Fiber Continuity: An Anisotropic Prior for ODF Estimation

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INTRODUCTION: The accurate and reliable estimation of fiber orientation distributions based on diffusion-sensitized magnetic resonance images is a major prerequisite for tractography algorithms or any other derived statistical analysis. In this work we formulate the principle of fiber continuity (FC), which is based on the simple observation that the imaging of fibrous tissue implies certain expectations to the measured images. From this principle we derive a prior for the estimation of fiber orientation distributions based on high angular resolution diffusion imaging (HARDI). We demonstrate on simulated, phantom and in vivo data the superiority of the proposed approach.

METHODS: There are numerous methods for estimating orientation distribution functions. Starting from classical Q-ball imaging (1), constrained spherical deconvolution (2), proper probability density estimation (3) and spatially regularized density estimation (4). The idea presented in this work is also based on the principle of spatial regularity but is less restrictive than the approach of (4). In (4) a spherical neighborhood is assumed, i.e. all values at a certain voxel should be similar to the voxels in a spherical surrounding. Instead of assuming a spherical neighborhood our approach uses an adaptive elongated neighborhood depending on the actual gradient direction. The idea is motivated by the fact that the underlying tissue is of fibrous nature. If a fiber passes a volume element $\mathbf{x}$ with direction $\mathbf{n}$, then, under the assumption of *fiber continuity*, the same fiber has to pass volume element $\mathbf{x}+\alpha\mathbf{n}$, that is $f(\mathbf{x},\mathbf{n}) = f(\mathbf{x}+\alpha\mathbf{n},\mathbf{n})$, where f is the fiber ODF. By expanding the rhs the condition can be reformulated as $\mathbf{n}\cdot\nabla f(\mathbf{x},\mathbf{n}) = 0$. We cannot assume that this condition can be fulfilled exactly. It is used here as an approximation in order to guide the ODF-estimation procedure in the right direction. For the ODF-estimation we follow the CSD principle and use additionally the fiber continuity assumption as a regularizer. The cost function is defined as:

$$J(f) = ||Hf - S||^2 + \lambda \int_{\mathbb{R}^3 \times S_2} |\mathbf{n}^T \nabla f(\mathbf{x},\mathbf{n})|^2 \, \mathbf{dx}d\mathbf{n}$$

where S is diffusion MR-signal, H the convolution operator with the fiber response function and f the fiber ODF. For optimization a simple gradient descent scheme is applied with an additional positivity regularizer similar to the idea of Tournier (1).

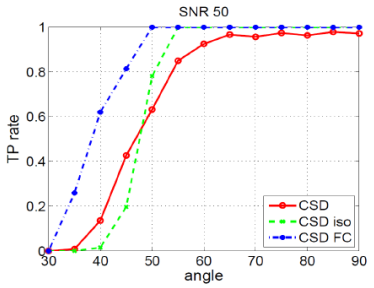

FIGURE 1: SIMULATION RESULTS.

RESULTS: The method was applied to simulations, phantom and in-vivo measurements. The in-vivo measurements were acquired on a Siemens 3T TIM Trio using an SE EPI sequence, with a TE of 95 ms and a TR of 8.5 s. The whole brain was covered with contiguous 2 mm slices in an in-plane resolution of 2x2 mm^2. The diffusion encoding was performed in 61 directions with an effective b-value of 1000 s/mm^2. The phantom data were provided by (5). We simulate crossings with varying angle and bD=1 and SNR = 50. To measure the performance local maxima are extracted. A crossing voxel is said to be successfully resolved if both 'ground truth' directions are within a range of 10° to a local maximum of the estimated ODF. The number of all successfully resolved crossings divided by the number of all crossing voxels is called the true positive rate (TP rate). In Figure 1 the TP rate is plotted against the crossing angle. Our approach (CSD FC) is compared with direct CSD (1) and isotropically reg. CSD (4). In Figure 2 the results for a crossing of the phantom (5) are shown. Figure 3 compares deterministic tracking results (based on FACT) for the corticalspinal tracts (CST) and the transcallosal fibers (CC). The CST fibers are selected by a seed region at the level of the genu. For the CC the whole corpus callosum was used as the seed region. The FC-regularization parameter λ=0.01,0.03 was varied.

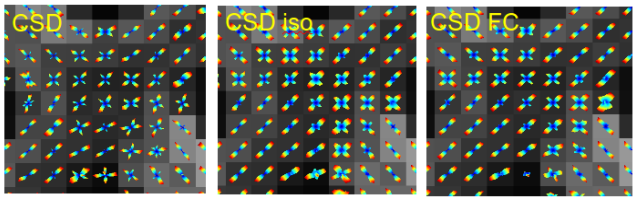

FIGURE 2: PHANTOM RESULTS. Fiber ODFs at crossing.

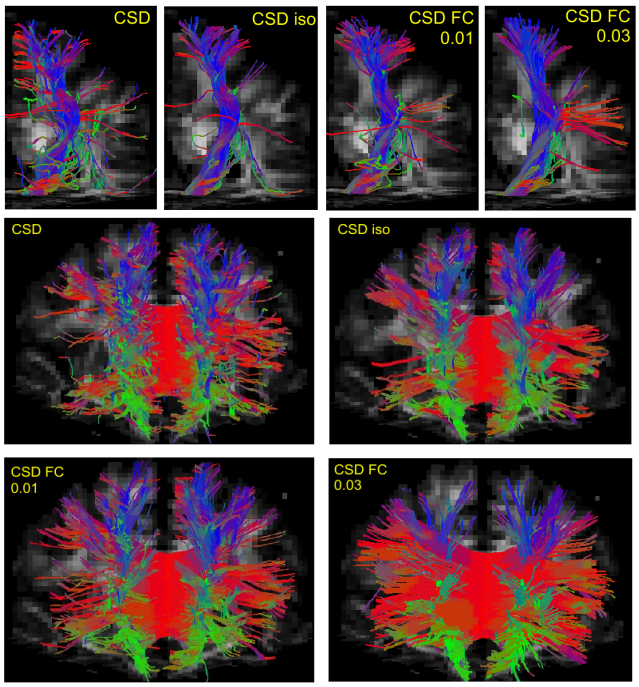

FIGURE 3: Top: FACT-Tracking results for the CST. Bottom: FACT-Tracking results for the transcallosal fibers.

DISCUSSION: The simulation shows that the FC driven ODF estimation seems to be more robust than pure CSD and isotropically regularized CSD. The visual comparison on the phantom also suggests that the FC driven approach is able to resolve fiber crossings more cleanly than pure CSD. The noise is reduced and correct directions are emphasized. Finally, the tracking results on in-vivo data for the CST show the lateral projections to the motor homunculus more pronounced, which are usually difficult to detect for a deterministic tracker. Considering the CC the picture is similar, not astonishingly CSD is more noisy and CSD-FC is pronouncing the lateral projections, with growing λ.

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