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To cite this version:

HAL Id: hal-01360440
https://hal.archives-ouvertes.fr/hal-01360440
Submitted on 5 Sep 2016

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Multi-Spherical MRI: Breaking the Boundaries of Diffusion Time

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Abstract: Effective representation of the diffusion signal’s dependence on diffusion time is a sought-after, yet still unsolved challenge in diffusion MRI. We propose a functional basis approach that is specifically designed to represent the dMRI signal in this four-dimensional space - that we call the multi-spherical space. We provide regularization tools to drastically reduce the number of measurements we need to probe the properties of this multi-spherical space.

1 The Multi-Spherical Space

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 MRI [2] describes diffusion restriction by fitting the diffusion signals over varying:
• Gradient strength (G)
• Gradient direction (g)
• Diffusion time (τ)

We call this four-dimensional space the Multi-Spherical Space.

We sampled this space on 35 different "shells", varying only g, for different G ranging from [50-490] mT/m and τ ranging from [9.1-18.3] ms.

2 Modeling the Multi-Spherical Space

Multi-Spherical MRI uses a separable Fourier Basis to reconstruct diffusion propagator \( P(r, τ; c) \) from signal attenuation \( E(q, τ; c) \), represented in coefficients \( c \).

\[
\hat{E}(q, τ; c) = \sum_{i} c_i \Phi_i(q) T_i(τ) \quad \Rightarrow \quad \hat{P}(r, τ; c) = \sum_{i} c_i \Psi_i(r) T_i(τ)
\]

\( \Psi_i(r) = FT(\Phi_i(q)) \): 3D Fourier basis over \( q \) and displacement \( r \) [3].

\( T_i(τ) \): Exponential diffusion time basis over \( τ \) [4].

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

\[
\arg\min_c \left\{ \int [E(q, τ; c) - \hat{E}(q, τ; c)]^2 dq \text{d}τ + \int \left[ \nabla^2 E(q, τ; c) \right]^2 dq \text{d}τ + \| c \|_1 \right\}
\]

Where smoothness is imposed using closed-form Laplacian regularization.

Once fitted, all q-space indices [3] can be estimated for any τ. As examples we show:
• Mean Squared Displacement (MSD), related to restriction
• Return-To-Origin Probability (RTOP), related to cellularity

3 In-Silico results

We study fitting performance under random subsampling by simulating the multi-spherical diffusion signal from gamma-distributed axons using Camino [5].

• Combined sparsity and Laplacian regularization produces the lowest fitting error (left).
• Time-dependent MSD and RTOP follow expected trends - MSD increasing and RTOP decreasing over time - down to about 200 DWIs (right two)

4 Application In-vivo Mouse Data

After eddy current correction, we chose an ROI of 173 voxels in Corpus Callosum. After subsampling we find:
• Stable fitting errors from 400 down to 200 DWIs
• Expected trends for time-dependent MSD and RTOP

5 Discussion and Conclusions

• Multi-Spherical MRI allows for the characterization of diffusion restriction through time-dependent q-space indices.
• Through signal sparsity and smoothness, our approach can represent the multi-spherical signal with less samples, allowing more realistic acquisition schemes.
• Additional signal or propagator constraints can be conveniently included in the optimization.
• Through resampling, our approach could be used as a pre-processing for other methods studying properties of the multi-spherical space, e.g. axon packing [6].

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)

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