Theoretical characterization of angular resolution for linear ODF estimation

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Introduction:
White matter tractography is a powerful tool for medicine and neuroscience, but fiber tracking accuracy is often confounded by crossing fibers. Despite much progress in the development of advanced q-space sampling [1-3] and orientation distribution function (ODF) estimation strategies [4,5], the design of an optimal ODF measurement approach still remains a longstanding unsolved problem. We address this issue by introducing a new model-free theoretical framework for characterizing resolution in ODF estimation. This framework can be used to compare and evaluate different q-space sampling schemes and ODF estimation methods, without requiring modeling assumptions or extensive empirical evaluations. Building off of previous work [4,6,7], our approach relies on a novel theoretical relationship between the estimated ODF and the true ensemble average propagator (EAP), a probability distribution describing local molecular diffusion.

Methods:
The ODF with constant solid angle correction [2], is defined as
\[
\text{ODF}(u) = \int f(\alpha u) \alpha^2 d\alpha,
\]
where \( u \) is an orientation unit vector, and \( f(\Delta) \) is the EAP.

Extending previous work [7] and neglecting noise for simplicity (noise is easily included), we can derive that any linearly estimated ODF \( \hat{O}(u) \) is related to the EAP by:
\[
\hat{O}(u) = \int \Delta(x) g(u,x) dx,
\]
where \( g(u,x) \) is the “EAP response”, and is easily evaluated using similar techniques to [7]. The EAP response can be interpreted as a point spread function (PSF) for ODF estimation that depends only on the q-space sampling scheme and the ODF estimation method. We hypothesize that measures like the main-lobe width of the EAP response will indicate resolution (like with conventional PSFs) and strongly correlate with empirical measures of angular resolution. If true, then it becomes possible to optimize data sampling and ODF estimation based on the EAP response.

To test our hypothesis, we calculated EAP responses for two ODF estimation schemes (FRACT [6] and SHORE [8]) and several multi-shell sampling schemes (\( b = \{1000,2000,3000\} \), \( 2000,3000,4000 \), \( 3000,4000,5000 \) and \( 4000,5000,6000 \) s/mm\(^2\)). We used a single-shell (\( b=3000 \) s/mm\(^2\)) acquisition for FRACT and same diffusion orientations as the human connectome project (HCP) 3-shell...
protocol [9]. Main-lobe width was calculated as the full-width at half maximum at the peak of the EAP response along the axis perpendicular to $u$.

Empirical simulations and real HCP data were used to assess the correlation between the EAP response characteristics and the empirically-observed ODF resolution. ODF estimation and visualization were implemented using BrainSuite [10] (http://brainsuite.org/). We quantified empirical ODF resolution by simulating multiple voxels, each containing two diffusion tensors with equal volume fraction and diffusion coefficients in the range 1-3 mm$^2$/s, and measuring the minimum angle of separation (MAS) between the tensors at which the two distinct orientations are unresolvable.

Results:

Fig. 1 shows that both MAS and EAP response main-lobe width were correlated, suggesting that the EAP response predicts angular resolution. Fig. 2 shows the EAP response of FRAC and SHORE for the HCP data. FRAC has a lower main-lobe width, predicting higher angular resolution than SHORE for this data. This prediction is consistent with qualitative examination of the ODFs. Note that our goal in this comparison was to demonstrate the usefulness of the EAP response -- FRAC is not always better than SHORE, and the performance difference is specific to the q-space sampling scheme and the set of estimation parameters that were used.

![Graphs showing correlation between minimum angle of separation and main-lobe width with varying b-values.]

Fig 1: This figure plots the minimum angle of separation and the main-lobe width of the EAP response versus b-value for SHORE estimation with different 3-shell q-space sampling schemes. The proposed theoretical assessment of angular resolution yields results that are consistent with the empirical measure.
Conclusions:

We have proposed using EAP responses to assess angular resolution in linear ODF measurement. We demonstrated that the proposed metric correlated with empirical angular resolution, and believe that such a theoretical approach will prove useful for improving ODF measurement methods.

Imaging Methods:

Diffusion MRI

Modeling and Analysis Methods:

Diffusion MRI Modeling and Analysis
Exploratory Modeling and Artifact Removal
Methods Development

Keywords:

Design and Analysis
Modeling
MRI
STRUCTURAL MRI
White Matter
WHITE MATTER IMAGING - DTI, HARDI, DSI, ETC

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