Multiple-Quantum Vector Imaging

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Abstract
A new methodology based on measurements of the dipole field (intermolecular multiple-quantum coherences) is proposed for tracking the vector orientation of parallel fiber bundles or other anisotropic structures in materials or biological tissues. For the very special case of fibrous structures, the signal from CRAZED (Warren *et al.*, *Science* **262**:2005-9, 1993) images for correlation gradients along X, Y and Z can be used to determine θ and Φ, the polar and azimuthal angle of the fiber orientation with respect to the applied field.

Theory
The NMR signal from a CRAZED sequence with a correlation gradient whose wave vector is **k**, in the limit of weak spin polarization, is a linear functional of the dipole field: $\mathbf{T}(\mathbf{k})=\int(\mathbf{M}\times\mathbf{B})(\mathbf{r})d^3r$, where **M** is the magnetization following a CRAZED preparation and **B**=**B**[**M**] is the dipolar field exerting a torque on it. **M** can be modulated by T_1, T_2 relaxation times, proton density or resonance frequency offsets. If the material exhibits a sufficient degree of structural anisotropy in these NMR parameters on the length scale of the correlation distance $d_c = \pi/\gamma GT = \pi/k$ a subtraction of X and Y gradient signals from the Z gradient signal, |Gz|-|Gx|-|Gy| (**Figure 1**) exhibits a familiar $(3\cos^2\theta-1)$ dependence on θ, the polar angle of the fiber axis with respect to the applied field. **Figure 1** is a calculation of CRAZED signal on a 128^3 grid using the dipolar field from an array of 4 cylinders with length 80 pts, radius 10 pts, magnetization 1.0 and zero elsewhere and rotating the fibers away from the Z axis towards the Y axis. The correlation distance is 14 pts. For angles θ near 0º, the subtraction signal is negative and for θ near 90º the signal is positive and near θ=57º it approaches zero. The azimuthal angle Φ can be determined by comparing the X and Y gradients when rotating the fibers in the XY plane, pointing towards Y axis and rotating towards the X axis. We define the ratios GXR=4|Gx|/(|Gz|+|Gx|+|Gy|) and GYR=4|Gy|/(|Gz|+|Gx|+|Gy|), and graph in **Figure 2** the difference GXR-GYR and observe a relationship similar to the empirical function $(2\cos^2\Phi-1)$.

Figure 1 |Gz|-|Gx|-|Gy|.

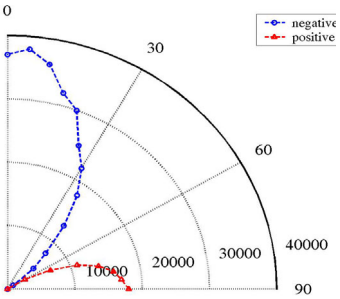


Figure 2 GX-GY.

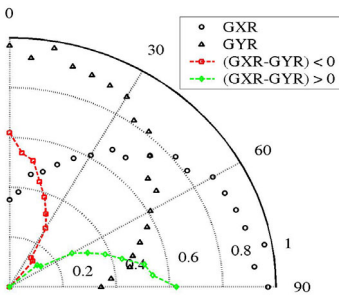
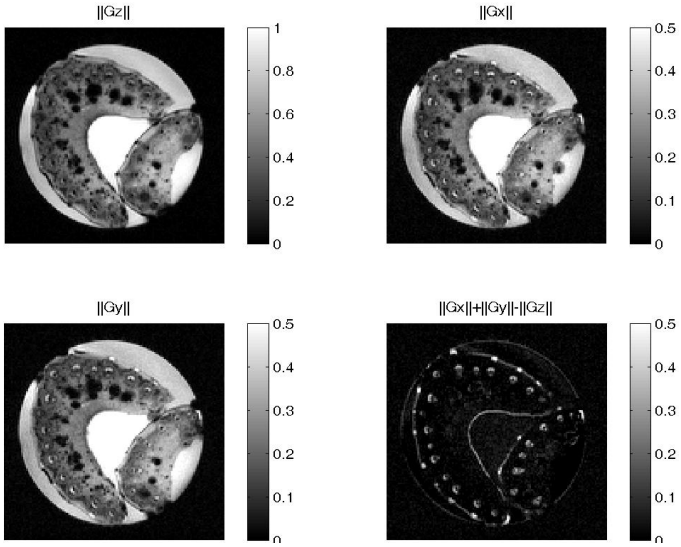


Figure 3 Subtraction |Gx|+|Gy|-|Gz| for CRAZED signal.



Experimental
Magnetic resonance images of the petiole of celery in water were acquired at 7T on a Bruker Biospect animal spectrometer using a double quantum CRAZED sequence with adiabatic pulses and the following parameters TR=3s, TE_{eff}=90ms, τ=6ms, 3 cm field of view, 128×128, 4mm slice.

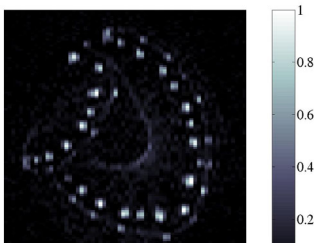
Results
Figure 3 illustrates a subtraction |Gx|+|Gy|-|Gz| of X,Y and Z gradient CRAZED images. Each image is normalized to the water signal on the Gz image. The subtraction very clearly highlights the vascular bundles and collenchyma vessels. The tube and celery walls can also be seen in the subtraction. The correlation distance in **Figure 3** was 120 μm. We obtained nearly identical results with correlation distances of 200 and 300 μm, which are well outside any diffusion weighting regime. Thus, anisotropy can be clearly detected in a structured material without the need for strong diffusion gradients.

The observed subtraction signal on the vascular bundles is due to their shorter relaxation times (700ms-1s compared to 2s for the surrounding parenchyma tissue), while the signal at the tube edges is due to the abrupt change in magnetization density.

Figure 4 shows a subtraction experiment |Gx|+|Gy|-2|Gz| for a conventional pulsed-field gradient diffusion weighted NMR image with diffusion delay Δ=20ms and helix pitch 40 μm. In this case, it is the vascular bundles that are brightest; by comparison, the CRAZED subtraction highlights the collenchyma more clearly.

Tilting the celery sample by 20º away from the applied field and normalizing to the total signal, results in a signal decrease of 10%, which, according to **Figure 1** corresponds to approximately θ=15±5º. Rotating the tilted sample in the XY plane gave results consistent with **Figure 2**.

Figure 4 DWI subtraction



Conclusion
Measurements of the dipolar field can detect structural anisotropy in materials. A subtraction of X, Y and Z gradient images can resolve the vector orientation (θ, Φ) of fibers or other structural heterogeneities. This method finds potential applications in the materials and biomedical sciences. It could perhaps be of use in detecting tumor vascularity or for mapping trabecular bone anisotropy.