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

Rutger H.J. Fick, Alexandra Petiet, Mathieu Santin, Anne-Charlotte Philippe, Stéphane Lehéricy, Rachid Deriche, Demian Wassermann

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

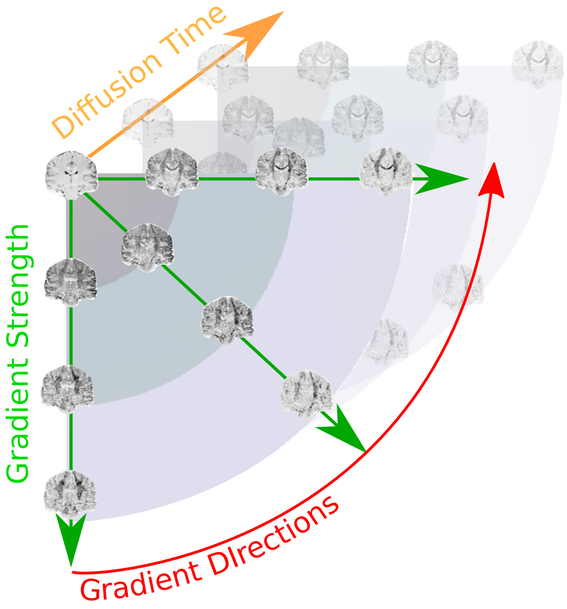
Rutger **Fick*** Alexandra **Petiet**† Mathieu **Santin**† Anne-Charlotte **Philippe**†
Stephane **Lehericy**† Rachid **Deriche*** Demian **Wassermann***

* Université Côte d'Azur, INRIA, France † CENIR, ICM, Paris, France

Contact - rutger361988@gmail.com / demian.wassermann@inria.fr **http://team.inria.fr/athena/**

Abstract: We assess the test-retest reproducibility of time-dependent q-space indices (qτ-indices) in three C57Bl6 wild-type mice. To estimate qτ-indices from the four-dimensional qτ 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 qτ-indices for two out of three subjects, where acquisition artifacts caused the offsets of the last subject.

1 The 4D qτ-diffusion signal

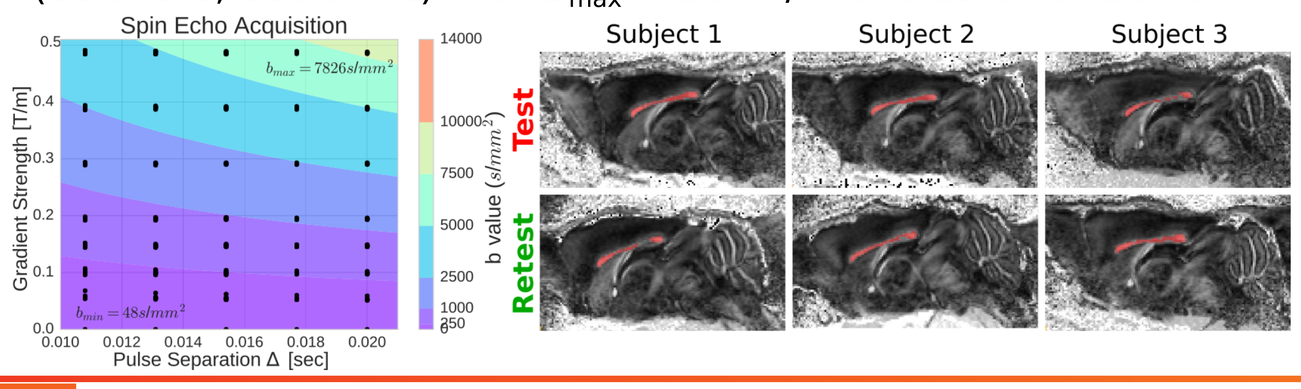


Diffusion restriction occurs when water diffusion is obstructed by tissue boundaries. The amount of restriction is **time-dependent**, meaning that the observed diffusion coefficient will change for varying diffusion times [1].

Multi-Spherical dMRI (MS-DMRI) [2] describes the qτ-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_{max}=490mT/m and 10.8<τ<20ms.



2 Modeling the qτ-signal using MS-dMRI

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

$$\hat{E}(\mathbf{q},\tau;\mathbf{c}) = \sum_i^{N_\mathbf{q}} \sum_k^{N_\tau} \mathbf{c}_{ik}\, \Phi_i(\mathbf{q})\, T_k(\tau) \quad \overset{\text{FT}}{\Longleftrightarrow} \quad \hat{P}(\mathbf{r},\tau;\mathbf{c}) = \sum_i^{N_\mathbf{q}} \sum_k^{N_\tau} \mathbf{c}_{ik}\, \Psi_i(\mathbf{r})\, T_k(\tau)$$

$\Psi_i(\mathbf{r}) = FT(\Phi_i(\mathbf{q}))$: 3D *Fourier* basis over **q** and displacement **r** [4].

$T_m(\tau)$: Exponential diffusion time basis over τ [5].

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

$$\text{argmin}_\mathbf{c} \overbrace{\iint \left[E(\mathbf{q},\tau) - \hat{E}(\mathbf{q},\tau;\mathbf{c})\right]^2 d\mathbf{q}d\tau}^{(1)\text{ Data Fidelity}} + \overbrace{\iint \left[\nabla^2 \hat{E}(\mathbf{q},\tau;\mathbf{c})\right]^2 d\mathbf{q}d\tau}^{(2)\text{ Smoothness}} + \overbrace{\|\mathbf{c}\|_1}^{(3)\text{ Sparsity}}$$

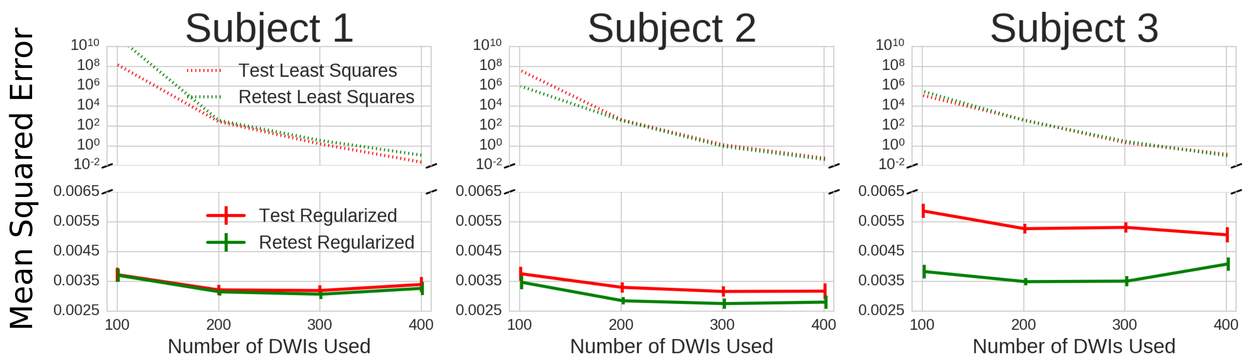
Once fitted, we can estimate, for any τ, the q-space indices Mean Squared Displacement (MSD) and Return-to-Origin, Axis and Plane Probability (RTOP, RTAP, RTPP) [4]:

- MSD: related to restriction • RTAP: perpendicular 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.

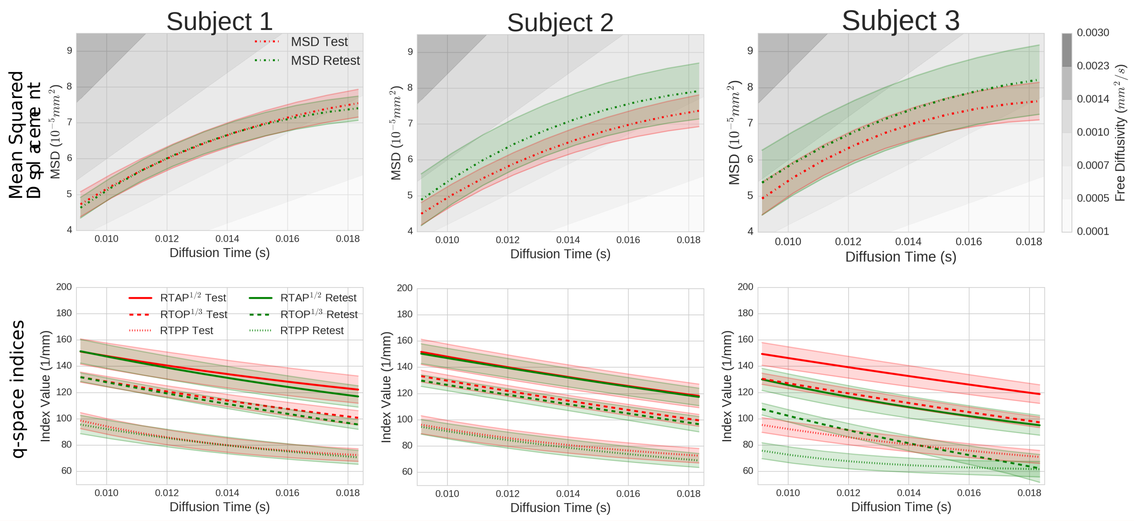
- Without regularization (dashed) the fitting error is up to 10 orders of magnitude larger than with regularization (solid).
- Only Subject 3 has inconsistent test-retest fitting errors.
- With regularization we find a **lower bound of 200 DWIs** while ensuring a low fitting error (solid lines).



4 Test-Retest of qτ-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 RT*X*P indices, small offset MSD.
- Subject 3: Offset for both RT*X*P indices and MSD.



5 Discussion and Conclusions

- We studied the test-retest reproducibility of fitting error and qτ-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 qτ-indices in in-vivo acquisitions, underlining its feasibility to estimate τ-dependent features.

Acknowledgements: This work has received funding from the European Research Council (ERC) under the Horizon 2020 research and innovation program (ERC Advanced Grant agreement No 694665 : CoBCoM) and from the ANR-13-MONU-0009 MOSIFAH project.

References

[1] Fieremans et al. NeuroImage 129 (2016): 414-427. [2] Fick et al. CD-MRI 2016. [3] Novikov et al. arXIV:1612.02059 (2016) [4] Özarslan et al. NeuroImage 78 (2013): 16-32. [5] Fick et al. IPMI 2015.