Simulations of DTI voxel size resolution on fiber tract measurements

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Introduction Diffusion tensor imaging (DTI) is being increasingly used to determine the orientation, size, and degree of anisotropy of individual white matter tracts for research studies and clinical practice protocols. The relatively low resolution for DTI, with a 8 mm^3 voxel size as the lower limit for most clinical scans in order to limit acquisition time, leads to voxels that will partially sample anatomically separate tracts throughout the white matter when tracts have a similar size or smaller. Although this phenomenon has been posited when modeling individual voxel compartments (1), a study of the effect of sampling idealized white matter tracts of a structure of known size by voxels of different resolutions has not been systematically conducted.

Methods Idealized fiber tracts were simulated with high-resolution synthetic tensor fields for the calculation of eigenvector, eigenvalue and anisotropy indices at a resolution of 10x10x10 µm. In the case of a simulating a straight cylindrical fiber bundle with a idealized homogenous diffusion profile (Figure 1A), cylinders were simulated with varying fractional anisotropy (FA) (1.0, .80, .60) in a background of FA=0.0. In these simulations, cylinder diameter varied between 1 mm and 2.5 mm and the isotropic voxel sampling this cylinder ranged from 10 µm to 1 mm for each dimension. These ranges were picked in order to most completely study a range of cases where voxels both closely approximate and are significantly smaller than the structure. Figure 1C represents the results of resampling a cylinder in each case with a diameter of 2 mm with a voxel of 1x1x1 mm with random jitter in three dimensions, demonstrating how the observed size and shape varied from the cylinder.

A curved cylinder using a torus function was modeled for fiber tracking simulations (Figure 1B). Similar to the straight cylindrical simulations, eigenvector and eigenvalue values were calculated that resulted in a quarter torus (or cylinder curving 90 degrees through the field of view) with primary eigenvectors that followed the curvature of the torus and FA values that were consistent through the entire volume. For each voxel resampling and fiber tracking simulation, 10^5 runs were performed with random jitter in three dimensions with cylinder diameter size between 1 and 2.5 mm and isotropic voxel sampling outer dimensions of 10 µm to 1 mm. Fiber tracking simulations were performed using a basic FACT deterministic fiber tracking algorithm written in Matlab (described in (2)). The simulated FA map and primary eigenvector matrices were used to determine the number of fibers that reached from one end of the torus to the other after resampling of eigenvector and FA information (a single example shown in Figure 1D).

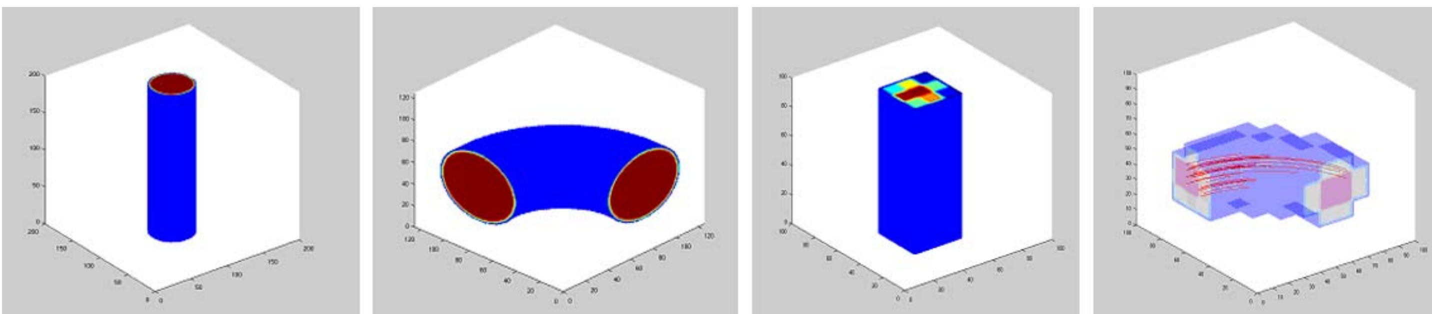

Figure 1: Idealized tract as cylinder (1A) and quarter torus (1B). Cylinder (1C) and torus (1D) diameter of 2 mm sampled by 1x1x1 mm voxel.

Results Following 10^6 simulations, Figure 2 demonstrates the uncertainty inherent in sampling a straight cylindrical tract at an absolute 1000:0 contrast with voxels of 10x10x10 µm to 1x1x1 mm and with tract diameters between 1-2.5 mm. Individual measurements are plotted in light blue with the observed cylinder volume:voxel volume plotted against the known cylinder volume:voxel volume with a cylinder:background FA contrast of 1000:0. The diffuse gray background envelope was added to demonstrate a range of observed cylinder volumes, and the dark blue line represents an average cylinder volume with a bin size of 1000 for this contrast. The other two thick lines (green and red) correspond to averages of individual simulations when contrasts of cylinder FA=.8 and FA=.6 and the background remains FA=0.0. At the point where an 8 mm^3 voxel samples a 2 mm diameter cylindrical fiber (marked by the yellow line in Figure 2), the range of observed cylinder volumes ranges from one to three times the true cylinder volume, with an average observed volume of 1.86 times true cylinder volume. Figure 3 demonstrates 10^5 fiber tracking simulations performed with torus:background contrasts of 1000:0. Similarly to the region of interest up-sampling simulations in Figure 2, these simulations demonstrate increasing uncertainty in the number of observed fibers as the voxel size sampling the torus increased to tract size. In this case where an 8 mm^3 voxel samples a 2 mm diameter cylindrical fiber (marked by the yellow line in Figure 3), there is a range of observed fiber number from 0 to nearly 8 times the expected number.

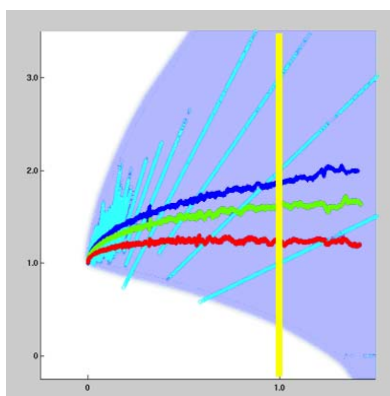

Figure 2. Average variability of sampling idealized cylindrical tracts with voxels of increasing size.

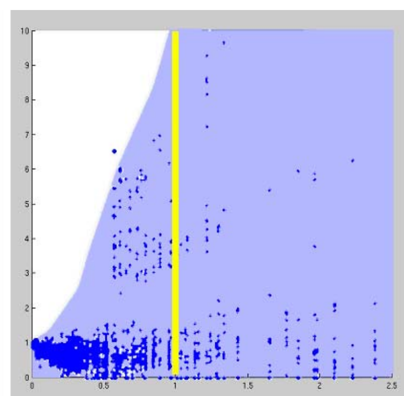

Figure 3. The observed number of fibers passing through an idealized curved cylinder varies as the cylinder is sampled by larger voxels.

Discussion This initial study demonstrates significant observed uncertainty when idealized white matter tracts are sampled by DTI voxels of the resolution commonly used by DTI acquisitions. Furthermore, the uncertainty that comes from under-sampling anatomical structures may result in unreliable fiber tracking results. Further studies using additional simulation parameters and *in vivo* data are needed to verify and extend these initial simulation results.

References

1. Alexander, AL et al. Magn Reson Med, 45, 770-80, 2001.
2. Mori S et al. Ann Neurol, 45, 265-9, 1999.