Multi-Spherical Diffusion MRI: An in-vivo Test-Retest Study of Time-Dependent q-space Indices

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Abstract: We assess the test-retest reproducibility of time-dependent q-space indices (qt-indices) in three C57Bl6 wild-type mice. To estimate qt-indices from the four-dimensional q-t diffusion signal - varying over 3D q-space and diffusion time - we use our recent Multi-Spherical Diffusion MRI (MS-dMRI) method. Using MS-dMRI we could reliably estimate qt-indices for two out of three subjects, where acquisition artifacts caused the offsets of the last subject.

1 The 4D qt-diffusion signal

Diffusion restriction occurs when water diffusion is obstructed by tissue boundaries. The amount of restriction is time-dependent, meaning that the observed diffusion coefficient will change for varying diffusion times [1].

Multi-Spherical dMRI (MS-dMRI) [2] describes the qt-diffusion signal [3] over varying:

- Gradient strength (G)
- Gradient direction (g)
- Diffusion time (τ)

Data Description: We acquire 3 test-retest mouse datasets (35 shells, 580 DWIs) with $G_{\text{max}} = 490 \text{mT/m}$ and $10.8 < \tau < 20\text{ms}$.

2 Modeling the qt-signal using MS-dMRI

MS-dMRI uses a separable Fourier Basis to reconstruct diffusion propagator $P(r;\tau;c)$ from signal attenuation $E(q;\tau;c)$, represented in coefficients $c$.

$$\hat{E}(q;\tau;c) = \sum_{k=0}^{N_q} \sum_{h=0}^{N_h} c_{kh} \Phi_h(q) T_k(\tau) \quad \leadsto \quad \hat{P}(r;\tau;c) = \sum_{k=0}^{N_q} \sum_{h=0}^{N_h} c_{kh} \Psi_h(r) T_k(\tau)$$

$$\Psi_h(r) = FT(\Phi_h(q)): 3D \text{ Fourier basis over } q \text{ and displacement } r \quad [4] \quad ; \quad T_m(\tau): \text{ Exponential diffusion time basis over } \tau \quad [5].$$

We constrain the fitting of $c$ to respect boundary conditions of the signal and impose signal smoothness and sparsity:

$$\min_{c} \int \left[ E(q;\tau,c)^2 + \int \left[ \nabla^2 \hat{E}(q;\tau;c)^2 \right] dqdr + \|c\|_1 \right]$$

Once fitted, we can estimate, for any $\tau$, the q-space indices Mean Squared Displacement (MSD) and Return-to-Origin, Axis and Plane Probability (RTOP, RTAP, RTPP) [4]:

- MSD: related to restriction
- RTOP: related to cellularity
- RTPP: parallel restriction

3 Test-Retest of Subsampling Fitting Error

We draw an ROI in the corpus callosum in each data set. We estimate the fitting error using MS-dMRI when randomly subsampling the qt-signal down from 400 to 100 samples.

- Without regularization (dashed) the fitting error is up to 10 orders of magnitude larger than with regularization (solid).
- Only Subject 3 has inconsistent test-retest fitting errors.
- With regularization we find a lower bound of 200 DWIs while ensuring a low fitting error (solid lines).

4 Test-Retest of qt-index Estimation

Using the whole data, we estimate the progress of the average MSD, RTOP, RTAP and RTPP and 0.75 standard deviation over time. The gray tones show MSD isolines for different free diffusion coefficients. Notice the non-Gaussian MSD progress.

- Subject 1: Great test-retest reproducibility all indices.
- Subject 2: Similar overlap for RTXP indices, small offset MSD.
- Subject 3: Offset for both RTXP indices and MSD.

5 Discussion and Conclusions

- We studied the test-retest reproducibility of fitting error and qt-index estimation in the corpus callosum of three mice.
- Through signal sparsity and smoothness, MS-dMRI can represent the qt-signal using only 200 samples, allowing more realistic acquisition schemes.
- The acquisition protocol can still be improved to avoid excessive acquisition noise like in Subject 3.
- Overall, we found that MS-dMRI can robustly and consistently estimate qt-indices in in-vivo acquisitions, underlining its feasibility to estimate τ-dependent features.

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