The effects of the finite q-space sampling in diffusion spectrum imaging

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Background

By using a pulsed gradient spin echo (PGSE) pulse sequence, q-space signal measurements and the diffusion probability density function (PDF) are related through the Fourier transform [1]. The diffusion behavior can be empirically described by the PDF without any underlying model assumptions such as a Gaussian diffusion. The directional information can be described by the orientation distribution function (ODF), which is the radial integral of the PDF [2]. Diffusion spectrum imaging (DSI) was developed as a method to map the fiber orientations using the ODF [2,3]. The optimization of encoding parameters for DSI has been studied in terms of the estimation of angular fiber distribution [4]. However, by sampling the full q-space, the DSI experiment contains other potentially important information in addition to the ODF, such as the zero displacement probability and the displacements at equal probability surfaces of the PDF. The effects of the q-space sampling range ($|q_{max}|$) on these measures were explored in this study. The results may provide useful information in optimization of DSI experiments.

Materials and Methods

DSI experiments on a 3T GE SIGNA were performed on two healthy subjects. The q-space sampling was an 11x11x11 Cartesian lattice with a spherical aperture with 515 total diffusion encoded measurements. The diffusion parameters were maximum gradient of 3.98 G/cm and the diffusion duration and separation δ/Δ= 45/55 ms giving maximum diffusion weighting of 9413 s/mm^2. The maximum q = 76.26 mm^{-1} and Δq= 15.25 mm^{-1} corresponded to PDF resolution of 6.6 μm and FOV of 66 μm. The image parameters for a single 5 mm coronal slice were TR/TE = 1000/110 ms, matrix size of 64x64, FOV of 20 cm. For each voxel the PDF was obtained by Fourier transforming the q-space signal S(**q**); i.e. $P(\mathbf{R}) = FT^{-1}[S(\mathbf{q})]$. Several measures of PDF were investigated: (i) The zero displacement probability (P(0)) map, $P(\mathbf{R}=0) = \int S(\mathbf{q})d\mathbf{q}$, (ii) the FWHM maps, $2R_i$ in three orthogonal directions, i.e., $i = x, y, z$ ($P(R_i) = P(0)/2$), and (iii) the shape of PDF at equal probability surfaces (EPS) of the PDF, $P(\mathbf{R} \in EPS_n) = P(0)/n$. To study the effects of finite q-space sampling on these measures, the q-space data was resampled for several levels of maximum DW between 1500 and 7600 s/mm^2. The PDF and other DSI measures were recalculated for each range of q.

Results and Discussion

The zero displacement probability (P(0)) and FWHM maps for "full" q-space are shown in Fig. 1. High tissue contrast between GM and WM is observed in the P(0) map. The fibers orientation along three orthogonal directions were highlighted according to their anatomical orientations. For example, the $FWHM_x$ map is hyperintense in the corpus callosum. These maps provide quantitative measures of PDF and may potentially have high sensitivity in the pathological changes in the brain tissue. Similar measures have been applied in MS [5,6], although the q-space sampling was much sparser.

With this protocol, the GM signal is not detectable above b=2000 s/mm^{-1} independent of the diffusion directions. Conversely, WM still has significant signal at b=16000 s/mm^{-1} along certain directions, which is similar to the results described in [7]. The spherical q-space aperture used in our DSI experiments is a truncated, uniform modulation transfer function (MTF): $\tilde{S}(\mathbf{q}) = S(\mathbf{q}) \cdot MTF(\mathbf{q})$. Thus, the estimated PDF is the true PDF convolved with the point spread function (PSF) from finite sampling $\tilde{P}(\mathbf{R}) = FT^{-1}[S(\mathbf{q}) \cdot MTF(\mathbf{q})] = P(\mathbf{R}) \otimes PSF(\mathbf{R})$. A small q-space aperture should truncate high q features, which will influence the ODF. Further, the finite sampling volume underestimates the P(0) of the WM due to incomplete integral of $P(0) = \int_{-q_{max}}^{q_{max}} S(\mathbf{q})d\mathbf{q}$. This is illustrated in Fig 2 where the P(0) maps were generated from the lattice subsets in the q-space. The tissue contrast increases as the q-space aperture increases. The finite sampling also affects the FWHM estimation (Fig 3). Similar to the P(0) maps, the FWHM of WM and the tissue contrast increases as the q-space aperture increases.

References:

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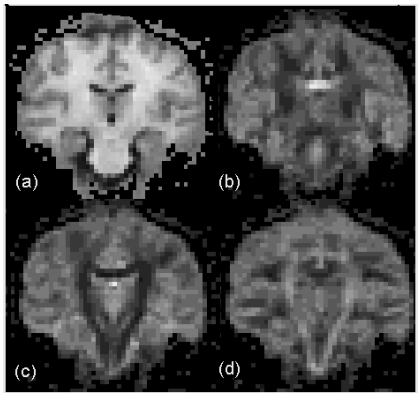

FIG. 1
The PDF measures with b_{max} = 9413 s/mm^2. (a) The zero displacement probability, P(0), map. The FWHM map along x (b), y (c) and z (d) direction.

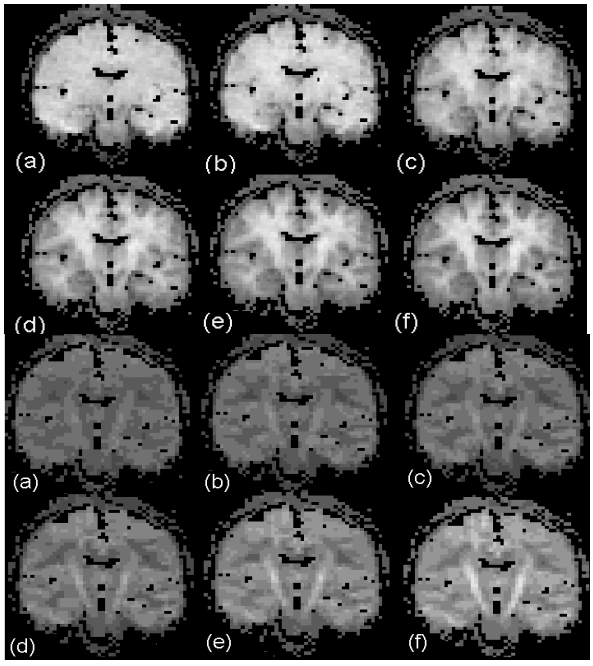

FIG. 2
The zero displacement maps for DSI with different maximum diffusion weighting, whose b_{max}= (a) 1500, (b) 2350, (c) 3400, (d) 4600, (e) 6000 and (f) 7600 s/mm^2, respectively. The tissue contrast increases as the b_{max} increases.

FIG. 3
The FWHM maps along z direction for DSI with different maximum diffusion weighting, whose b_{max}= (a) 1500, (b) 2350, (c) 3400, (d) 4600, (e) 6000 and (f) 7600 s/mm^2, respectively. Increasing intensity of the pyramidal tracts was observed as the b_{max} increases.