

Dual Q-ball imaging reveals intravoxel orientation distribution functions for laminar structures in the heart.

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Introduction: Besides fiber structure, diffusion tensor imaging (DTI) and microscopy techniques have revealed a secondary (laminar) microstructure in myocardial tissue. Nowadays, it is commonly acknowledged that the bulk of the heart muscle consists of aligned uniaxial fibers embedded in a collagen matrix, which exhibits cleavage planes as well [1]. In a leading hypothesis these adjacent layers (or sheets) slide against each other during cardiac contraction, thereby reducing mechanical shear stresses [2]. When considering the three diffusion tensor eigenvectors, the eigenvector e_f having the largest eigenvalue is associated with dominant fiber orientation, whereas the smallest eigenvalue is thought to yield an eigenvector e_n pointing along the sheet normal.

Problem: There is an ongoing debate on the precise nature of the sheet architecture, and no consensus model has been reached [3,4]. In particular, histological techniques have witnessed certain mid-myocardial regions where two nearly orthogonal populations of cardiac sheets can coexist. Since DTI can only record monomodal Gaussian diffusion, it is not adapted to capture such complex microstructure. On the other hand, existing histological and microscopy methods are implicitly destructive and the tracking of fibers and sheets using these methods is challenging.

Methods: In brain white matter, a similar problem is found in terms of fiber crossings. High angular resolution diffusion MRI such as Q-Ball Imaging (QBI) manages to estimate the fibers' orientation distribution function (ODF) on a voxel-to-voxel basis [5]. Hence QBI quantifies the probability that the fibers in a particular voxel point in a given direction and thus can, to some extent, resolve multiple fibers within a voxel.

Starting from the net spin displacement probability function $P(\mathbf{r})$, we propose a sheet normal distribution function (SNDF) in analogy to the ODF (see figure 1), for all directions with unit vector \mathbf{u} :

$$\text{ODF} : \psi(\mathbf{u}) = \frac{1}{Z} \int_{u_{\parallel}} P(\mathbf{r}) d^3\mathbf{r}, \quad \text{SNDF} : \xi(\mathbf{u}) = \frac{1}{Z} \int_{u_{\perp}} P(\mathbf{r}) d^3\mathbf{r} \quad (1)$$

In this, Z are normalization constants setting the overall probability equal to one. Relying on the narrow pulse condition for diffusion weighting and the Fourier slice projection theorem, we have been able to relate the SNDF to the Q-Ball signal. This relation was tested in two ways:

A) Numerical simulation of restricted spin diffusion in a configuration with crossing sheets.

B) *Ex vivo* QBI measurement in 3 slices of a wedge-shaped transmural sample of canine myocardium (in anterior left ventricular free wall), with resolution 0.4 mm x 0.4 mm x 1.0 mm, in 162 directions, with various b -values: 1500, 3000 and 4500 s/mm².

Since our method exploits in many ways the mathematical duality between fibers and cleavage planes, we term it dual Q-Ball Imaging.

Results:

- As for the ODF, the SNDF guarantees linear superposition of partial volume effects. Therefore it is highly suitable for untwining multiple sheet populations within the same voxel and estimating their relative abundances.
- We were able to prove theoretically that given a Q-ball sampled signal, estimating the ODF and SNDF with unweighted projections as in (1) is only possible using standard and dual QBI reconstruction, respectively.
- Since dual QBI makes use of the same scan protocol as QBI for fibers, knowledge of both fiber and sheet structure can be inferred from the same scan data.
- Random walk simulations demonstrate that dual QBI is capable to resolve crossing sheets.
- We show the first example of intravoxel sheet crossing obtained by diffusion MRI means in cardiac tissue (figure 2).

Conclusions: We have developed, investigated and preliminary validated the method of dual QBI. The technique should be applicable to any object/tissue where restricted diffusion within laminae is present.

References:

- [1] Pope A.J. et al., Am J Physiol 295, H1243-H1252 (2008).
- [2] Costa K.D. et al., Am J Physiol 273, H1968-H1976 (1997).
- [3] Gilbert S. H. et al., EJCTS, 32(2): 231-249 (2007).
- [4] Helm P.A. et al., Magn. Reson. Med. 54:850-859 (2005).
- [5] Tuch D.S., Magn. Reson. Med. 52:1358-1372 (2004).

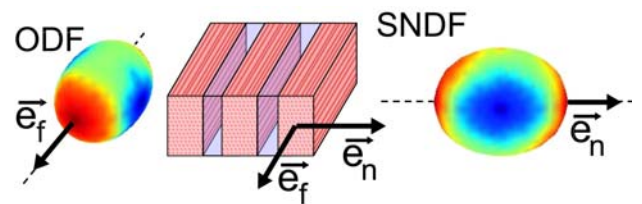


Figure 1: As the ODF describes fiber orientation (left), the SNDF reflects underlying sheet geometry (right). Color denotes local maxima (red) and minima (blue).

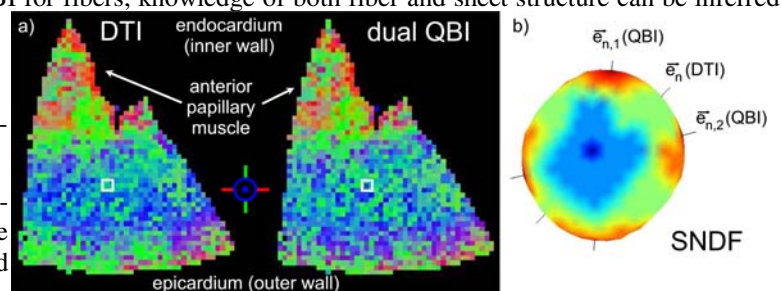


Figure 2: Same axial slice of sheet normal directions from DTI and QBI in 162 directions ($b=4500$ s/mm²). In panel a), colors encode principal sheet direction and both techniques show good qualitative agreement. However, closer inspection of the SNDFs shows intravoxel sheet crossing which cannot be resolved with conventional DTI. Panel b) illustrates this for the framed voxel from a), where the DTI sheet normal direction lies in between two distinct sheet populations whose normal directions appear as two local maxima of the SNDF.