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Indetermination-free cytoarchitecture measurements in brain gray matter via an inverse diffusion MRI signal separation method

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Objective:

- Quantify grey matter cytoarchitecture using diffusion MRI
- Estimate tissue parameters with no indetermination: a unique solution is returned and there is no need to choose between several mathematical and biological possible solutions.

1 Introduction

3 compartment model

7 parameters to estimate:

- Compartment signal fractions: f_n, f_s and f_{ecs}
- Diffusivities: D_a and D_{ecs}
- An exiting **new parameter modulated by soma radius**: $C_s(r_s, D_s)$
- ODF anisotropy invariant: p_2

$$\frac{S(q)}{S(0)} = f_n S_{neurites}(q) + f_s S_{soma}(q) + f_{ecs} S_{ecs}(q)$$

Hypothesis:

- No exchange between the 3 compartments[3]
- $f_t + f_s + f_{ecs} = 1$

Intra-cellular space	
Neurites	**Soma**
0-radius tubes[1]	Spheres with fixed radius[2]
$S_{neurites}(q) = \frac{1}{4\sqrt{\pi \tau D_a}} q^{-1}$	$-\log S_{soma}(q) = C_s(r_s, D_s)\, q^2$

Extra-cellular space
Ellipsoid
$-\log S_{ecs}(q) = (2\pi q)^2 \tau D_e$

2 Methods

① Estimate D_{ecs} from CSF (free diffusing fluid)

② Spiked LEMONADE

- Low b-value approximation (b ≤ 3 ms μm^{-2})
- Based on cumulant decomposition of the dMRI signal[4]

$$\begin{cases} M^{(2),0} = f_n D_a + 3\frac{f_s C_s}{(2\pi)^2 \tau} + 3 f_{ecs} D_e \\ M^{(2),2} = f_n D_a p_2 \\ M^{(4),0} = f_n D_a^2 + 5 f_s \left(\frac{C_s}{(2\pi)^2 \tau}\right)^2 + 5 f_{ecs} D_e^2 \\ M^{(4),2} = f_n D_a^2 p_2 \end{cases}$$

③ RTOP:[5] $$RTOP(q_{max}) = \frac{1}{(2\pi)^3} \int_0^{q_{max}} S(q)\, dq$$

- High b-value approximation (b ≥ 3 ms μm^{-2})
- Least square regression

$$RTOP(q_{max}) = a_{fit} + b_{fit} q_{max}^2$$

$$\begin{cases} a_{fit} = \frac{f_s \sqrt{\pi}}{(2\pi)^3 4 C_s^{3/2}} + \frac{f_{ecs}}{32 \pi^{5/2} (2\pi\sqrt{D_e \tau})^3} \\ b_{fit} = \frac{f_n}{4(2\pi)^4} \sqrt{\frac{\pi}{D_a \tau}} \end{cases}$$

④ Solve the non-indetermination system of 7 equations and 6 unknowns using LBFGS

3 Results

Simulations

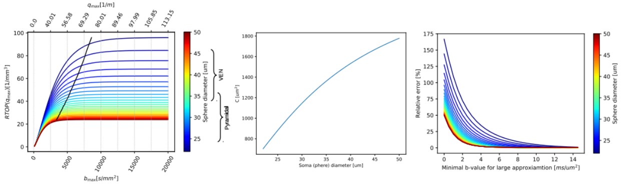


Fig. 1. (a) C_s is modulated by the sphere diameter. (b) RTOP of the soma signal depends on the sphere diameter. (c) Relative error of C_s estimation. The bigger the soma, the lower b-values for a better relative error.

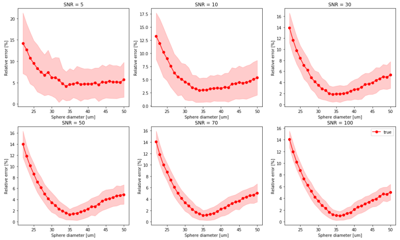


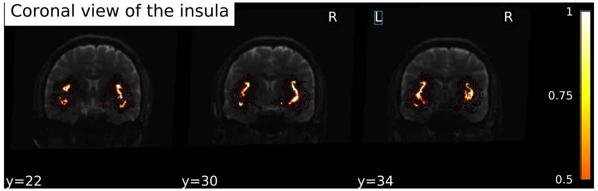
Fig. 2. Evolution of the relative error of C_s with respect to soma radius for varying SNR. Estimation is better for big soma and is robust towards noise.

HCP MGH database

δ/Δ = 12.9 / 21.8 ms
b = 0, 1, 3, 5, 10 ms μm^{-1}

Fig. 3. C_s in the insula. An increasing soma size change can be observed from inferior to superior, agreeing with literature[6].

Coronal view of the insula



4 Discussion and Conclusion

- C_s : an exiting new parameter modulated by soma radius
- Low requirements: only 5 b-values needed, comprising 3 b-values superior or equal to 3 ms μm^{-2}
- Unicity of the solution, unlike NODDI or SANDI[3], making fitted parameters reliably interpretable
- Robust to noise
- No training on simulations required as in SANDI[3]

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