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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.

\[ \hat{E}(q, \tau; c) = \sum_{i} c_i \Phi_i(q) T_i(\tau) \]

\[ P(r, \tau; c) = \sum_{i} c_i \Psi_i(r) T_i(\tau) \]

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

\[ T_m(\tau): \text{Exponential diffusion time basis over } \tau \]

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

\[ \text{argmin}_{c} \int \left[ \hat{E}(q, \tau; c) - E(q, \tau; c) \right]^2 dq \tau + \int \nabla^2 \hat{E}(q, \tau; c)^2 dq \tau + \| c \|_1 \]

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.
• Additional signal or propagator constraints can be conveniently included in the optimization.
• Through signal sparsity and smoothness, our approach can represent the multi-spherical signal with less samples, allowing more realistic acquisition schemes.

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References

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