Reduction of the effect of cardiac-induced motion for typical DTI protocols

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Introduction

Cardiac-induced pulsatile motion can reduce signal intensity in raw diffusion weighted images (DWI). Consequently, gating has been advocated for diffusion tensor imaging (DTI)[1,2]. This recommendation has been made based on the signal reductions observed when diffusion gradients are applied along a single (most sensitive) direction without signal averaging (1-NEX)[1,2]. Gating is not universally adopted, however, because it causes inconsistency in protocol (dependent on heart rate), increased scan time and patient setup. In practice, many investigators do not notice the effects of cardiac-induced artifacts for their protocols and hence do not believe the benefits of gating warrant the sacrifice. A recent comparison of two protocols (with NEX/number of diffusion gradient directions = 6/11 & 2/35) at 3T showed that gating had no statistically significant effect on the resulting FA maps[3].

Purpose

This study investigates cardiac-induced signal reduction for a typical DTI protocol that includes signal averaging by increasing the number of excitations (NEX >1). The goal is to reconcile the seemingly contradictory observations: lack of gating results in signal reduction for 1-NEX DWI and yet FA maps for two protocols (with NEX>1 and number of gradient directions>6) were not significantly affected by gating[3]. The assessment of the effect of cardiac-induced motion for a DTI protocol with NEX > 1 is crucial to evaluate the importance of such an effect when an overdetermined system of equations (>6) is used to calculate tensor values.

Theory

To consider the effect of averaging, assume that cardiac-induced signal reduction can be characterized as discrete and binary: a fraction of the time, represented by probability p , signal, s, is either reduced by a fractional amount f. The probability of such a reduction occurring at a given pixel is given by p ($0<=p<=1$). It is clear that p depends on the timing parameters of the DTI protocol and subject heart rate while f depends on the amount and direction of cardiac-induced motion and the gradient direction. If a DTI volume is acquired many times, for a given diffusion gradient direction, then the expectation value of the signal at a given pixel is given by: $<s>=(1-p)s+p(1-f)s = s(1-fp)$. The signal reduction factor for an averaged DTI volume is therefore approximately fp. For example, taking f=.5 and p=.2 yields only a 10% signal reduction compared to 50% signal loss for a 1-NEX scan. Previous studies[3] show that this decrease in effect, combined with a sampling of more than six directions, makes non-gated DTI an attractive option.

This formulation suggests that although signal fluctuations will decrease as NEX increases, yielding a more reproducible DWI, lack of gating will reduce signal by by an amount fp regardless of NEX. This argument has previously been suggested[2] and is an important consideration when selecting a protocol. Modelling the signal reduction as discrete and binary is a simplification that is often made implicitly. The formulation above can easily be extended to include a more realistic discrete or continuous probability distribution if required.

Methods

Data were acquired on a 3.0T whole-body, research dedicated MRI system (3T Signa EXCITE, E2/M4 software, GE HealthCare, Milwaukee, WI, USA) using a quadrature birdcage headcoil. Three data sets were acquired without gating on a single subject using an EPI-based DTI protocol repeatedly taken at 1 NEX, 2 NEX and 4 NEX (10 times for 1-NEX and 2-NEX scans, 8 times for the 4-NEX scan). Data volumes consisted of 8 slices located in regions known to exhibit cardiac-induced signal reduction[1]. The scanning parameters were: 11 gradient directions, FOV = 240x240mm, 128x128 matrix, slice thickness = 4mm, B-value = 1000

Images of signal variance for repeated 1-NEX measurements were calculated at each slice and for each gradient direction. The average signal in a small highly affected region of the DTI volumes (highlighted in the variance images at 1 NEX) was calculated for each volume of a given data set to estimate the expectation value and fluctuations of the signal in that region for a particular NEX.

Results

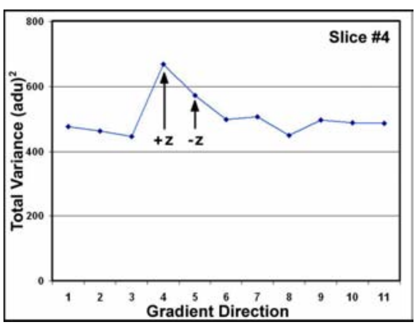

Fig.1 Total variance vs gradient direction for slice #4 of the 1-NEX scans.

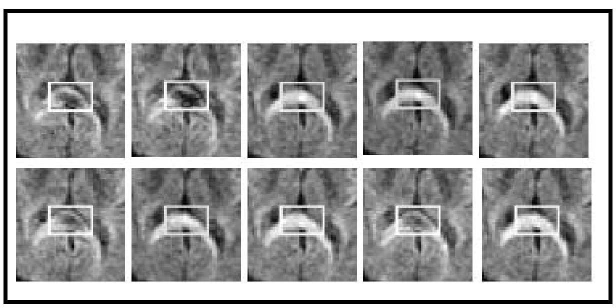

Fig.2 Zoomed DWIs of the region containing the ROI (slice#4) for the 1-NEX scans with diffusion gradient #4.

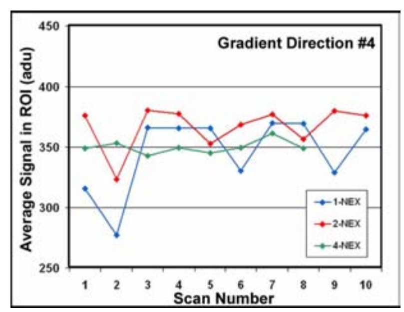

Fig.3 Average signal in the ROI for each scan in a data set.

Each variance image (from the 1-NEX data set) was assigned a total value by summing over all pixel values in the image. This total variance was plotted as a function of diffusion gradient direction for all slices. Only two slices exhibited significant increases in variance for two or three gradient directions (an example is shown in Fig.1). Upon inspection, it was found that the most affected pixels were in the splenium of the corpus callosum when the ±z-direction (through-plane) diffusion gradients were applied (consistent with previous findings[1]). An ROI in this region was selected for further analysis as shown in Fig.2. Fig.3 shows plots of the average signal in the ROI for each image of a given data set. This shows that as NEX increases, the signal fluctuations decrease and that the mean value is consistently lower than the 'unaffected' signal (approximated by the maximum values achieved in the 1-NEX/2-NEX protocols~380). Given the formulation above, assuming the average of the 4-NEX signal $\sim<s>=350$, the signal reduction factor can be approximated for this case: $fp\sim9\%$.

Conclusion

Based on this study and considering the many restrictions introduced by gating, it appears that an ungated, single-shot EPI-based DTI scheme with 11 gradient directions acquired at 4 NEX provides reproducible DWI with a tolerable cardiac-motion induced signal reduction factor at 3T. FA values are currently being computed to further evaluate the effect of averaging for an 11-direction protocol. Future work entails repeating this study on several subjects and for several affected regions of interest as well as running computer simulations to determine the sensitivity of the tensor calculation to signal reductions for an 11-direction protocol.

References: [1] Nunes, R. et al., *ISMRM*, 2005; 13. [2] Skare, S & Anderson, *M*RI, 2001; **19**:1125. [3] Chavez, S. et al., *ISMRM-DTI* workshop, 2005;