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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-dimensional 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.

\[ \hat{E}(q, \tau; c) = \sum_{i} \sum_{j} c_{i,j} \Phi_i(q) \Psi_j(\tau) \]

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

\[ \arg \min_{c} \int [E(q, \tau) - \hat{E}(q, \tau; c)]^2 \, dq \, dr + \int \nabla^2 \hat{E}(q, \tau; c)^2 \, dq \, dr + \frac{1}{\|c\|_1} \]

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 studying 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.

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References