signal intensity acquired using δ = 2 and TE = 12 ms was the highest due to less T2-decay. At *b* = 4,000 s/mm^2, although TE was prolonged at a longer δ, the DW signal intensity along various directions were similar between each condition.

Fig. 2 shows the ODF maps obtained from QBI of the 45º fibre-crossing phantom at *b* = 4,000 s/mm^2. The ODF patterns were preserved when a longer δ was used even though the TE was increased. Table 1 summarizes the angular uncertainties of QBI using various δ and TE, showing that the separation angle and success rate between different conditions were not changed significantly at *b* = 4,000 s/mm^2.

Discussion

As a longer δ can preferentially enhance the radial DW signal and thus the angular contrast, it should be advantageous for clinical MR system due to the limited hardware system. The results in this study show that at *b* = 4,000 s/mm^2 the DW signal intensity was maintained using a longer δ, and therefore the angular accuracy in resolving crossing fibres was also maintained even though TE was much longer. On the other hand, the effect of long δ was less evident at *b* = 1,000 s/mm^2 and the overall signal was largely decreased by T2 attenuation. Nevertheless, this study shows that for most current DW MRI techniques to map complex fibre architecture, which utilize intermediate to high *b*-values, the application of a long δ may not be problematic for the purpose of fibre orientation estimation.

References

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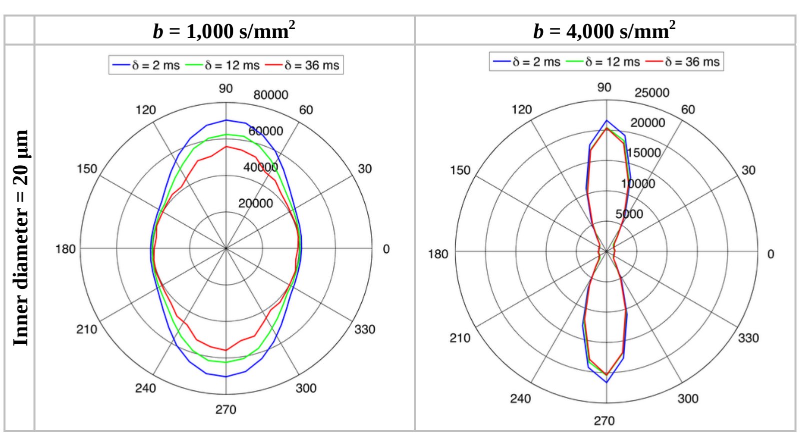

Fig. 1. Polar plots of DW signals derived from a phantom using *b* = 1,000 and 4,000 s/mm^2.

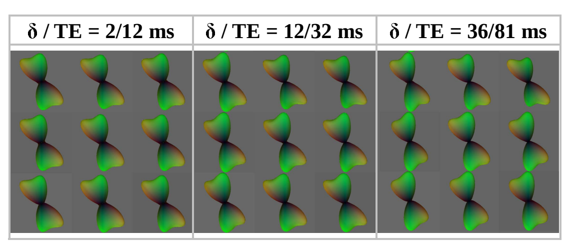

Fig. 2. ODF of QBI obtained using various δ. (*b* = 4,000 s/mm^2)

Table 1. Angular uncertainties in resolving crossing fibres

	Separation angle	Success rate
δ / TE = 2 / 12 ms	40.1° ± 2.3°	96 %
δ / TE = 12 / 32 ms	40.5° ± 2.7°	100 %
δ / TE = 36 / 81 ms	40.5° ± 1.6°	97 %