Diffusion encoding with 2D gradient trajectories yields natural contrast for 3D fiber orientation

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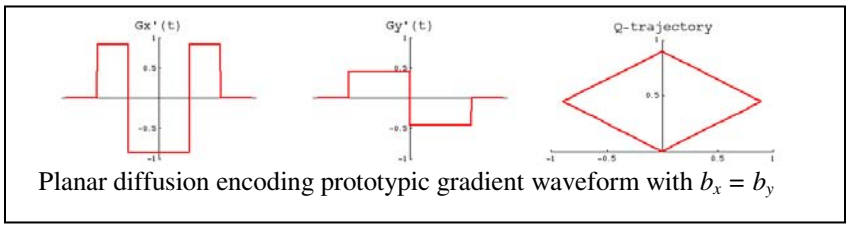
Consider the question: Can we identify all fibers of a particular orientation in a single shot? In present diffusion MRI, we take it for granted that linear diffusion encodings are applied in multiple directions and signals associated with specific fiber orientations reconstructed by 3D geometric transform, 3DFT in diffusion spectrum imaging (DSI), Radon transform in q-ball imaging (QBI), etc. This approach is indirect, but necessary because linear bipolar gradients are only *partially* specific for fiber orientation, each encoding retaining signal of all fiber populations oriented perpendicular to the gradient.

Suppose, however, that we apply two diffusion encodings successively within a single shot, say *Gx* and *Gy*. Then the persistent signal (as *b* increases) will reflect exclusively spins with restrictions in *both* in *x- and* in *y-*. To a first approximation, these are spins associated with fibers along *z-*. This suggests that if we think of diffusion encoding as a geometric filter, the natural encoding of a single fiber orientation is a 2D or planar diffusion encoding perpendicular to this orientation.

Methods and Results: To test experimentally the mapping of fiber orientation with 2D diffusion encoding, we compared CNS tractography in two acquisitions of "DSI-type": a conventional DSI incorporating bipolar gradients, and another incorporating 2D planar diffusion encodings [1]. More specifically, this sequence for planar contrast was constructed by substituting into a DSI sequence for each bipolar gradient waveform q a new waveform q^+ that encodes diffusion 2-dimensionally in the plane perpendicular to q, with gradients of intensity and duration equal to its bipolar counterpart pulse.

Rather than the sequential bipolar pulses outlined above, we use as a prototype 2D gradient waveform a more efficient one: a parallelogram. Letting *{x',y'}* be orthonormal axes in the q^+-plane, then the *x'*-gradient is a temporal *{1,-2,1}*-pulse, and the *y'*-gradient a bipolar pulse of the same net duration half as intense as the *x'* (Fig 1). This waveform is symmetric to 1st order, having no preferred axis in the *x'-y'* plane: its *x'*- and *y'*- components are temporally uncorrelated and have equal individual diffusion *b* values, $b_x = b_y$ (its autocorrelation tensor $\int G(t)G^T(t)\,dt$ is isotropic [2]). This waveform has net diffusion sensitivity $b = (\Delta - \delta/3)\int|k(t)|^2dt$ that is greater by a factor of $\sqrt{5}$ than that of sequential bipolar gradients of equal intensity and duration.



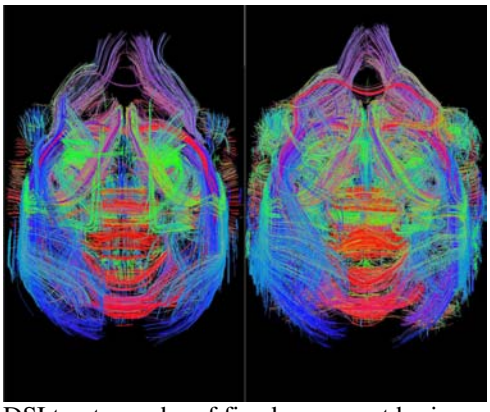
Planar diffusion encoding prototypic gradient waveform with $b_x = b_y$

To reconstruct these data, the conventional DSI are reconstructed by *3DFT: S(q) -> p(r),* then reduced to an orientation density function (odf) by radial integration $o(u) = \int p(ru)\, r^2 dr$ where u is a unit vector. In the planar contrast experiment, we refer to each 2D encoding q^+ by its perpendicular vector q, defining $S^+(q) = S(q^+)$. $S^+(q)$ should be highest when q is parallel to fibers and accordingly, we construct an odf directly from the signal $S^+(q)$ by radial integration, without reconstruction by integral transform: $o(u) = \int S^+(ru)\, r^2 dr$.

DSI data with conventional and 2D diffusion contrast were obtained in formalin-fixed marmoset brain at 4.7T, SE 750/60 3DFT spatial encoding with 400μisotropic resolution, 515 diffusion encodings comprising, bipolar DSI with $b_{max} = 4.0\ 10^4\ s\ cm^{-2}$ planar DSI with $b_{max} = 2.24\ 10^4\ s\ cm^{-2}$. Normal volunteers were scanned at 1.5T, multi-slice DSI with 3 mm resolution, DSI with a 258 q-values comprising a hemispherical grid, $b_{max} = 8.5\ 10^3\ s\ cm^{-2}$, 2D DSI with $b_{max} = 4.75\ 10^3\ s\ cm^{-2}$. *Ex vivo,* tractography with conventional and with planar contrast appear qualitatively quite similar (Fig. 2). In both *ex vivo* and *in vivo* studies, the planar tractography shows a higher noise level.

Discussion Successful tractography of planar contrast without reconstruction indicates, as predicted, that planar diffusion contrast identifies the signal contribution of fibers of specific orientations. In a sense, this mechanism embeds the enabling logic of high-resolution diffusion imaging, fibers <=> restriction perpendicular to fibers, entirely within the diffusion encoding.

An important difference between planar and conventional 1D diffusion contrast is their contrasting potential for measurement of fiber diameters. While conventional DSI would tend to reflect fiber diameter in the width of reconstructed orientational peaks [3], planar contrast should do so in the radial fall-off of such peaks, as signal will be maintained until the spatial scale of the encoding falls below cross-axis dimensions of the compartment, in fibers, fiber diameter. Such measurements should be robustly tolerant of orientation heterogeneity, where conventional DSI measurements is not.


DSI tractography of fixed marmoset brain, horizontal slice. Conventional bipolar diffusion encoding (left) and DSI with planar contrast without reconstruction (right).

[1] Wedeen VJ, Hagmann P, Tseng W-Y, Reese TG, Weisskoff RM. Magn Res Med. Published Online 24 Oct 05 [2] Paul Moran 1989, personal communication. [3] Avram L, Assaf Y, Cohen Y. J Magn Reson 2004 Jul; 169(1):30-8.