Tradeoffs Between Tensor Orientation and Anisotropy in DTI: Impact of Diffusion Weighting Scheme

B. A. Landman[1], J. A. Farrell[2,3], S. A. Smith[2,3], S. Mori[1,3], and J. L. Prince[1,4]

[1]Biomedical Engineering, Johns Hopkins University School of Medicine, Baltimore, Maryland, United States, [2]F.M. Kirby Research Center for Functional Brain Imaging, Kennedy Krieger, Baltimore, Maryland, United States, [3]The Russell H. Morgan Department of Radiology and Radiological Sciences, Johns Hopkins University School of Medicine, Baltimore, Maryland, United States, [4]Electrical and Computer Engineering, Johns Hopkins University School, Baltimore, Maryland, United States

Introduction

Diffusion tensor imaging (DTI) provides MR contrasts sensitive to tissue microstructure. Diffusion tensors can be estimated from 1 non-diffusion-weighted (DW) and at least 6 DW images [1], but more are common-place to boost the signal-to-noise ratio. Substantial theoretical and experimental work has gone into developing optimized DW schemes with varying numbers of DW directions each designed to address different tissue constraints and imaging objectives [2-3]. The effects of DW schemes on the accuracy and precision of tensor estimation and derived contrasts have been investigated by simulation and with *in vivo* data to improve reliability. Strong evidence supports that increasing the directional resolution (the number of unique directions) is preferable to increased scan repetitions of a lower directional resolution scheme with equal scan time [3-4]. However, the specific types of gains and losses (if any) in estimation errors that occur when choosing between high and low directional resolution potential energy (PE) optimized DW schemes have not been systematically evaluated.

We seek to directly characterize how the directional resolution of PE optimized DW schemes impacts fractional anisotropy (FA), mean diffusivity (MD), and principal eigenvector (PEV) measurements relative to the orientation of diffusion tensors through direct experimental analyses. We identify the intricate relationships between DW scheme, underlying diffusion model, and tensor estimates (e.g., the computed DTI contrasts) in an *in vivo* context. This study details differences between DTI studies, tantamount to proper comparison across studies and to interpretation of subtle findings which may be close the experimental precision.

Methods

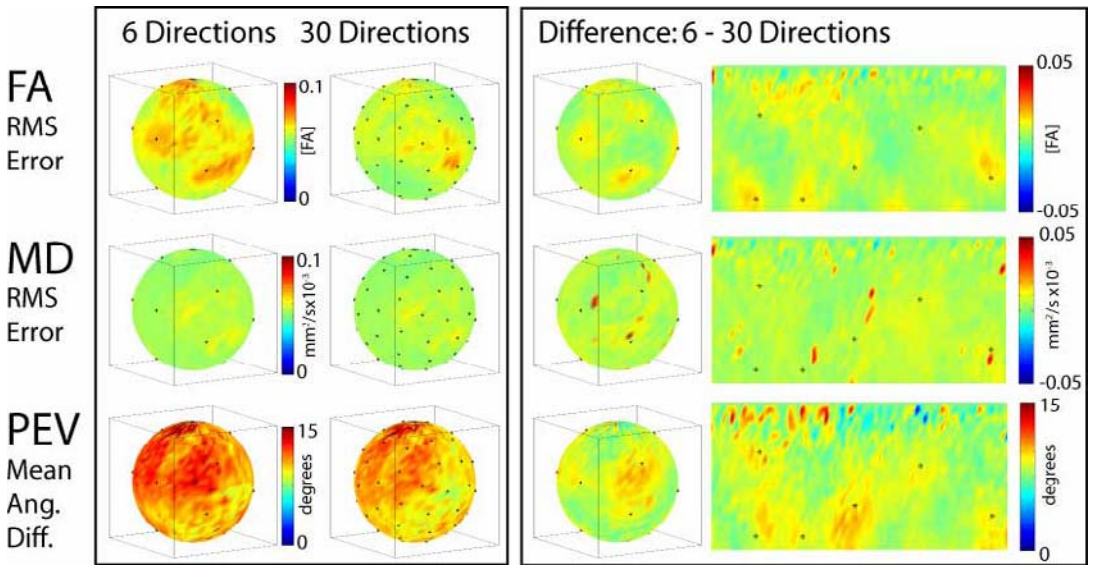
A healthy 24 year old male was studied in 3 scanning sessions, each consisting of 15 DTI scans on a 1.5T system (Intera, Philips Medical Systems, The Netherlands) after written informed consent. A multi-slice, spin echo, single-shot EPI sequence (SENSE = 2.0) was used to acquire 25 slices (parallel to AC-PC) with 2.5 mm isotropic voxels (no slice gap). Diffusion weighting was applied along 30 PE optimized directions (b = 1000 s/mm^2, G = 19.5 mT/m, TR/TE = 2956/100 ms). Five minimally weighted images (b0) were also acquired and averaged. Data were co-registered with FSL FLIRT (FMRIB, Oxford, UK). To provide an equal scan time comparison, subsets of 5 repetitions of 6 DW directions were selected without replacement from the full 30 set using minimum PE criteria.

Gold standard results were obtained by averaging the 3 analyses, each using all 15 DTI scans in 1 session. To assess tensor estimation as a function of the underlying fiber orientation, all voxels with a gold standard FA>0.25 were binned by their gold standard PEV orientation. Error metrics were averaged over the bins. Mean square errors (MSEs) relative to the gold standard contrast (over all data) were reported for FA and MD, while orientation effects were assessed by reporting the mean angular differences (MADs) between the observed PEV and the gold standard PEV.

Results and Discussion

The *in vivo* results agree with previous reports: the error orientation profiles can be thought of "as a rubber sheet, and the sampling vectors as 'fingers'" that serve to even out the surfaces [4], i.e., more independent sampling directions yield less orientation dependence in the precision and accuracy of derived metrics at equal scan time. Specifically, we show that the low directional resolution scheme has a large impact on RMS errors of DTI derived metrics and this effect depends on the alignment of the underlying tensor (**Fig., left column**). For tensors aligned with a sampling direction (versus away from one), PEV is more accurately determined at the expense of less accurate FA. The higher directional resolution scheme minimizes the variability of RMS measures for a tensor of unknown orientation (**Fig., center column**). The orientation differences between the low and high directional resolution schemes highlights the differences in reliability that occur with differing DW schemes (**Fig., right columns**)

The choice between sampling at independent directions versus repeated directions produces a tradeoff between determining the anisotropy/shape (e.g., FA and MD) and orientation (e.g., PEV) of the diffusion tensor. The measured information about an underlying tensor is contained in the set of sampled DW directions and is dependent on the tensor and noise (arising from patient motion, field inhomogeneity, and EPI-related distortions). The observation that the accuracy and precision of DTI-derived contrasts may not be optimal for tensors aligned with the DW directions can be appreciated by considering the "diffusion peanut" for a prolate tensor [10]. For a prolate tensor, the diffusivity changes less rapidly at the poles and equator. A DW scheme that oversamples slowly changing regions (low orientation variance) on the diffusion peanut, determines the eigenvalues well (hence, FA). Over-sampling the rapidly changing regions of the diffusion peanut determines the orientation well (hence, PEV).



We show that use of different DW schemes introduces systematic differences in orientation and anisotropy. These differences are small and should have minimal impact on interpretation of typical clinical studies. Yet, for large population or high SNR studies, the effect of the DW scheme should be taken into account to understand and avoid potential biases in results.

References: 1) Basser, et al., JMR B 1994 103(3):247 2) Conturo, T.E., et al., MRM 1996 35(3):399 3) Hasan, K.M., et al., JMRI 2001 13(5):769 4) Jones, D.K. MRM 2004 51(4):807 5) Jones, D.K. and P.J. Basser, MRM, 2004 52(5):979