Rotating field gradient (RFG) MR for direct measurement of the diffusion orientation distribution function (dODF)

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Target Audience - Basic scientists interested in mapping neural connectivity, pulse sequence developers, MR physicists and engineers.

INTRODUCTION: We hypothesize that the diffusion orientation distribution function (dODF) can be directly measured using two oscillating gradients applied simultaneously along two perpendicular directions with a 90° phase shift between them. The resulting rotating field gradient (RFG) waveforms can be utilized as the building blocks for more sophisticated sequences. E.g., two RFGs with a 90° phase shift, applied around the180° RF pulse in a spin echo sequence, yield rank-2**b**-matrices. When multiple such acquisitions are performed by varying the axis of rotation, the orientation associated with the maximum signal value corresponds to the orientation along which the diffusion constant is greatest. Since this property holds for all compartments within the voxel, the aggregate signal profile represents the dODF. Thus, the technique obviates the need for transforming the signal into the displacement domain. Experiments on an asparagus specimen performed using a GE clinical scanner confirmed the predicted signal dependence in anisotropic environments.

THEORY: For simplicity, we shall work in a reference frame in which the axis of rotation is along the *z*-axis. Further, we shall consider a heterogeneous specimen comprising *N*arbitrarily oriented, anisotropic, Gaussian subdomains in slow exchange regime. For such a system, the signal is given simply by the expression $E(\mathbf{b}) = \sum_{n=1}^{N} f_n \exp\left(-\mathbf{b}:\mathbf{D}^{(n)}\right)$, where f_n represents the signal fraction of the *n*th subdomain, characterized by the diffusion tensor $\mathbf{D}^{(n)}$. The components of the **b**-matrix associated with the pulse sequence shown in Figure 1 are given by $b_{ij} = \frac{4\pi(\gamma G)^2}{\omega^3}\left(\delta_{ix}\delta_{jx} + \delta_{iy}\delta_{jy}\right)$, where γ is the gyromagnetic ratio, G is the gradient magnitude, ω is the angular frequency of rotation, and δ is the Kronecker delta. The total signal is then given by $E(\mathbf{b}) = \sum_{n=1}^{N} f_n \exp\left(-\frac{4\pi(\gamma G)^2}{\omega^3}\left(D_{xx}^{(n)} + D_{yy}^{(n)}\right)\right)$. Clearly, the signal contribution from each compartment takes its maximum value when the axis of rotation is along the orientation of largest diffusivity. The aggregate signal is just a weighted sum of *N* such profiles.

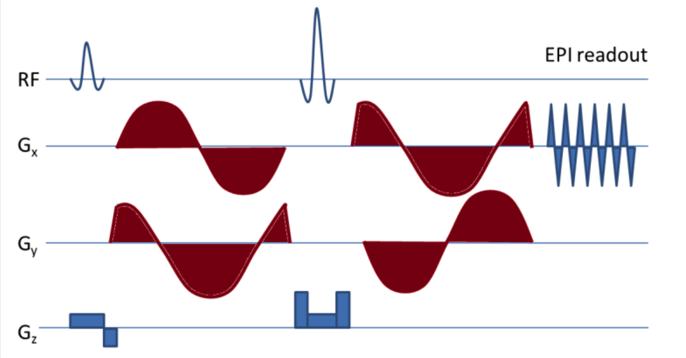

Fig. 1: The pulse sequence employs two RFGs around the 180° RF pulse with a 90° phase shift between them. Each RFG comprises sine- and cosine-modulated gradient waveforms along two orthogonal directions. These directions define the plane of rotation, and the normal to the plane is denoted by **n**.

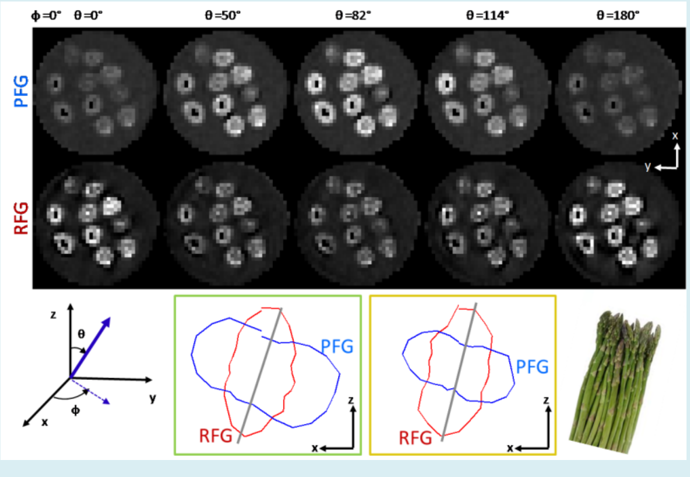

Fig. 2: Top panel: diffusion signal attenuation maps derived from DWIs of a collection of asparagus stalks acquired using PFG and RFG dMRI pulse sequences with **n** sampling the *zx* plane (□=0°, θ=0° to 180°). Bottom panel: diffusion signal attenuation in two representative voxels as a function of orientation in the *zx* plane. The RFG signal attenuation follows the orientation of the asparagus stalks, suggesting the possibility to directly sample the dODF without the need for Fourier Transform from q-space in PFG-based methods (i.e. Q-ball imaging, DSI). The gray lines depict the fiber orientation estimated from a complementary "sagittal" image of the specimen.

EXPERIMENTS & RESULTS:A specimen containing parallel stalks of asparagus oriented along the direction of the main field (*z*) was scanned using both conventional pulsed field gradient (PFG) spin echo and the proposed RFG diffusion pulse sequences with the following imaging parameters: 9 slices with 5 mm thickness, a 64×64 imaging matrix over a 128×128 mm^2 field-of-view (FOV), and TR=5s. The echo times were 83ms and 110ms for PFG and RFG dMRI, respectively. For PFG dMRI 25 diffusion directions **n** were used to sample the *zx* plane, while for the RFG dMRI, rotating gradients were applied in planes orthogonal to the same 25 directions using a *b*=1350s/mm^2. The eddy current corrected DWIs [1]were used to compute images and voxel-wise 2D orientation plots (in the *zx* plane) of the diffusion signal attenuation in the PFG and RFG experiments, respectively (Fig. 2).

DISCUSSION& CONCLUSION: The RFG signal attenuation follows the orientation of the asparagus stalks, confirming the possibility to directly sample the dODF without the need for q-space Fourier Transform as in PFG-based methods (e.g., Q-ball imaging [2], DSI [3]).

Traditional PFG measurements yield **b**-matrices that are rank-1. Others have designed pulse sequences with isotropic, hence rank-3,**b**-matrices using PFGs as well as RFGs [4]. Having a rank-2 **b**-matrix, provides "equatorial averaging" at the acquisition stage, which is performed in PFG-based QBI at the reconstruction (post-processing) stage.

The RFG sequences can be easily implemented in different settings including clinical platforms. The ability to directly measure the dODF is expected to provide a viable and potentially more powerful alternative to traditional approaches in studies aiming to map the anatomical connections between different regions of the nervous system.

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