A Model for Some Subcortical DTI Planar and Linear Anisotropy

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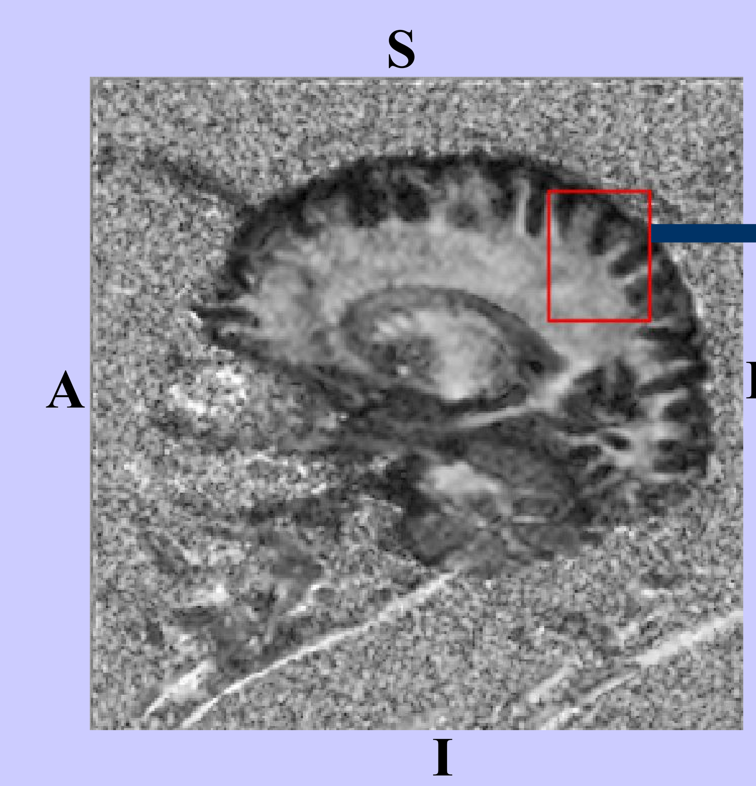
Introduction

Linear anisotropy, planar anisotropy and isotropy [1] are used as metrics for different kinds of diffusion in diffusion imaging. While linear anisotropy is reported to correlate to coherent neural fiber structures, the cause of planar anisotropy remains ambiguous. We hypothesize that overlapping linear structures and partial-volume averaging generate the planar anisotropy. We identify a subcortical region containing both linear and planar anisotropy in a human volumetric diffusion tensor image (DTI), propose a model of the anatomy and of the imaging process, and calculate simulated diffusion images of the anatomical model that qualitatively correspond to the human DTI.

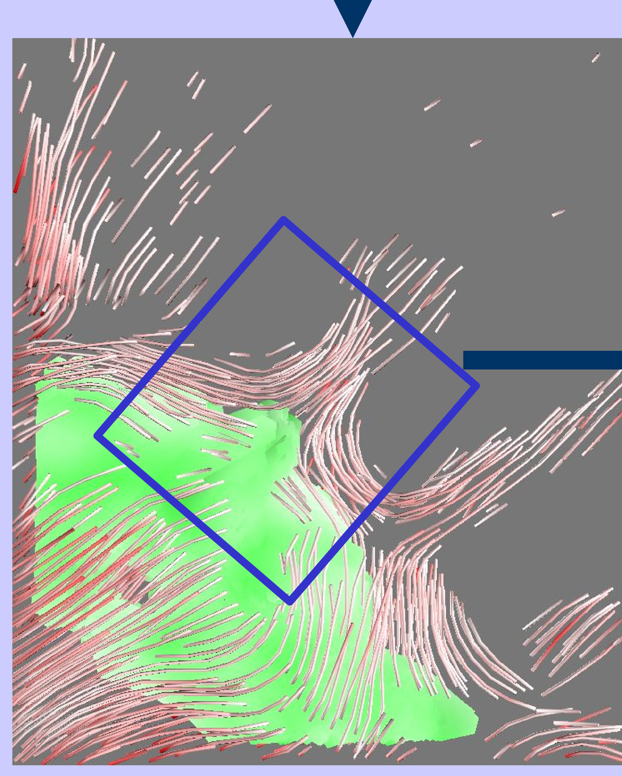
Method I: Identify the region

Regions of planar anisotropy are common immediately beneath the cortex. We choose one such region, shown in the red box on the Fractional Anisotropy (FA) map. The dimension of the region is $34\times44\times5$ mm, with the left-right direction being the shortest.

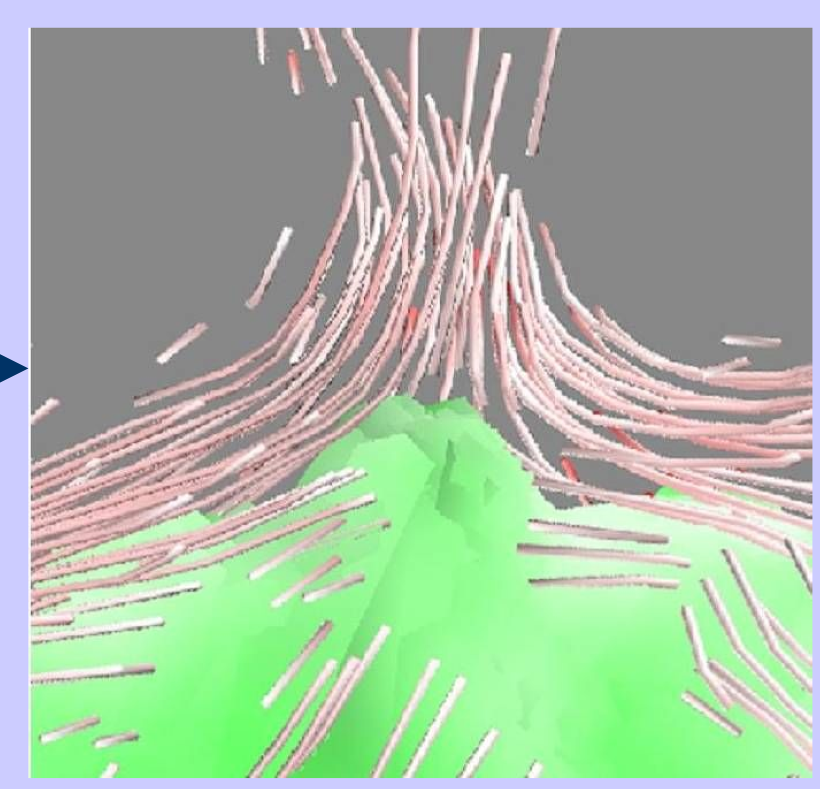


Method II: Visualization

(a) shows a visualization of the DTI data in the region that we chose. The red streamtubes run along the direction of fastest diffusion in regions of linear anisotropy; the green surfaces show regions of planar anisotropy [2]. The redder tubes have higher linear anisotropy; the greener surfaces have higher planar anisotropy. (b) shows the feature we model.



(a)



(b)

Method III: Modeling DTI data

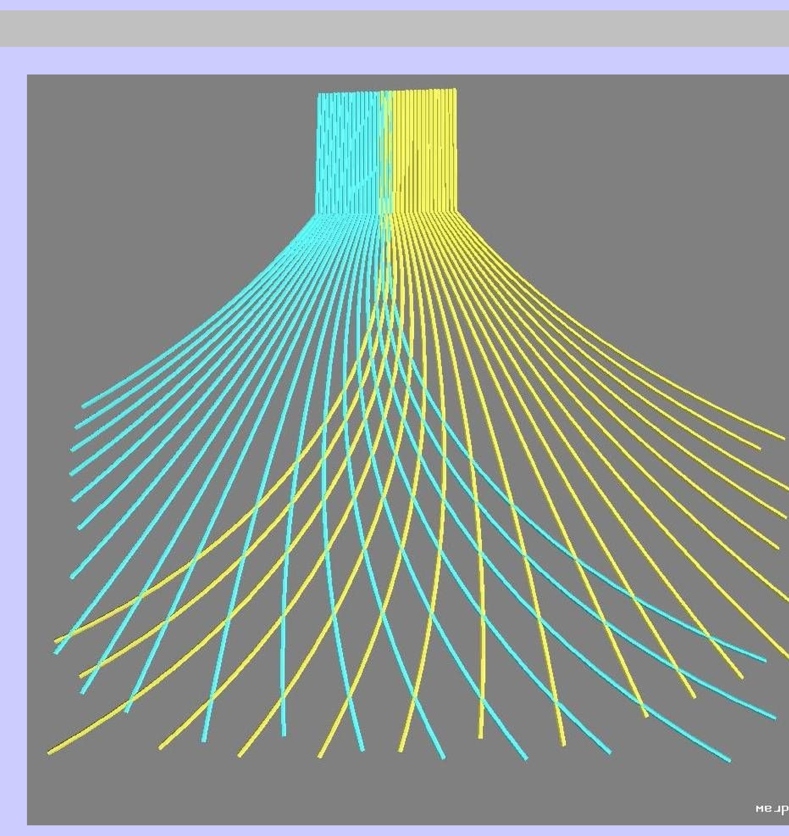
- We constructed the phantom model shown in (c) to be analogous to the region shown in (b). The two fiber tracts indicated by blue and yellow curves start from the top coherently and then fan out at the bottom part of the figure and cross each other in the middle.
- We generate DWIs for each voxel p from the anatomical model based on the relationship between the echo intensity and diffusion tensor given in [3].

$$I^q(p)=\sum_m I^q(m,p)\,v(m,p),$$

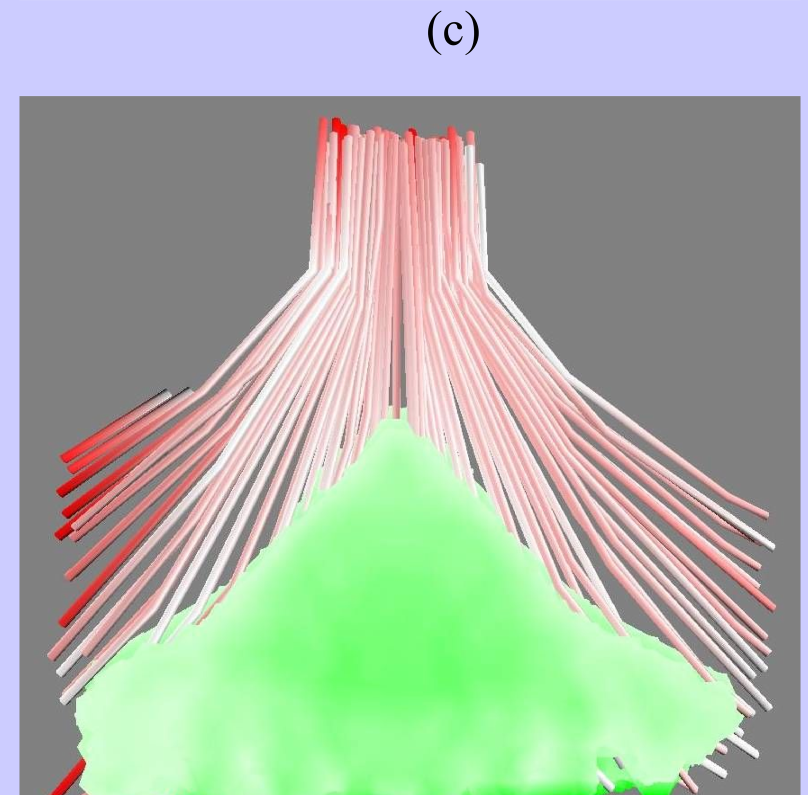
$$I^q(m,p)=I_0(m)\exp\left(-\sum_{i=1}^{3}\sum_{j=1}^{3} b_{ij}^q T_{ij}(m,p)\right)$$

where m is either water or a compartment of coherent neural fibers, q is the direction of diffusion encoding, v is the partial volume, I_0 is the zero-weighted diffusion image, b is the b-matrix, and T is the diffusion tensor that is either linear or isotropic. We synthesize 25 DWIs (12 directions with b values of 500 and 1000 and a non-weighted diffusion image) from the model and fit the DWIs to create a DTI.

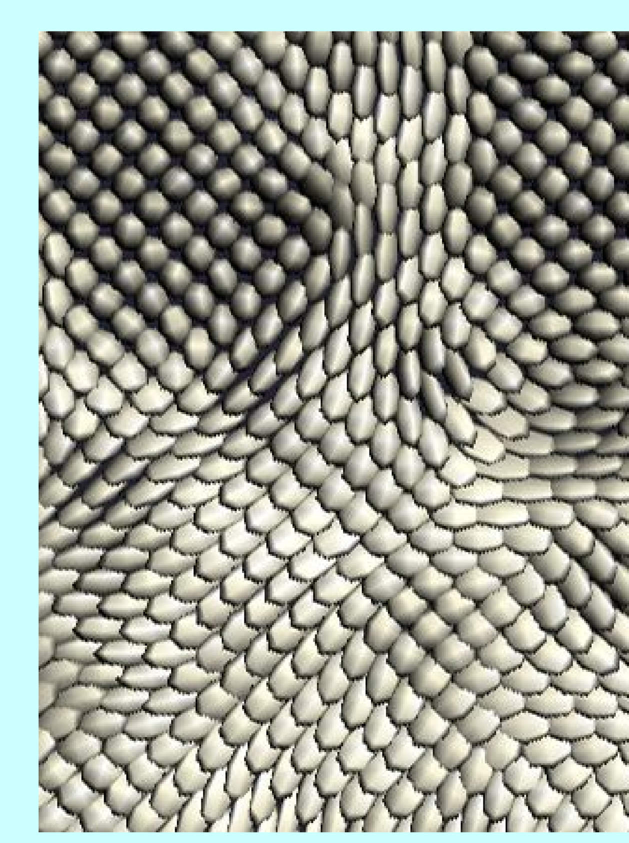
- We represent fluid with isotropic diffusion tensors, and use linear diffusion tensors whose major eigenvectors align with the tangent of the phantom model to represent these linear structures. We model neural fibers with cubic B-spline curves and a constant circular cross section.
- To simulate the partial-volume effect, we supersample each voxel with a $2\times2\times2$ grid and then average the echo intensity over all of the subsamples within the voxel.
- We use the same visualization method in (a) and (b) to analyze our synthetic diffusion images of the anatomical model visually(d).



(c)



(d)



(e)

Results and discussion

- (b) shows a small subcortical region in which fibers emerge from the top, then splay out and cross each other, creating the planar anisotropy in the center of the figure.
- (e) is an ellipsoid visualization of the feature in the original data set. Note that the complex pattern is not completely captured by our linear model. This suggests that more sophisticated modeling methods might be necessary to achieve a more accurate model.
- (c) shows our anatomical model. Note that (c) has fewer fibers than the real model and is a 2D illustration of the 3D model.
- (d) visualizes the synthesized data from the anatomical model.
  - the fiber structures in the coherently linear area generate streamtube patterns similar to those in (b),
  - the partial-volume effect in the region of crossing fibers creates planar anisotropy patterns similar to those in (b),
  - the various crossing patterns and fiber densities result in various planar anisotropies, reflected by the different shades of green in the results.
  - we also found that the direction of the streamtubes in the crossing area is biased. The result supports our hypothesis that overlapping structures and partial-volume averaging generate the planar anisotropy and also bias the direction of fastest diffusion in some regions of linear anisotropy away from the actual fiber direction.
  - compensating for these distortions may be important in synthesizing accurate quantitative DTI analyses.

Conclusions

- Because of the partial-volume effect in diffusion images, incoherent linear structures can produce planar anisotropy in DTI images.
- Modeling with only linear structures results in data that agrees qualitatively with the diffusion imaging data.
- In some subcortical areas, DTI forms complex patterns that might need more sophisticated modeling methods than existing ones.

Acknowledgments

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References

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[3] P. Basser and J. Mattiello and D. LeBihan, Estimation of the effective self-diffusion tensor from the NMR spin echo. J. Magn. Reson. B 103:247-254(1994)