Higher order descriptions of orientation

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Due to the low spatial resolution that can typically be achieved with diffusion-weighted imaging (DWI), a very high proportion (~90%) of white matter voxels will contain contributions from different fibre tracts with distinct orientations [1]. Such voxels are not well described by the commonly used diffusion tensor model, and the fibre orientations provided by this model will generally be incorrect in these cases. This is particularly problematic for fibre-tracking applications, which rely on accurate estimates of fibre orientation, as this may cause the tracking algorithm to establish connections that do not exist in reality or to fail to identify connections that do exist.

It should be emphasized that in the context of DWI, so-called ‘crossing fibres’ effects are not limited only to white matter regions where fibres are intermeshed at the axonal level. They will also (and more generally) occur due to partial volume effects, for example in voxels located at the boundary between two different but adjacent fibre bundles. More complex arrangements may also be observed in voxels where fibres diverge or curve significantly.

Over the past decade, more sophisticated models have been developed specifically to address the limitation of the DTI framework, facilitating the estimation of fibre orientations in the presence of crossing fibres (see [2] for recent review). Conceptually, these higher order methods can be categorised into two main approaches; those based on q-space theory [3], and ‘mixture model’ (or slow exchange) approaches.

Diffusion Spectrum Imaging (DSI) is based directly on the q-space formalism, and involves acquiring images with q vectors arranged in a rectilinear grid, suitable for direct Fourier transformation [4]. In this way, an estimate of the 3D spin propagator can be obtained for each voxel. Although DSI provides the most complete characterisation of the diffusion process within each voxel, there are some distinct disadvantages to its use. In particular, the large number of images required to reconstruct the spin propagator translates into prohibitively long scan times.

Most recently proposed fibre-resolving techniques are based on the so-called high angular resolution diffusion-weighted imaging (HARDI) acquisition scheme [5]. The HARDI approach is to acquire images with the DW gradients applied along a relatively large number (40+) of uniformly distributed orientations, using a constant b-value (corresponding to a single spherical shell in q-space). This scheme is arguably the most time-efficient data acquisition strategy to enable reconstruction of fibre orientations, as it focuses purely on the angular dependence of the DW signal, rather than its b-value dependence, the latter of which is less likely to contain useful orientation information.

Data acquired using the HARDI acquisition strategy can be analysed using a number of reconstruction algorithms. These techniques can be broadly divided into two classes: those based on q-space theory, and those based on the slow exchange limit. [Note that this class of q-space-based methods is different from eg DSI described above, in that the latter requires more extensive sampling of q-space than the single spherical shell acquired in HARDI]

Approaches based on the q-space framework that make use of HARDI data include e.g. Q-ball [6], PAS-MRI [7] and DOT [8]. These rely on the fact that diffusion of water molecules along the fibre tracts is more rapid than diffusion across the tracts, so that the spin propagator is expected to have high probability ‘ridges’ along the fibre orientations. However, as the DW signal is only available on a spherical shell in q-space, the required Fourier transform cannot be performed directly. To make the problem tractable, assumptions need to be made, for example about the radial dependence of either the DW signal or of the spin propagator.

“Mixture model” approaches (based on the slow exchange limit) include e.g. multi-tensor fitting [5,9,10], spherical deconvolution (SD) [11], FORECAST [12], and constrained SD [13]. These rely on the assumption that water exchange between the different fibre tracts is slow, so that the DW signal is a linear combination of the signals originating from each distinct fibre bundle. This is generally thought to be valid in normal white matter, as axons are usually bundled into fascicles whose diameter is typically greater than hundreds of microns, compared to a diffusion distance of approximately five to ten microns for a typical DWI experiment. The signal for each fibre orientation can be modelled using the diffusion tensor model [5,9,10,12], or by assuming a generic form for its angular dependence that can be measured from the DW data [11,13].

The presentation will cover many of the above issues in more detail.