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MR imaging of fiber-tract direction and diffusion in anisotropic tissues

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Purpose

In brain white matter[1-3] and skeletal muscle[4], the apparent diffusivity of water is largest when the diffusion gradient and fiber-tract directions are parallel; it is smallest when they are perpendicular[1-4]. We exploit this phenomenon to image fiber-tract orientation noninvasively, using NMR. More generally, we image mean diffusion distances and other functional quantities derivable from the effective diffusion *tensor*.

Theory

We previously presented an equation for estimating the effective diffusion *tensor*, $\underline{D}^{eff}$ in each voxel from spin-echo, pulsed-gradient experiments[5]:

$$\ln\left(\frac{A(TE)}{A(0)}\right) = - \sum_{i=1}^{3}\sum_{j=1}^{3} b_{ij} D_{ij}^{eff} , \qquad (1)$$

where A(0) and A(TE) are magnetization amplitudes, TE is the echo time, and b_{ij} are elements of the b-matrix[5].

The tissue's three orthotropic axes coincide with the eigenvectors of $\underline{D}^{eff}$. The effective diffusivities along these principal directions are the eigenvalues of $\underline{D}^{eff}$, i.e., λ_1, λ_2, and λ_3. The tissue's fiber-tract direction is given by the eigenvector with the largest principal diffusivity.

Also associated with $\underline{D}^{eff}$ are three *scalar invariants*[6], I_1, I_2, and I_3:

$$I_1 = \lambda_1 + \lambda_2 + \lambda_3 = \mathrm{Tr}(\underline{D}^{eff}),$$
$$I_2 = \lambda_1\lambda_2 + \lambda_3\lambda_1 + \lambda_2\lambda_3, \quad \text{and}$$
$$I_3 = \lambda_1\lambda_2\lambda_3 = |\underline{D}^{eff}|, \qquad (2)$$

which are independent of the sample's orientation with respect to the lab frame of reference and depend on the tissue's microstructure[5].

We propose three dimensionless *anisotropy ratios*. The first, λ_2/λ_3, indicates the degree of rotational symmetry about the longest (fiber-tract) axis; λ_1/λ_2 and λ_1/λ_3 are the relative diffusivities parallel and perpendicular to the fiber-tract axis.

Finally, we can construct an *effective diffusion ellipsoid*[5] from $\underline{D}^{eff}$ in each voxel The material's local orthotropic directions coincide with the ellipsoid's principal axes, with the longest axis parallel to the fiber-tract direction. The mean diffusion distances (at time t) along these orthotropic directions are the lengths of the ellipsoid's principal axes.

Materials and Methods

Using a 4.7-T imaging system, we acquired 135 diffusion-weighted sagittal images of *ex vivo* cat brain by applying combinations of diffusion gradients in the read, phase, and slice directions[5]. We measured A(TE) for each voxel in the image, and analytically calculated[7] a b-matrix from each (diffusion and imaging) gradient sequence. Using Eq. (1), $\underline{D}^{eff}$ was optimally estimated in each voxel by weighted multivariate linear regression[5].

Results and Discussion

From the estimated $\underline{D}^{eff}$ in each voxel, we imaged $I_1=\mathrm{Tr}(\underline{D}^{eff})$ for *ex vivo* cat brain (Fig. 1). $\mathrm{Tr}(\underline{D}^{eff})$, a measure of water mobility *independent of tissue orientation*, is significantly different in gray and white matter, fissures, ventricles, and the corpus callosum. $\mathrm{Tr}(\underline{D}^{eff})$ and the other scalar invariants will be useful for accurate assessment of tissue microstructure and its physiological state (e.g., in stroke monitoring).

We also constructed a *diffusion ellipsoid* image from $\underline{D}^{eff}$ in each voxel (Fig. 2). In a ROI near the corpus callosum, voxels in a CSF-filled ventricle appear as large spheres, indicating high isotropic diffusion, while voxels in white matter appear as prolate ellipsoids, indicating anisotropic diffusion with their longest axes correctly aligned with known fiber-tract direction.

Conclusion

MR diffusion *tensor* imaging is feasible. It reveals *intravoxel* microstructural information (that scalars such as proton density, T_1, and T_2 do not), embodied in images of diffusion ellipsoids, scalar invariants, and anisotropy ratios constructed from $\underline{D}^{eff}$.

Fig 1: $\mathrm{Tr}(\underline{D}^{eff})$ image of cat brain (sagittal section) with ROI.

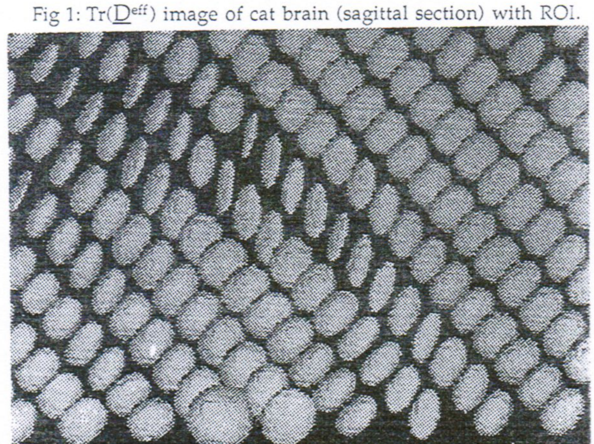

Fig 2: Diffusion ellipsoid image of ROI (rotated c.w. by 90°).

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