NMR CHARACTERIZATION OF CYLINDER RADII DISTRIBUTIONS USING A SHORE-BASED REGULARIZATION METHOD

Gonzalo Sanguinetti[1], Matt G Hall[2], Daniel C Alexander[2], and Rachid Deriche[1]

[1]*Athena Project-Team, INRIA, Sophia-Antipolis, France,* [2]*Centre for Medical Image Computing, Department of Computer Science, University College London, London, United Kingdom*

TARGET AUDIENCE: Diffusion MRI scientists interested in brain micro-structure. Biophysical modelers.

PURPOSE: In this work, we extend the framework presented in [1] by adding a regularization term for better measuring the moments of a cylinder radii distribution by means of NMR acquisitions. The added value of the regularization term is tested and validated using Monte Carlo simulations of NMR signals from complex white matter-like environment. The open source toolkit CAMINO [2] is used for computing the simulations and an excellent agreement is obtained between the ground truth and the estimated moments.

INTRODUCTION: Using diffusion MRI to measure the axon diameter distribution (ADD) in white matter (WM) is an active area of research in the MR community. Methods like AxCaliber [3] or ActiveAx [4] are able to characterize the ADD in areas with large anisotropy like the Corpus Callosum where all the axons belong to the same fiber path and are coherently oriented. A problem of these techniques is that they may rely on solving ill-posed optimization problems so non-linear techniques and good initial conditions are needed. Based on a different paradigm, the framework proposed in [1] allows for the retrieval of the moments of the radii distribution from an ensemble of cylindrical pores using the PSGE experiment. Central to this approach, is the continuous approximation of a discretely sampled NMR signal by a linear combination of function elements from the 1D-SHORE basis. The fitting of the signal is achieved by solving a least square problem. Under some hypotheses about the acquisition protocol (narrow gradient pulses and long diffusion time), it is possible to relate the moments of the radii distribution to the value of some integral operators acting on the continuous NMR signal. Then, explicit formulas exist relating the radii moments with the coefficients of the representation in the SHORE basis. In [5], an extension of [1] is proposed, so similar ideas can be used to recover brain micro-structure parameters.

METHODS: We incorporated the regularization strategy presented in [6] for the SHORE basis, which is based on adding a Laplacian penalty term. As in [6], the optimal penalty weight parameter is selected by using generalized cross validation (GCV). The regularization term avoids the over-fitting that can capture the spurious oscillatory behavior of the noise. The method is validated on synthetic data generated using Monte-Carlo simulations performed with the CAMINO toolkit [2]. This simulation framework was introduced in [2,4] to accurately reproduce the diffusion in an environment like WM and was used in the past to test ADD related methods [4,7]. In the simulations, WM is a 3D environment (called substrate) formed by randomly placed parallel cylinders. A total of 22 different substrates were considered, each one containing 10000 cylinders whose diameter are randomly chosen so their distribution approximates the ADDs observed in histology data. The acquisition protocol consists of 25 q-samples between 0 and 600mm^{-1} (δ = 1ms, Δ=100ms) with gradient direction perpendicular to the axis of the cylinder. To ensure convergence, a large number of particles (more than 10^6) needed to be set. To be coherent with the model in [4], we consider the signal produced by the intra-axonal space (only from inside the cylinders).

RESULTS: Some of the substrates and their respective signals obtained with CAMINO are visualized in Fig 1. For completeness, we compare these data with real measurements reported in [8]. In Fig. 2 we show the result of applying the moment retrieval method using 20 coefficients for the SHORE approximation (with and without regularization). In most of the cases an excellent agreement can be observed between the ground truth and the estimated moments. However, some outliers exist amongst the moments recovered with the non-regularized method (blue dots). All the outliers disappeared when the regularization (purple squares) was used rendering the approximation much more accurate.

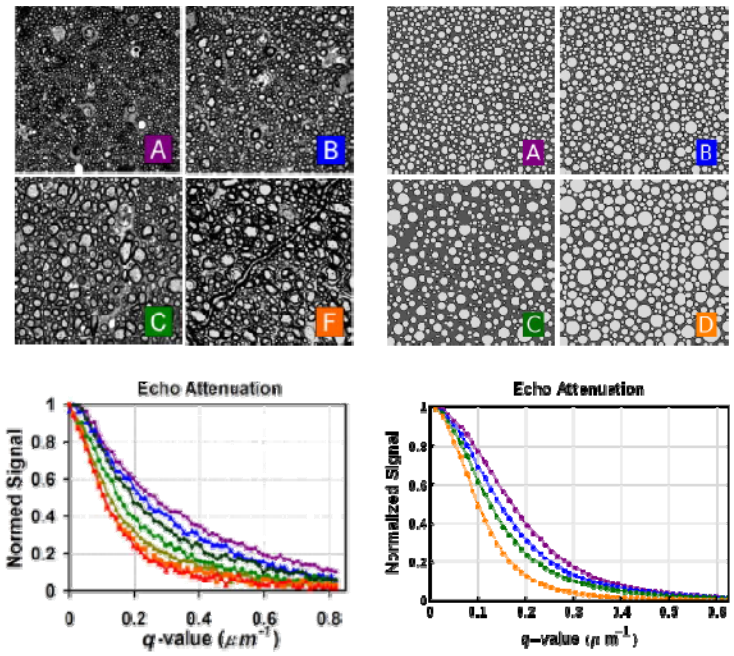

Fig 1. (Left) The images on the top 4 panels are taken (and adapted) from [8] and show optical images from different WM track sections from a mouse cord spine. The graph on the bottom shows the respective sampled q-space echo attenuation. (Right) The panels on the top are parts of the cross-section of 4 different substrates from the CAMINO simulations. On the bottom graph their respective simulated signal attenuation are shown. The continuous line is the regularized SHORE approximation with 20 coefficients.

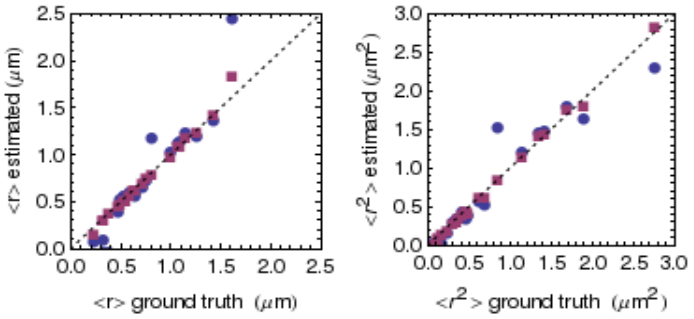

Fig 2. Plots of the measured first moment <r> (left) and the second moment <r^2> (right) against the ground truth value. The blue circles correspond to the values computed without regularization, while the purple squares correspond to the values computed with regularization. The SHORE approximation was performed using 20 coefficients.

DISCUSSION AND CONCLUSIONS:

We extended the method for the measurement of the cylinder radii distribution proposed in [1] by adding a regularization term to the least squared fitting. The improvement given by the regularization term was validated on experiments. An additional contribution of this report is the application of the method in [1] to CAMINO simulated data, and the excellent agreement obtained between the ground truth and the estimated moments. We interpret this as an alternative validation of the operator method with a new type of signal source. From a different perspective, we highlight the good agreement between Monte-Carlo simulations with cylindrical substrates and measurements taken from real white matter signals, as shown in Fig. 1.

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