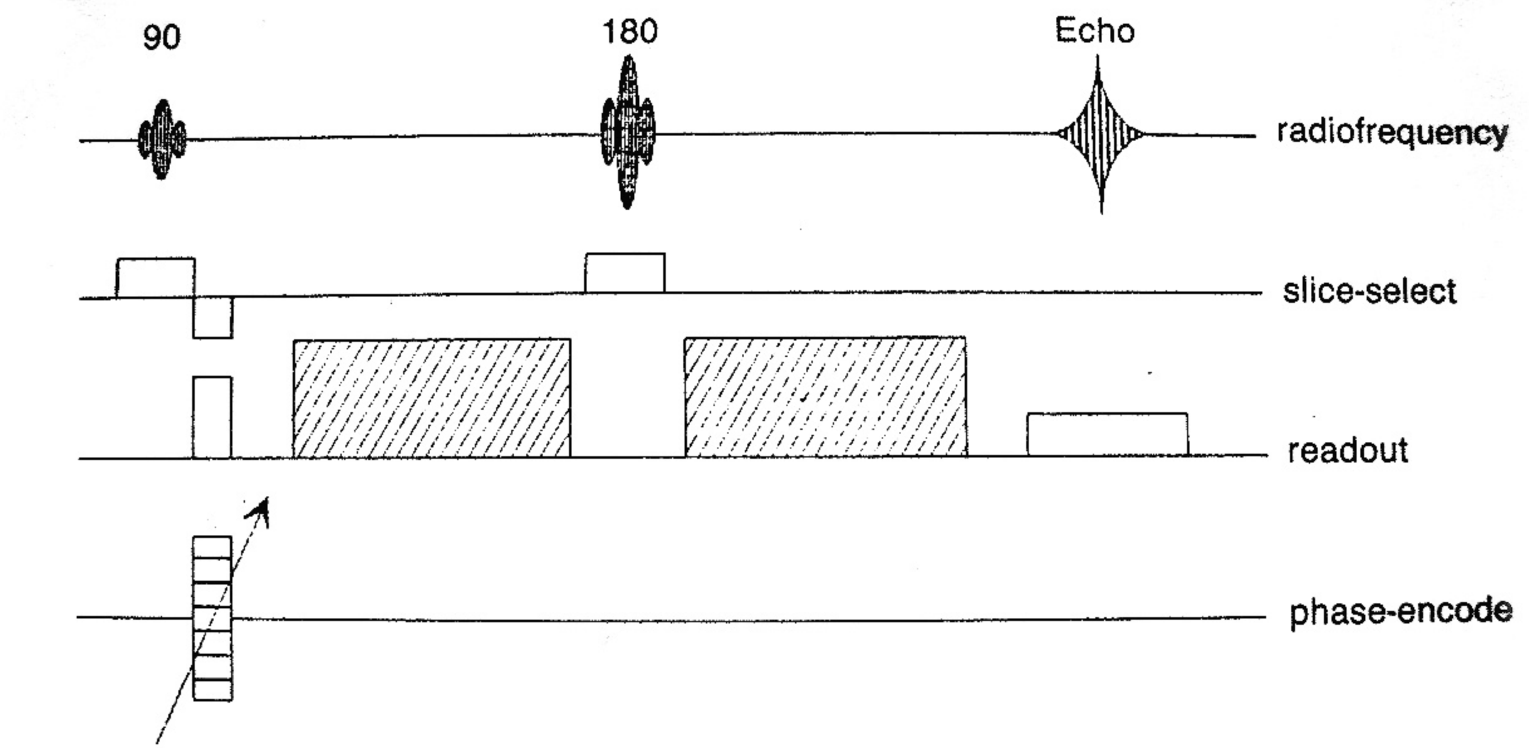
DIFFUSION MAGNETIC RESONANCE IMAGING

- from spectroscopy to imaging
- apparent diffusion coefficient
- ADC-Map
- anisotropy
- diffusion tensor (imaging)

Jan-Philip Gehrcke

Combining Diffusion NMR with MR Imaging

- **diffusion gradient impairs voxel localisation in imaging sequence!**



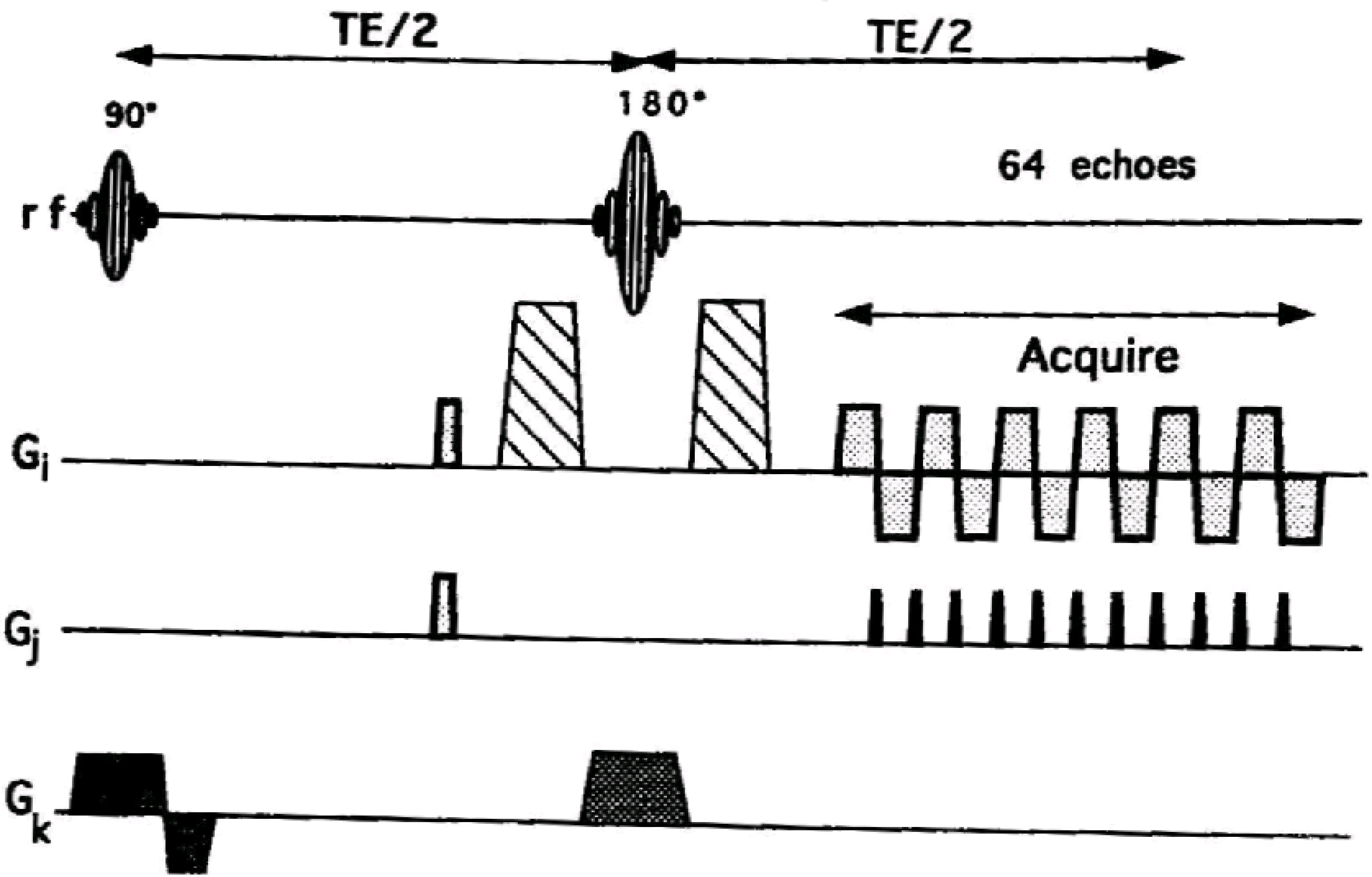
→ diffusion gradient must be turned off during imaging pulses

→ b factor must be recalculated incorporating all gradient fields (diffusion AND imaging gradients)

Motion Artifacts

- presence of motion causes unpredictable changes in signal phase between repeated applications of the same diffusion-weighting experiment
- single-shot imaging experiments have an advantage as they have no reliance on phase-consistency between excitations
- actually the best way to avoid motion artifacts is using EPI
- molecular displacements in micron range from images with millimeter resolution in organs that may move a few millimeter can be determined
- (this is due to different time scales of displacements)

Diffusion Imaging with EPI



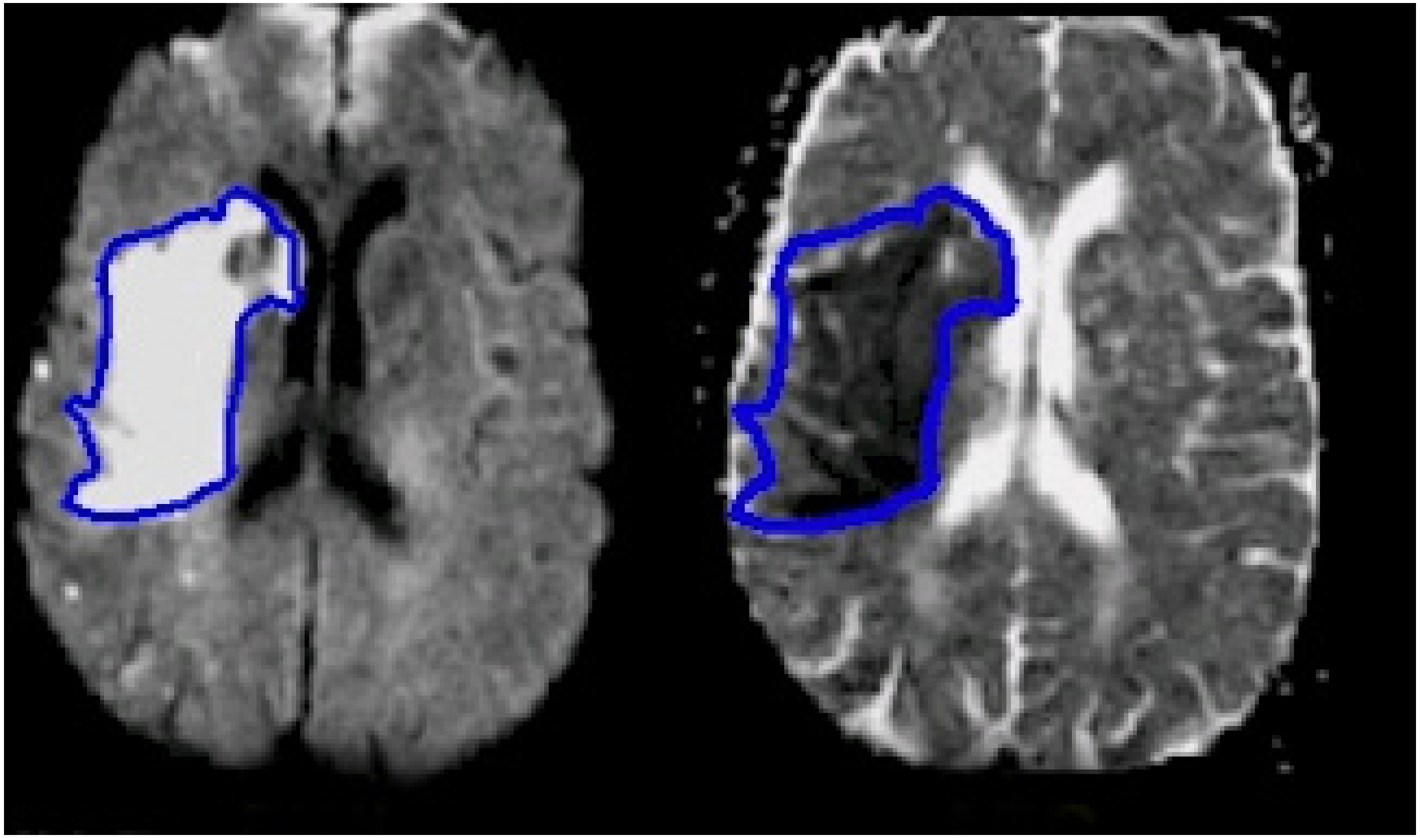
Apparent Diffusion Coefficient (ADC)

- NMR diffusion spectroscopy / imaging on heterogeneous media: an apparent diffusion constant is measured
- depending on microstructure of the voxel, pulse parameters (e.g. length), gradient direction
- gray matter: scalar ADC independent of direction: appears to be isotropic
- white matter / muscle tissue: anisotropic

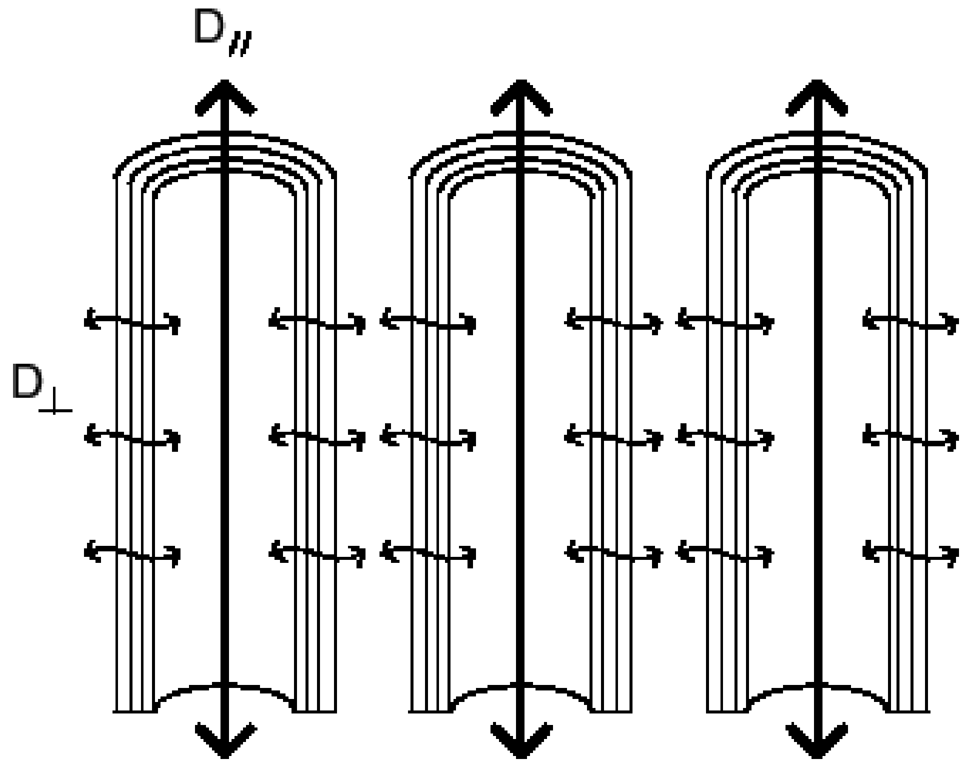
→ ADC depends on angle between fiber-tract axis and applied field gradient

- ADC largest when gradient parallel to fiber-tract direction
- ADC smallest when gradient perpendicular to fiber-tract direction

Diffusion Weighted Image (and ADC Map) shortly after stroke



Restricted Diffusion



- three dimensional process of diffusion may not be the same in all directions (anisotropy)
- limited diffusion due to opstacles (e.g. (im-)permable barriers like sheaths of axons in brain) is called restricted diffusion

Introduction of the Diffusion Tensor (DT)

- in anisotropic diffusion, the effective diffusion coefficient is replaced by an effective diffusion tensor

$$\vec{J} = -\underline{D}\,\nabla\,\vec{C}$$

- the echo attenuation at a given gradient field $\vec{G}$ then becomes

$$\frac{M(\vec{G})}{M_0} = \exp\left(-\sum_{i=1}^{3}\sum_{j=1}^{3} b_{ij}(\vec{G})\,D_{ij}\right)$$

- the b factor also turns into a matrix

The Diffusion Tensor (DT)

- $\underline{D}$ must be symmetric due to reversibility of thermodynamics
- graphically represented by a diffusion ellipsoid
- gives the microscopic mean displacements of e.g. water and leads to the orientation of fibrous tissues (fiber tracking)
- eigenvalues of three orhogonal eigenvectors (ON eigensystem) can be combined to scalar quantities. They are rotation-invariant (the orientation of the sample within the magnet does not matter) and characterize the local (voxel) microstructure within anisotropic tissues

Measurement of $\underline{D}$ in Principle

- because of symmetry only six coefficients have to be measured to determine the complete tensor
- therefore we need the measured echos of at least six noncollinear diffusion gradients and M_0
- with $A(\vec{G}) = -\log(\frac{M(\vec{G})}{M_0})$ we get a set of six linear equations for six unknown variables:

$$\begin{pmatrix} A^{(1)} \\ A^{(2)} \\ A^{(3)} \\ A^{(4)} \\ A^{(5)} \\ A^{(6)} \end{pmatrix} = \begin{pmatrix} b_{xx}^{(1)} & b_{yy}^{(1)} & b_{zz}^{(1)} & 2b_{xy}^{(1)} & 2b_{xz}^{(1)} & 2b_{yz}^{(1)} \\ b_{xx}^{(2)} & b_{yy}^{(2)} & b_{zz}^{(2)} & 2b_{xy}^{(2)} & 2b_{xz}^{(2)} & 2b_{yz}^{(2)} \\ b_{xx}^{(3)} & b_{yy}^{(3)} & b_{zz}^{(3)} & 2b_{xy}^{(3)} & 2b_{xz}^{(3)} & 2b_{yz}^{(3)} \\ b_{xx}^{(4)} & b_{yy}^{(4)} & b_{zz}^{(4)} & 2b_{xy}^{(4)} & 2b_{xz}^{(4)} & 2b_{yz}^{(4)} \\ b_{xx}^{(5)} & b_{yy}^{(5)} & b_{zz}^{(5)} & 2b_{xy}^{(5)} & 2b_{xz}^{(5)} & 2b_{yz}^{(5)} \\ b_{xx}^{(6)} & b_{yy}^{(6)} & b_{zz}^{(6)} & 2b_{xy}^{(6)} & 2b_{xz}^{(6)} & 2b_{yz}^{(6)} \end{pmatrix} \cdot \begin{pmatrix} D_{xx} \\ D_{yy} \\ D_{zz} \\ D_{xy} \\ D_{xz} \\ D_{yz} \end{pmatrix}$$

Measurement of $\underline{D}$ in Reality

- when the signal to noise ratio is small, the determination of the tensor by only seven experiments yields poor estimates (bad accuracy)
- to get better results more measurements are performed with different gradients and then $\underline{D}$ is estimated statistically

Determining $\underline{D}$ in a voxel

- a series (at least six) of diffusion gradients leads to several different DC's
- for every gradient the b-matrix is calculated
- $\underline{D}$ is estimated statistically from this dataset

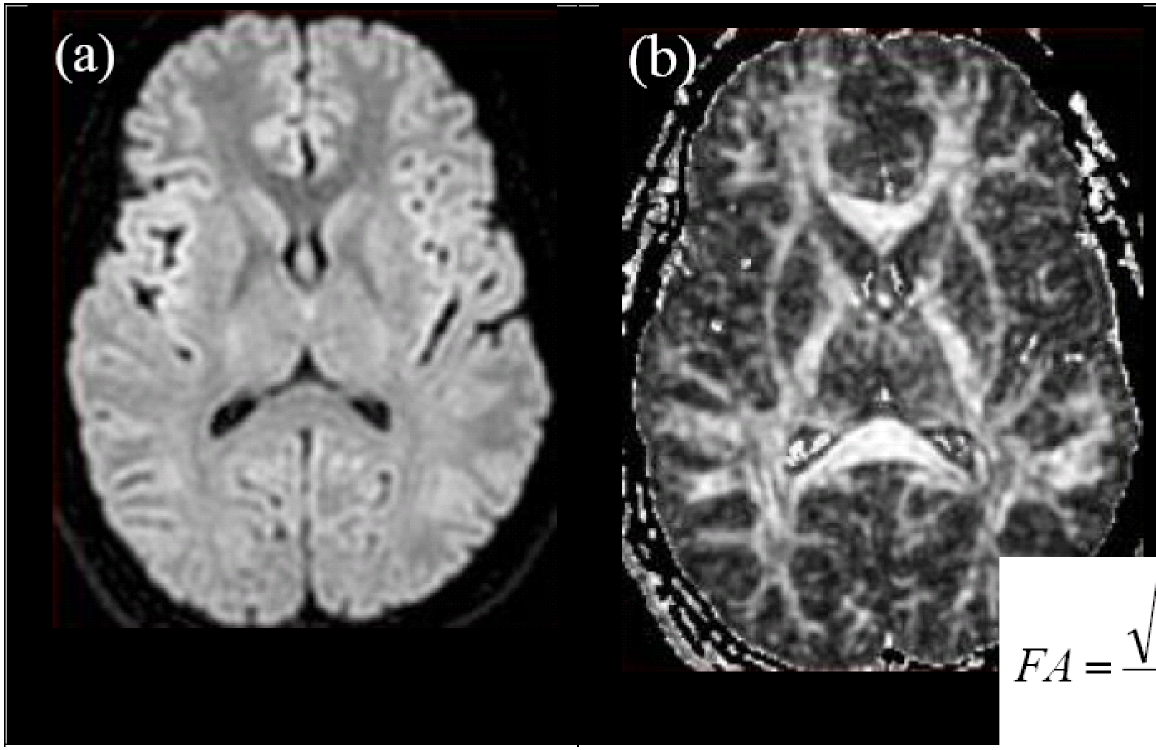
Extending to Diffusion Tensor Imaging (DTI)

- to perform DTI, the diffusion sequence is imbeded into an imaging sequence (like in DWI)
- the mass of data is acquisited as described before
- simple grayscale images are not suitable for the representation of complete tensor data

→

- tensor can be represented as an ellipsoid where the main axes lengths correspond to the eigenvalues and their direction to the respective eigenvectors
- trace and fractional anisotropy can be used to display data
- colorencoding the largest eigenverctor/value

Trace and Fractional Anisotropy



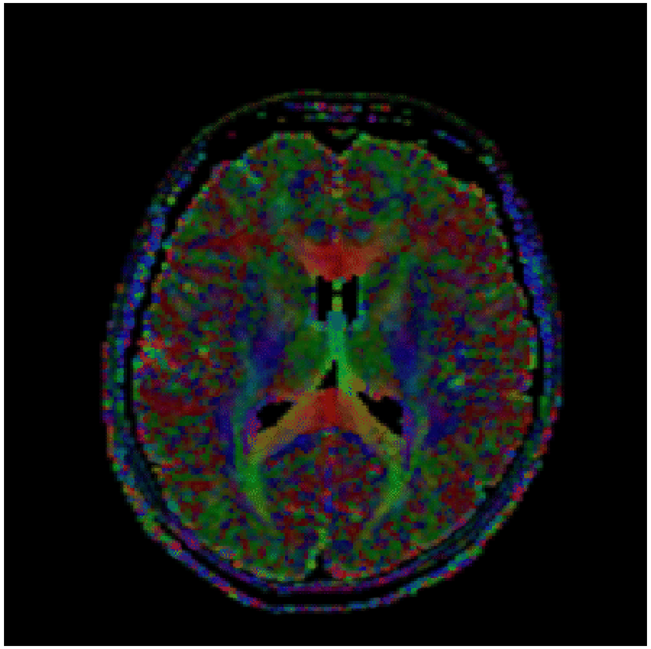
$$FA = \frac{\sqrt{3\left[\left(\lambda_1 - \langle \lambda \rangle\right)^2 + \left(\lambda_2 - \langle \lambda \rangle\right)^2 + \left(\lambda_3 - \langle \lambda \rangle\right)^2\right]}}{\sqrt{2\left(\lambda_1^2 + \lambda_2^2 + \lambda_3^2\right)}}$$

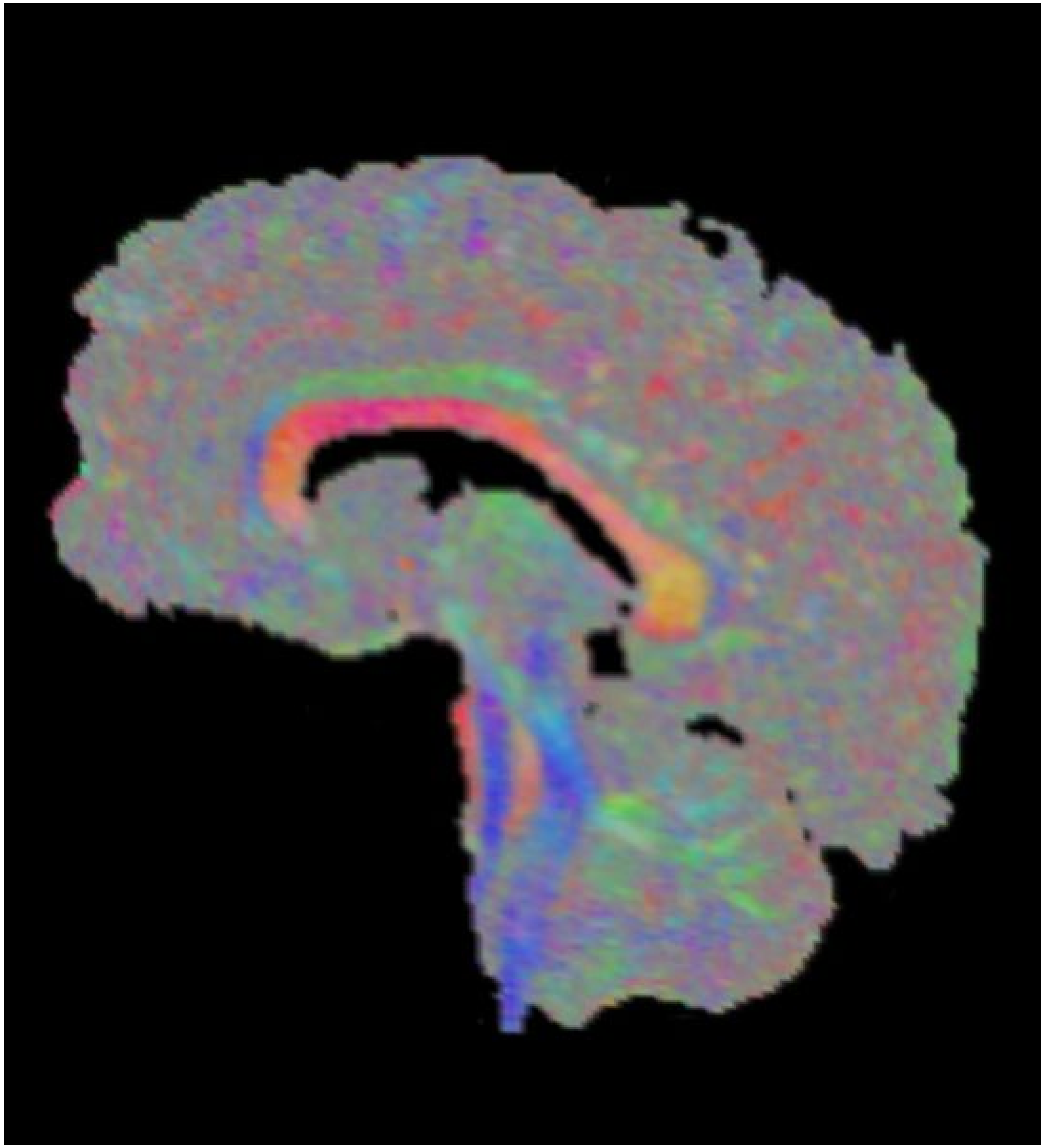
Figure 6. Scalar images obtained from the diffusion tensor (a) trace and (b) fractional anisotropy

- fractional anisotropy is a scalar measure of the degree of anisotropy in a given voxel
- trace is a scalar measure of the total diffusion within a voxel
- used clinically to localize white matter lesions

Cut View Imaging

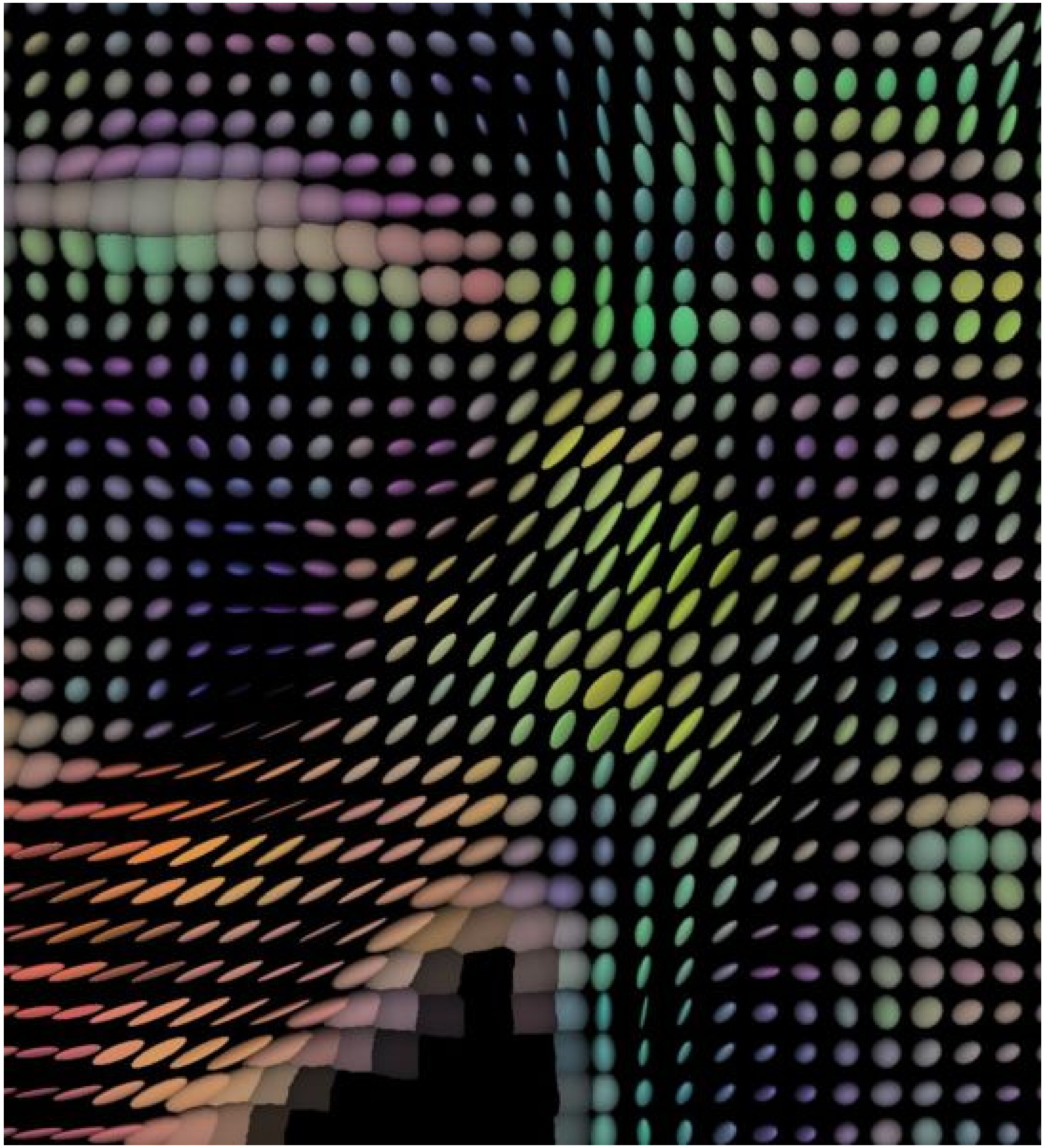
- color-encoded direction of largest diffusion coeffiecient
- popular in radiology





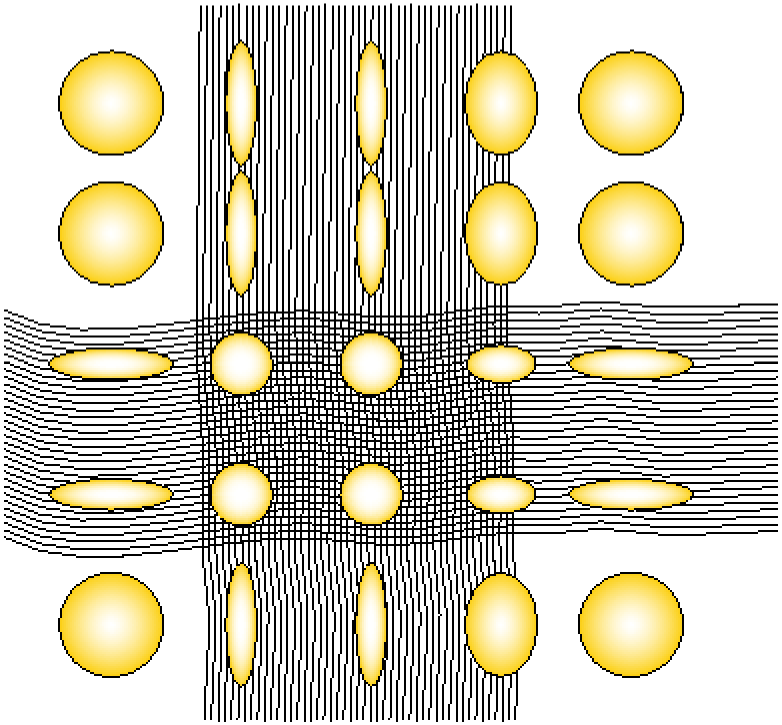
Ellipsoid Imaging

- main axes lengths correspond to the eigenvalues and their direction to the respective eigenvectors



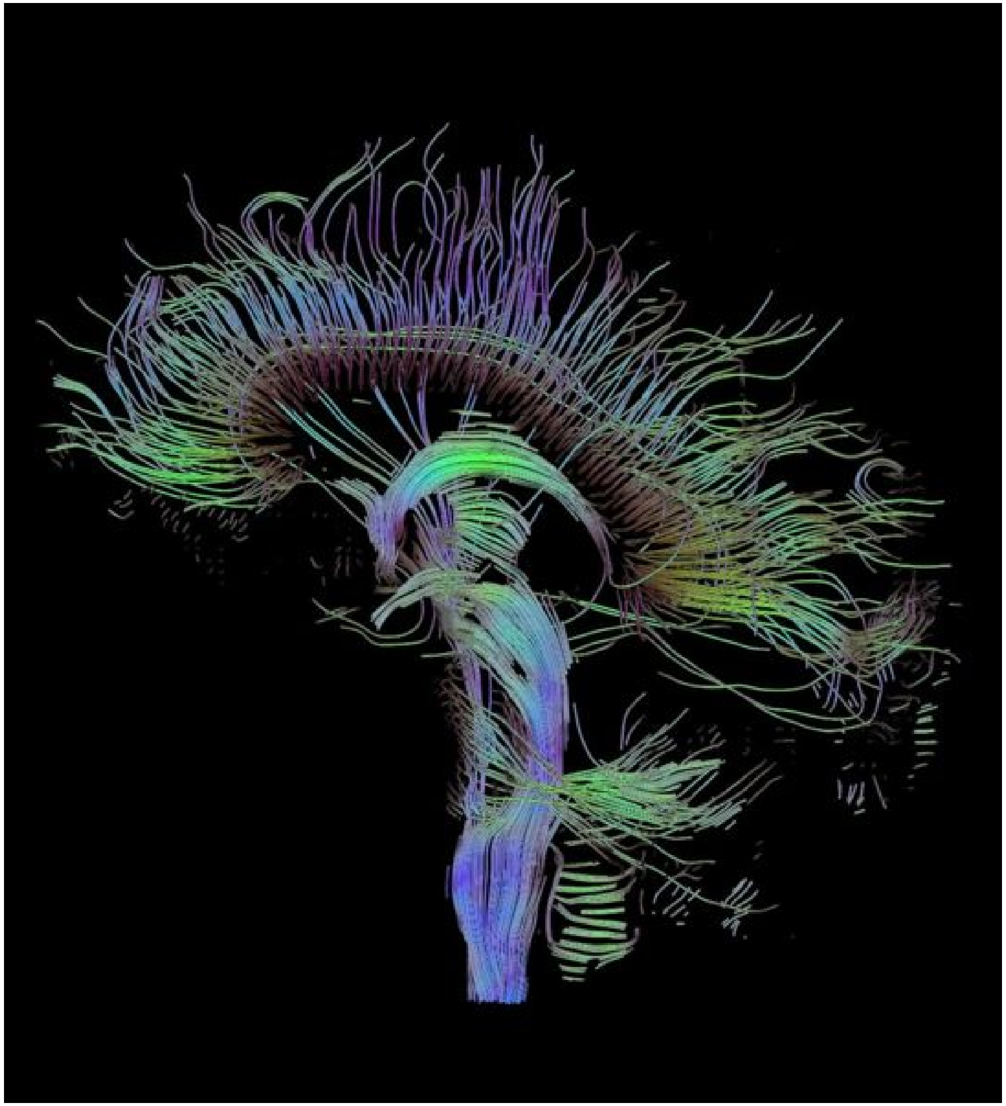
Fiber Tracking

- geometric nature of the measured diffusion tensor within a voxel is a meaningful measure of fiber tract organisation
- distinct bands of white matter fibers with parallel orientation may be distinguished from others running in different directions



→ • fiber tracking algorithms can be used to track fibers

Tractography



- diffusion tensor magnetic resonance has opened the way to explore noninvasively the structural anatomy of the white matter in vivo

Literature

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- David G. Norris: Diffusion Imaging of the Brain: Technical Considerations and Practical Applications, Diffusion Fundamentals Journal, 2005