In-vivo diffusion q-space trajectory imaging

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Introduction: The double pulsed field gradient (double-PFG) sequence is a recent and exciting development in diffusion MRI that allows for new ways to probe tissue microstructure. It uses two pairs of diffusion-sensitizing gradients instead of the current standard for diffusion MRI, which comprises a single gradient pair (single-PFG). Experimental results demonstrate that double-PFG analysis alleviates the demand for strong gradients for microstructure determination [Ozarslan08]. In the Gaussian approximation regime, the double-PFG sequence generates a planar diffusion encoding, where the two encoding gradients define the orientation of the plane. Double-PFG is an exiting development but limited by the tradition of pulsed encoding. Inspired by the magic angle spinning of the q-vector method (q-MAS) for achieving isotropic diffusion encoding [Eriksson13, Topgaard13], we here outline a framework for generating both isotropic and anisotropic diffusion encodings from q-space trajectories using a concept of a tensor-valued diffusion encoding.

Theory: In conventional pulsed field gradient diffusion MRI, the diffusion encoding is achieved by applying a pair of short gradient pulses separated by a diffusion time. Such a measurement probes a single axis in q-space. Here we will explore more general scenario with time-varying gradients that probe a trajectory in q-space. Fig. 1 visualizes a set of q-space trajectories. The geometry of the diffusion encoding can in the Gaussian approximation regime be described by a diffusion "measurement tensor" or "encoding tensor", extending the b-value to a tensor-valued entity. Here we define the encoding tensor by

$$\mathbf{B} = \int_0^\tau \mathbf{q}(t)\mathbf{q}^T(t)\, dt \;, \quad \text{where} \quad \mathbf{q}(\mathrm{t}) = \gamma \int_0^\mathrm{t} \mathbf{g}(\mathrm{t}')\mathrm{dt}'$$

where **g**(t) is the time-dependent gradient, and γ is the gyro magnetic ratio. In this general case when the q-vector is built up by a time-dependent gradient to traverse an arbitrary path in q-space, the rank of the **B** diffusion encoding tensor depends on the path. The rank of the diffusion encoding tensor is 1 in the single-PFG case, 2 for double-PFG, and 3 in the isotropic encoding case such as the triple-PFG [Valette12] or q-MAS [Eriksson13].

If we want to apply diffusion encoding with an arbitrary shape of the encoding tensor $\mathbf{B}_k$ this can be achieved by transforming a gradient waveform that produce isotropic encoding by scaling it with a transform $\mathbf{M}_k$ according to

$$\mathbf{q}(t)_k = \mathbf{M}_k \frac{\mathbf{q}(t)_{iso}}{\sqrt{b}} = \mathbf{M}_k \hat{\mathbf{q}}(t)_{iso} \;, \quad \text{with} \quad \mathbf{M}_k^2 = \mathbf{B}_k \;, \quad \text{since}$$

$$\begin{aligned} \mathbf{B}_k &= \int_0^\tau \mathbf{M}_k \hat{\mathbf{q}}(t)_{iso}\, (\mathbf{M}_k \hat{\mathbf{q}}(t)_{iso})^T\, dt \\ &= \mathbf{M}_k^2 \int_0^\tau \hat{\mathbf{q}}(t)_{iso}\, (\hat{\mathbf{q}}(t)_{iso}(t))^T\, dt \\ &= \mathbf{B}_k\, \mathbf{I} \end{aligned}$$

Method and results: We implemented q-space trajectory imaging (QTI) on a clinical MRI scanner (Philips Achieva 3T). Data was acquired in one volunteer. Imaging parameters were: TE = 160 ms, Tr(**B**) = *b* = 0, 200, 400, 600, 800, 1000, 1200, 1400, 1800, and 2000 s/mm^2, voxel size = 3x3x3 mm^3. The time varying gradients were designed to produce q-space trajectories generating linear, prolate, isotropic, oblate, and planar **B** encoding tensors, in six directions specified by the icosahedron (Fig 1). Fig. 2 shows MR signals from a b-value of 1800s/mm^2. Figure 3 shows the relative attenuation between the different types of diffusion encoding. The ratio between the different types is related to the microscopic anisotropy. It is interesting to see that the largest contrast is between the linear and the isotropic case, and not the linear and planar that has recently been explored using double-PFG. Fig 4 shows the result of estimating diffusion tensors from the q-space trajectory measurements.

Discussion and conclusions: Careful design of the q-space trajectory can produce diffusion encoding of a measurement tensor **B**. The presented work shows that it is possible to perform diffusion encoding imaging of the human brain with arbitrary q-space trajectories while maintaining good SNR. In conclusion, we propose that q-space trajectory imaging has a potential to serve as a basis for next-generation diffusion MRI.

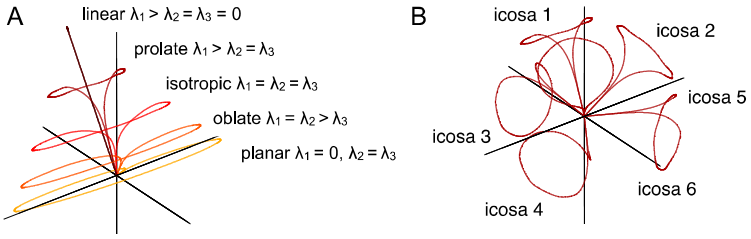

Fig. 1. Plot of q-space trajectories, with x-y-z axes. By varying the trajectory of q, diffusion encoding tensors of varying shapes can be produced (panel A). For example, conventional single-PFG encoding yields a linear encoding tensor, while double-PFG with orthogonal encoding yields planar encoding. Magic angle spinning of q yields isotropic encoding. Rotating the trajectory achieves directional encoding, for example, along the icosahedron scheme (panel B).

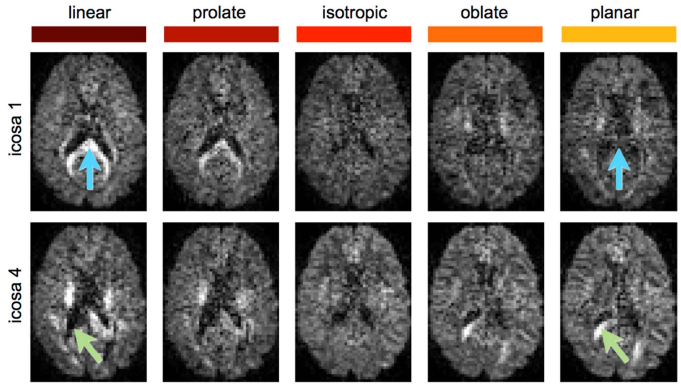

Fig. 2. MR signal from the five different types trajectories in Fig 1A, applied two different directions in q-space. The five types of trajectories produce measurement **B**-tensors with (from left to right) linear, prolate, isotropic, oblate, and planar shapes. Note that the linear and the planar measurement are orthogonal/dual, and thus, where the linear measurement is bright the planar is dark; see blue and green arrows.

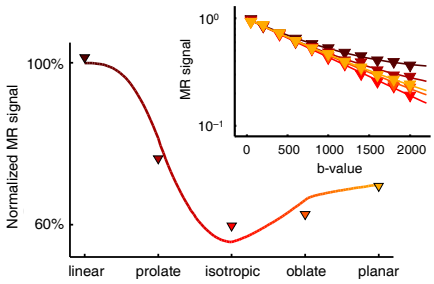

Fig. 3. The inset shows signal-versus-b curves from a ROI in the corticospinal tract from the trajectories, averaged across the six directions acquired. The main plot shows the relative attenuation from the various trajectories for a b-value of 1800 s/mm^2.

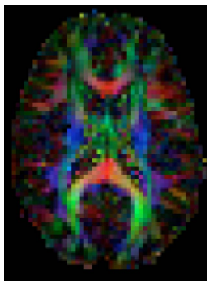

Fig. 4. Diffusion tensors estimated from all the data from a total of 6 directions, 5 different trajectories, 11 b-values (trace of **B**).

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