Trade-offs between Angular and Spatial Resolution in High Angular Resolution Diffusion Imaging

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Introduction: A key question for DTI is how to allocate the scanning time: higher spatial resolution or more angular resolution? HARDI is one of Q-space imaging techniques for resolving complex fiber geometries. Where fibers cross, standard DTI is inaccurate; fiber anisotropy measures are underestimated, and fiber orientations are poorly approximated by the fitted tensor. Increasing the number of diffusion-sensitized gradients can make fiber-tracking more accurate, as can increasing the spatial resolution, but both have the penalty of longer time. To limit patient discomfort, tradeoffs between angular and spatial resolution must be established to obtain the best image quality in a minimal amount of time. Prior studies have described how to boost SNR through lengthy imaging sessions, extensive q-space sampling, or repeated scans[1, 2]. Even so, no studies to our knowledge have examined the tradeoff between spatial and angular detail for SNR and temporal stability of HARDI-based measures (e.g.ODF).

Methods: Eight healthy subjects (age: 32.0 y ± 3.9SD; 4 male; 7 right handed) were scanned using a GE 3T MRI scanner running 14.0 M5 software and an 8-channel brain coil. To explore the trade-off between spatial and angular resolution, we used three separate acquisition protocols (see **Figure 1a** for parameters), each with a fixed acquisition time of 7 min ± 3 seconds (and b = 1000 s/mm^2). All imaging protocols aacquired 4 T2-weighted images without diffusion sensitization. All 48 sets of images (8 subjects, 3 protocols, 2 time points), were motion and eddy current corrected, and extra-cerebral matter was removed with FSL (http://fsl.fmrib.ox.ac.uk). All subjects' images were linearly registered to a high-resolution single subject template, the Colin27, using 9-parameter registration (FLIRT) in the FSL toolbox, using a mutual information cost function. In the registered images, we mapped DTI-derived Fractional Anisotropy (FA), TDF-derived Exponential Isotropy (EI) [3], which quantifies anisotropy based on the full reconstructed ODF, and the symmetrized Kullback-Leibler (sKL) divergence, to measure ODF stability over time (see **Figure 1b** for formulae). We used paired Student's t-tests to compare ROI-based (**Figure 2a**) and voxel-based anisotropy measures across time and to compare scanning protocols for all these parameters.

Results: As expected, larger voxels gave higher SNR, due reduced noise levels when data are aggregated over a larger region. The dependency between SNR and voxel size is likely to be nonlinear, but a simple regression analysis showed high correlations between voxel size and SNR (*blue line*, **Figure 2b**). **Figure 3** shows the stability (reproducibility) of EI over time and **Figure 4** shows the sKL, measuring the short-interval differences between two time points' ODFs, for the 3 protocols. Smallest changes are seen in the 3-mm scan. Voxels with more angular samples are more robust to noise. To quantify these differences, Figure 4 also shows a cumulative distribution function (CDF) of the normalized sKL.

Conclusions: In scans of fixed duration (here 7 minutes), those with higher angular sampling gave higher SNR, more reproducible ODFs, and more stable anisotropy indices when no true changes were present (i.e., between scans collected only 2 weeks apart). The optimal angular precision required depends on (1) the amount of fiber crossing and partial voluming in a voxel, (2) whether the angular resolution is sufficient to resolve the ODF peaks, and (3) the overall noise level in the data, which is higher for very short scans. Thus, the best tradeoff between angular and spatial resolution may depend on additional factors not modeled here. For example, use of higher (e.g., 32) channel count coils that give increased SNR may favor the smaller voxel sizes.

References: 1. Zhan, L. (2010), 'How does Angular Resolution Affect Diffusion Imaging Measures?', NeuroImage, vol. 49, no. 2, pp. 1357-1371.
2. Zhan, L. (2009), 'Investigating the uncertainty in multi-fiber estimation in High Angular Resolution Diffusion Imaging', MICCAI2009 Workshop on Probabilistic Modeling in Medical Image Analysis (PMMIA), vol. S4, pp. 256-267.
3. Leow, AD. (2009), 'The tensor distribution function', Magnetic Resonance in Medicine, vol. 61, no. 1, pp. 205-214.

(a)

Protocol	*P1*	*P2*	*P3*
Isotropic (mm)	**3.0**	**2.7**	**2.5**
DTI gradients	**48**	**41**	**37**
TR (ms)	7750	9000	9825
Number of slices	40	44	48
FOV -S/I (mm)	120	118.8	120
FOV-A/P (mm)	230.4	230.1	230.4
FOV-R/L (mm)	384	350	320

Table 1: Different parameters used for each scanning protocol.

(b)

$$\begin{cases} \mathrm{FA}_{\mathrm{DTI}} = \sqrt{\frac{3}{2}\left(\frac{(\lambda_1 - <\lambda>)^2 + (\lambda_2 - <\lambda>)^2 + (\lambda_3 - <\lambda>)^2}{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}\right)} \\ <\lambda> \geq \frac{\lambda_1 + \lambda_2 + \lambda_3}{3} \end{cases} \quad (1)$$

$$ODF(\hat{x}) = C \int_{D \in \bar{D}} P(D)(\det(D)\, \hat{x}^t D^{-1} \hat{x})^{-\frac{1}{2}} dD \quad (2)$$

$$sKL(p,q) = \frac{1}{2} \int_{\Omega} \left\{ p(x) \log\left(\frac{p(x)}{q(x)}\right) + q(x) \log\left(\frac{q(x)}{p(x)}\right) \right\} dx \quad (3)$$

$$EI\big(P(D)\big) = e^{-\int_{D \in D} P(D) \log P(D) dD} \quad (4)$$

Figure 1

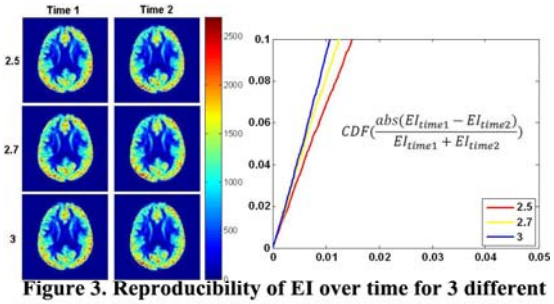

Figure 3. Reproducibility of EI over time for 3 different scanning protocols. Left: the EI plot for the 3 protocols at two time points (EI highlights gray matter). Right: the cumulative distribution function (CDF) is shown for the absolute value of the change in EI over a short time-interval of 2 weeks. Over such an interval, there should be no consistent biological change across subjects, so we assume any such changes are due to measurement error or noise. Scans with larger voxels (blue line) have a higher proportion of voxels with lower absolute changes in EI. EI is a HARDI-based analog of FA.

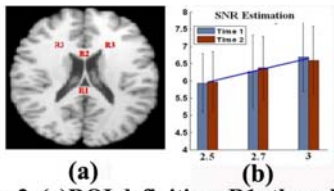

Figure 2. (a)ROI definition: R1: the splenium of the CC; R2: genu of CC; R3: fiber crossings among the SLF (superior longitudinal fasciculus), corona radiata, and corpus callosum. (b)SNR comparison among three protocols and two time points. The horizontal axis shows the voxel size; the vertical axis is SNR value (error bars denote SD). The figure shows a high (almost linear) correlation between voxel size and SNR

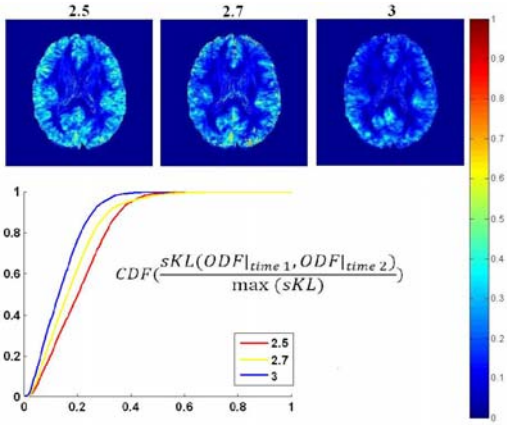

Figure 4. Changes over a 2-week interval in the ODFs are shown using a voxelwise map of sKLfor two time points' ODF for the 3 protocols. Top: sKL maps for 3 protocols: blue indicates lower sKL values (better reproducibility). Bottom: CDF plot for the normalized sKL, showing that voxels with more angular samples give better reproducibility. Based on the premise that there should be no consistent biological changes over a 2 week interval, the lower proportion of voxels with changes is a good sign; the 3-mm scans are most stable.