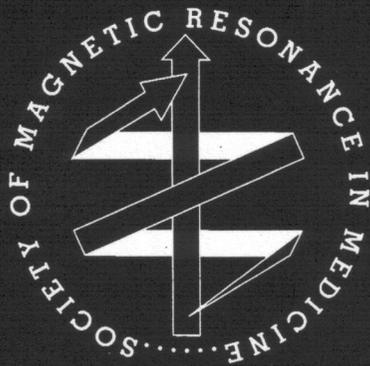


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Fiber orientation mapping in an anisotropic medium with NMR diffusion spectroscopy

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Purpose: The diagonal and off-diagonal components of the apparent self-diffusion tensor [1], \underline{D} , are used to construct a diffusion ellipsoid for a voxel that depicts both orientation of tissue microstructures, such as muscle fibers, and mean diffusion distances. New weighting parameters are also suggested for structural NMR imaging.

Principles: In heterogeneous, anisotropic media, \underline{D} relates the flux of spin-labeled protons to their concentration gradient. Since \underline{D} is symmetric and positive-definite, its three mutually orthogonal eigenvectors, ϵ_1 , ϵ_2 , and ϵ_3 , define the principal axes and its three positive eigenvalues, λ_1 , λ_2 , and λ_3 , are the diffusivities in these directions [2]. Continuum models of diffusion in heterogeneous media [3] suggest that the principal axes of \underline{D} coincide with those of the grain or fiber and the principal diffusivities of \underline{D} are related to the structure, geometry, and diffusivity of the various microscopic compartments within the heterogeneous medium.

The diffusion ellipsoid: In heterogeneous, anisotropic media [3], the macroscopic effective self-diffusion tensor, \underline{D} , appears in the conditional probability density function, which is the probability that a particle at x at time t was at x_0 at $t = 0$:

$$p(x|x_0,t) = \frac{1}{\sqrt{|\underline{D}|(4\pi t)^3}} \exp\left(-\frac{(x-x_0)^T \underline{D}^{-1} (x-x_0)}{4t}\right). \quad (1)$$

Setting the quadratic form to 1/2, i.e.,

$$\frac{(x-x_0)^T \underline{D}^{-1} (x-x_0)}{2t} = 1, \quad (2)$$

defines a diffusion ellipsoid whose principal axes constitute the local "fiber" frame of reference, and whose j^{th} major axis is the mean distance a spin-labeled proton diffuses in the j^{th} principal direction, $\sqrt{2\lambda_j \Delta}$, during the diffusion time, Δ .

The scalar invariants: Three scalar invariants of \underline{D} , I_1 , I_2 , and I_3 , are:

$$\begin{aligned} I_1 &= \lambda_1 + \lambda_2 + \lambda_3 = \text{Tr } \underline{D} \\ I_2 &= \lambda_1 \lambda_2 + \lambda_2 \lambda_3 + \lambda_3 \lambda_1 \\ I_3 &= \lambda_1 \lambda_2 \lambda_3 = |\underline{D}| \end{aligned} \quad (3)$$

They have the desirable properties of being independent of the coordinate system in which \underline{D} is measured, and insensitive to the scheme by which the λ_i are numbered, making them (or functions of them), ideal weighting factors in structural NMR imaging.

Data analysis: Diffusion ellipsoids for pork loin are constructed from two apparent self-diffusion tensors, \underline{D}^{0° and \underline{D}^{41° , estimated from spin-echo experiments [1]:

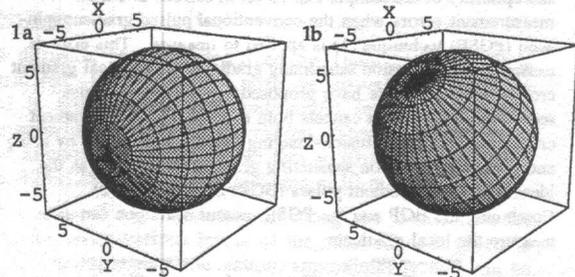


Fig. 1a,b: Diffusion ellipsoids of a pork loin sample. Laboratory coordinates, x , y , and z are in μm . The eigenvector corresponding to the largest eigenvalue defines the polar axis.

In Fig 1a, the grain of the sample was nearly aligned with the magnet's x axis. Eigenvalues (principal diffusivities) of \underline{D}^{0° are $\{\lambda_1 = (1.0406 \pm 0.0007)10^{-5}, \lambda_2 = (0.944 \pm 0.001)10^{-5}, \lambda_3 = (0.8532 \pm 0.0006)10^{-5}\}$ (cm^2/sec). In Fig. 1b, the same sample is rotated approximately 41° in the z - x plane. Eigenvalues of \underline{D}^{41° are $\{\lambda_1 = (1.0119 \pm 0.0003)10^{-5}, \lambda_2 = (0.9343 \pm 0.0006)10^{-5}, \lambda_3 = (0.8767 \pm 0.0018)10^{-5}\}$ (cm^2/sec).

Discussion: The eigenvectors that define the fiber frame follow the sample when it is rotated. This is represented by the tipping of the polar axis. The scalar invariants of \underline{D} differ by no more than 1% in both cases because they are intrinsic to \underline{D} , independent of the sample's orientation in the magnet. Both ellipsoids are nearly spherical, presumably because the diffusion time, $\Delta = 22.5$ ms, corresponding to a mean diffusion distance of $4.7 \mu\text{m}$, is too short for the majority of spin-labeled protons to encounter diffusional barriers.

Although a single voxel was used in this study, these principles can be generalized to multiple voxels. One could envision 3-D fiber maps [4] or diffusion ellipsoids displayed in each voxel, connected like link sausages that follow fiber tracts.

Conclusion: Constructing the diffusion ellipsoid requires knowledge of all diagonal and off-diagonal elements of \underline{D} . Inherently, \underline{D} contains unique directional, structural and anatomical information within a voxel that scalars such as T_1 or T_2 do not - information that is embodied in the diffusion ellipsoid and scalar invariants.

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