Sharpening Improves Clinically Feasible Q-Ball Imaging Reconstructions

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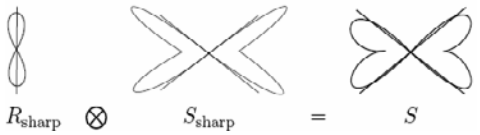
Introduction Recent High Angular Resolution Diffusion Imaging (HARDI) [1] acquisitions use low b-values (b = 1000 s/mm^2) and small number of gradient encoding directions, N, (< 100) to describe local non-Gaussian diffusion process in clinically feasible acquisitions. One such technique is Q-Ball Imaging (QBI) [1], which reconstructs the diffusion orientation distribution function (ODF) of water molecules in a biological tissue. However, at low b-values and small N and because of the intrinsic Bessel function smoothing in the Funk-Radon Transform used to reconstruct the ODF [1], the ODF profiles are quite smooth and ODF maxima (giving the underlying fiber orientation) are difficult to find and sometimes missed when compared to ODF reconstructed from research-oriented HARDI acquisitions with higher b-values (b ≥ 3000 s/mm^2) and large N (N > 100). In this work, we define a general sharpening operation that can be used with any HARDI reconstruction method and in particular, we show that if the sharpening is applied on the ODF, it considerably improves fiber detection and increases angular resolution of QBI.

Methods Sharpening Theory: The sharpening operation is a simple linear transformation of the spherical harmonic (SH) coefficients describing the input HARDI signal. The idea is inspired by that of Tournier et al [2] who proposed that the measured signal could be expressed as a convolution on the unit sphere of the fiber response function R with the fiber orientation density function [Fig.1, 4]. Here, we propose to look at the convolution between the inverse response function R^{-1}, which we now refer to as the sharpened profile R_{sharp}, and the measured signal S. Fig.1 is a sketch of this convolution. The convolution can also be viewed as the deconvolution of the signal S with the sharp fiber response function R_{sharp}. A common model for the response function is the Gaussian with ratio of eigenvalues e_1/e_2 ($e_1 \geq e_2 = e_3$). Hence, we can choose this e_1/e_2 ratio to define the desired sharpening profile. In practice, we find that a good ratio is 100. We use the Funk-Hecke theorem [3] to solve the convolution integral on the sphere of Fig.1 between sharp fiber response function R_{sharp} and SH function describing S. We thus obtain the sharpened signal in direction (θ,ϕ) as

Fig.1



$$S_{\text{sharp}}(\theta,\phi) = \sum_{k=0}^{L}\sum_{m=-k}^{k} f_k c_k^m Y_k^m(\theta,\phi) \qquad \text{with} \qquad f_k = 2\pi \int_{-1}^{1} P_k(t) R_{\text{sharp}}(t)\,dt \tag{1}$$

where Y_k^m is the SH of order k and degree m, P_k is a Legendre polynomial of order k, and c_k^m are the SH coefficients describing the signal S in the SH basis of order L. Eq.(1) can be evaluated numerically or pre-computed using definite integrals tabulated for the desired order of L. As illustrated in Fig.2, the sharpened ODF (Fig.2d), Ψ_{sharp}, is then reconstructed from S_{sharp} (Fig.2c) with recent analytical QBI solution of the Funk-Radon Transform (FRT) using spherical harmonics [4,5,6]. Without sharpening, the ODF (Fig.2a) reconstructed from input signal (Fig.2b) is much smoother.

Human Brain Dataset: The diffusion weighted images were acquired on a 3 T whole-body scanner with 81 gradient directions obtained with 3rd order tessellation of the icosahedron, 3 repetitions per direction, each with TR =5100 s, TE = 109 ms, b = 1000 s/mm^2, bandwidth 2170 Hz, 64 x 64 matrix, FOV 240 mm and phase partial Fourier 5/8. The voxels are 3 mm^3 with 24 slices of dimensions 64 x 64 slices. Synthetic Data Test: We generate synthetic ODF data using the multi-tensor model [1]. We use a tensor profile with eigenvalues [300,300,1700]x10^{-6} mm^2/s (Fractional Anisotropy (FA) = 0.8) and use complex Gaussian noise with standard deviation of σ, producing signal to noise ratio (SNR) of 1/σ. Then, the exact ODF is computed as in [1]. To evaluate fiber detection, we use noisy synthetic data generated with 1, 2, or 3 fibers chosen randomly with equal volume fraction and random angle between fibers. SNR is set to 35, we vary estimation order L = 4, 6, 8 and use b-values of 1000 and 3000 s/mm^2. We generate 100 such HARDI data separately, estimate the ODF with and without sharpening and count the number of times we correctly detect the number of ODF maxima. Then, we perform a numerical experiment to evaluate angular resolution limitations. We generate noise-free synthetic data for two fibers and for b-values of 1000 and 3000 s/mm^2. We vary the crossing angle between fibers to determine the critical angle at which only a single maximum is detected instead of two and also record the angular error made on the detected maxima in this process.

Results

Fig.2

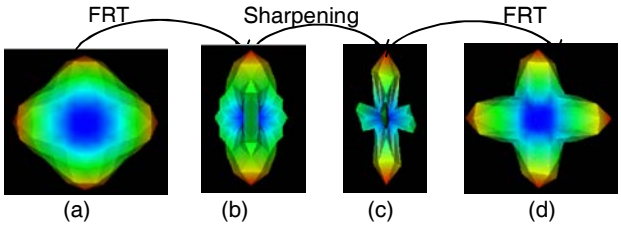


Table 1: Fiber detection success

	$b = 1000$ s/mm^2		$b = 3000$ s/mm^2	
order L	sharpening	no sharpening	sharpening	no sharpening
8	86%	65%	99%	87%
6	84%	64%	98%	85%
4	76%	62%	87%	77%

Table 2: Angular Resolution Limitations

	$b = 1000$ s/mm^2		$b = 3000$ s/mm^2	
order L	sharpening	no sharpening	sharpening	no sharpening
8	57°	68°	50°	53°
6	58°	68°	50°	54°
4	61°	71°	53°	60°

Fig.3

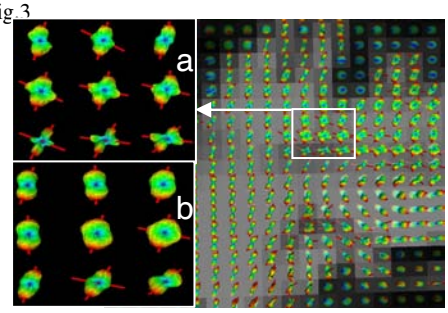


Fig. 3 shows a sagittal slice of the corona radiata in a region with diverging fibers and crossings with the superior longitudinal fasculus fibers. The multiple fiber distribution is enhanced and ODF maxima detected more easily in the sharpened ODF (Fig.3a) compared to the unsharpened ODF (Fig.3b). Tbl.1 confirms that sharpening increases the success rate of fiber detection. For b-values of 1000 and 3000 s/mm^2, the success rate increases by roughly 15% and 10% respectively. Note that sharpening the b = 1000 s/mm^2 data has the effect of improving fiber detection to nearly the level of b = 3000 s/mm^2 data without sharpening. Finally, Tbl.2 shows that angular resolution was improved by roughly 10° and 5° at b-values 1000 and 3000 s/mm^2 respectively. We recorded no noticeable difference in angular error made on the ODF maxima detected with and without sharpening. In all cases, a mean angular error of less than 5° for data with SNR > 15 was obtained.

Discussion As seen in the results, sharpening improves fiber detection and increases angular resolution of the ODF reconstruction while not affecting the accuracy of detected fibers. The added value of sharpening is even more significant at low b-values such as 1000 s/mm^2 used in clinical acquisitions. The sharpening is intuitive, simple, and fast to compute if working with a spherical harmonic basis. Overall, the convolution sharpening has the desired effect of enhancing the underlying fiber distribution while reducing its isotropic part, which can viewed as transforming the diffusion ODF [1] into a fiber ODF [2]. This is without having the instabilities and negative peaks reported in the deconvolution of [2]. It could thus be an important pre-processing tool to improve QBI-based fiber tracking and segmentation results.

References [1] Tuch, PhD thesis 2002. [2] Tournier et al, NeuroImage, 23:1176-1185, 2004. [3] Andrews et al, Cambridge Univ Press. 1999. [4] Descoteaux et al, In ISBI, Virginia, USA, 81-84, 2006. [5] Anderson et al, Magn Reson Med, 54:1194-1206, 2005. [6] Hess et al, Magn Reson Med, 56:117-124, 2006.