Lecture 12:
Magnetic Resonance Imaging II

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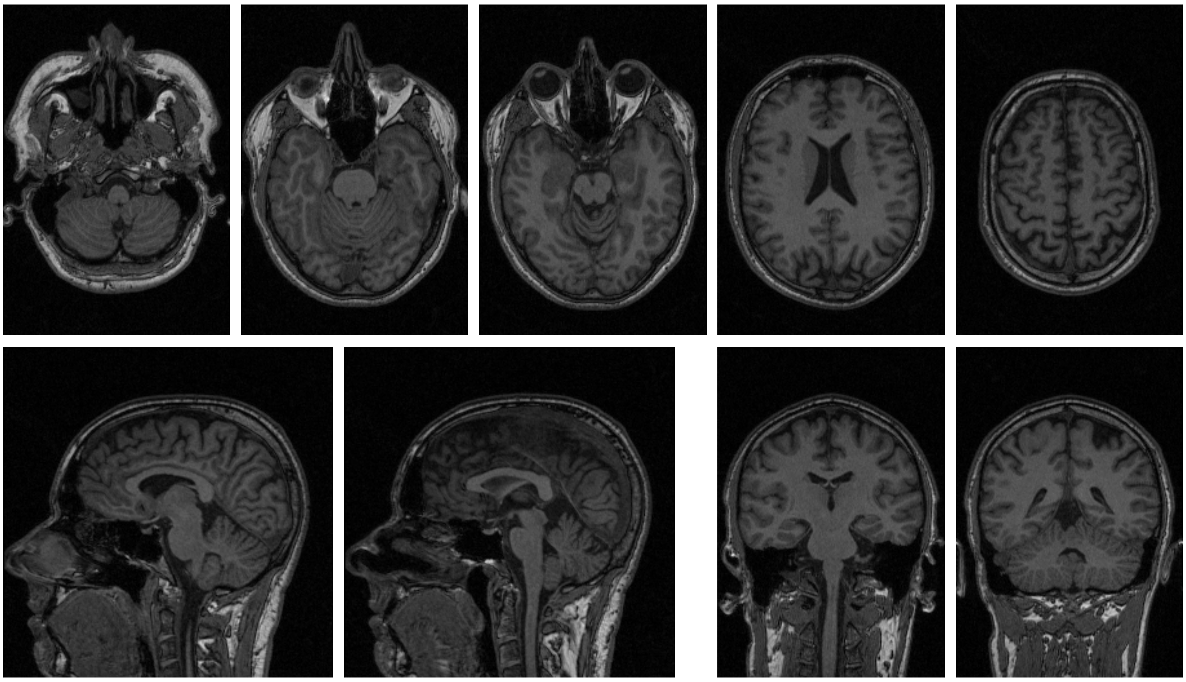
Another Brain MRI Example



Planar sections from a $176 \times 256 \times 256$ MRI data set of a human head. Resolution is $1\,\mathrm{mm} \times 1\,\mathrm{mm} \times 1\,\mathrm{mm}$. **Top, left to right:** Horizontal slices 77, 108, 117, 154, 179 (counted from bottom). **Bottom, left two images:** Vertical anterior-posterior slices 82, 87. **Bottom, right two images:** Vertical side-to-side slices 143 and 163. *Images measured by the group of Oliver Gruber, Saarland University Hospital, Homburg, 2005.*

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MR Resolution

- Medical MR images have resolutions down to ca. $1\,\mathrm{mm}$
- In laboratory images, resolutions of $1\,\mu\mathrm{m}$ are possible
- MRI is superior to X-ray CT in contrast resolution, though inferior in spatial resolution
- Magnetic field intensity is one parameter in determining the possible resolution: The stronger the field, the better the localisation of measured densities.

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Image Distortions

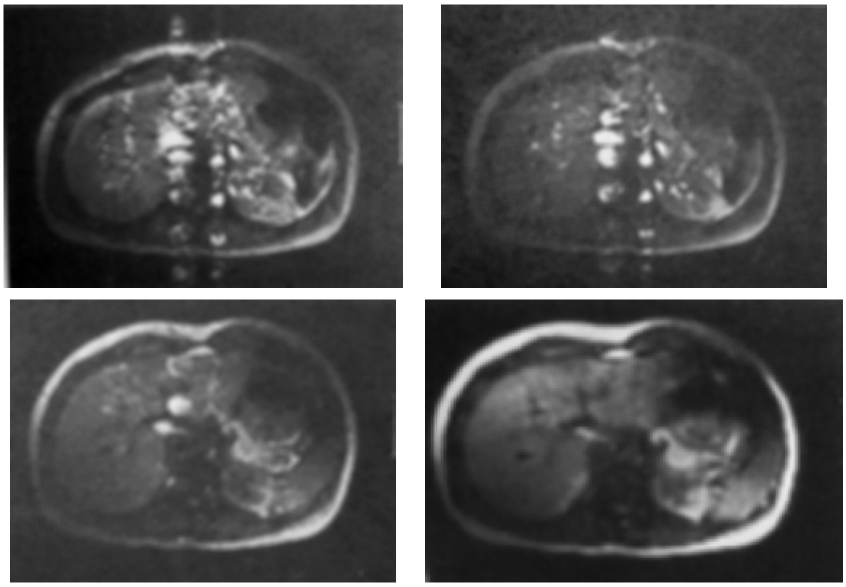
Motion Artifacts

We focus here on medical MRI.

- *Movement of patient's body during image acquisition.*
  This can be ruled out mostly.
- *Movement of organs by breathing and heartbeat.*
  - introduces artifacts
  - can be reduced by averaging multiple measurements
  - synchronising image acquisition with heartbeat could also be an option.
- *Blood flow.*
  - Flowing blood is mislocated in reconstruction in phase-encoding direction
  - Measurement sequences can be designed such that echoes from dislocated blood are reduced

Image Distortions (2)

Motion Artifact Examples



Motion artifacts in transaxial abdominal images. **Top left:** Single image acquisition (duration 21 s, with breathing). **Top right:** Same with breath-holding – **Bottom left:** Breath-holding and a special flow-suppression sequence. **Bottom right:** Breath-holding and a flow-suppression sequence with reduced repetition time and reduced spatial and phase resolution, measured four times and averaged. *(Webb 1988)*

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Image Distortions (3)

Imprecision Sources in the Measurement Method

- **Chemical Shift.**
  - The slightly different gyromagnetic constants (thus, Larmor frequencies) of atoms in different chemical surroundings lead to localisation errors.
  - Particularly, fat in reconstructed images is displaced systematically relatively to water
  - These artifacts are less problematic for brain imaging than for some other parts of the body.
- **Wrap-Around Artifacts.**
  - Occur if the same field intensity as in some measured region is also encountered at another location (note that the RF does not provide spatial resolution).

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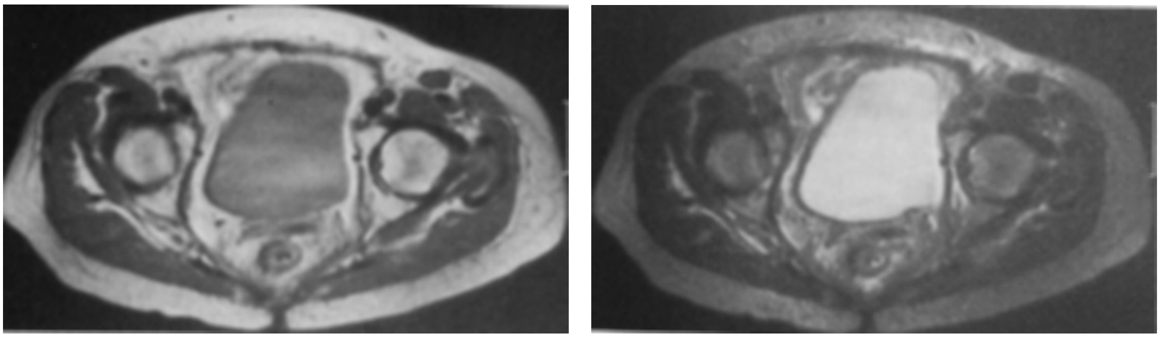
Chemical Shift Example



Chemical shift artifacts: Two transaxial images through the bladder of a cancer patient, acquired with different spin-echo sequences. Note the gaps and overlaps on opposite contours of the bladder. *(Webb 1988)*

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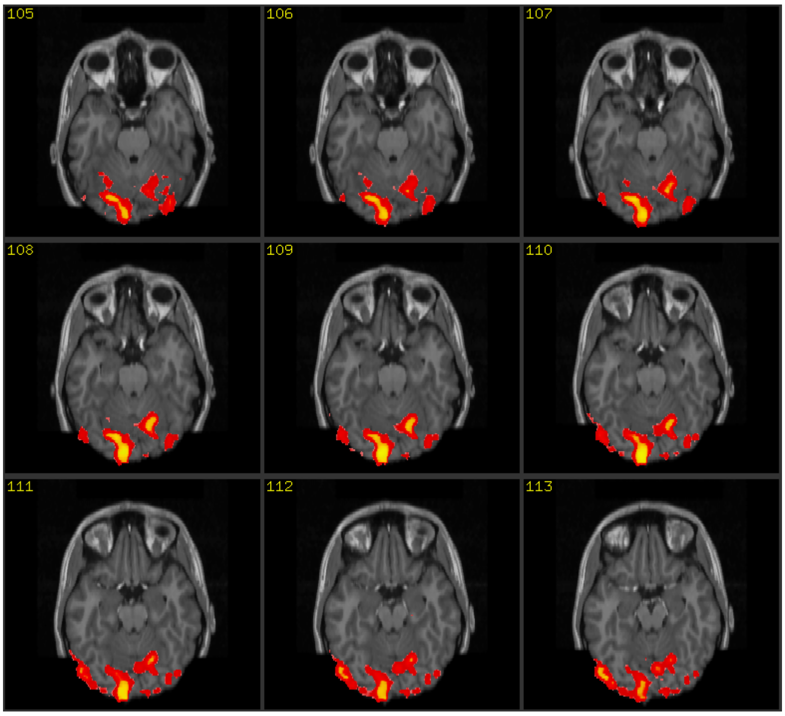
Functional MR Imaging (fMRI)

- Allows to measure changes in neural activity
- The brain is scanned repeatedly (in intervals of a few seconds) at low resolution
- **Blood oxygen level-dependent (BOLD) effect**:
  - Increased neural activity leads to higher oxygen consumption
  - Vascular system increases supply of oxygen, overcompensating for the higher demand
  - Oxygenated haemoglobin is therefore enriched in comparison to deoxygenated haemoglobin
  - Deoxygenated haemoglobin reduces MR signal
  - As a consequence, higher neural activity leads to higher MR signal, with a certain delay. Details are still under investigation

Functional MRI (2)

Example



Functional MRI example. fMRI information is displayed in pseudocolours overlayed over a higher-resolution anatomical MRI scan (grey-values). *(S. Smith 1998, http://www.fmrib.ox.ac.uk/fmri_intro)*

Diffusion MR Imaging (1)

Diffusion MR Imaging

- measures diffusion of water molecules within tissues
- In an isotropic medium (e.g. free water) water molecules move according to Brownian motion, without directional preferences
- In tissues, diffusion can be anisotropic because of e.g. membranes obstacling the free movement of water molecules

There are two main applications in sight:

- Bundles of neuron fibres can be detected since water preferably moves along the fibres but not across them.
  - studies of brain connectivity
  - stroke diagnosis; multiple sclerosis diagnosis
  - diagnosis of neurological diseases (schizophrenia)
- Muscle fibres can be investigated, in particular the heart muscle (myocard).
  - However, heart diffusion MRI still takes too long to be possible in human body

Diffusion MR Imaging (2)

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Diffusion Weighted Imaging (DWI)

- Spin-echo sequences can be sensitised for displacements of spins during measurement, e.g. by applying two phase-shifting step with a phase-inverting RF pulse between them. Stationary spins therefore experience no net phase shift.
- It is possible to measure diffusion in one direction.
- By repetition, diffusion in different directions can be measured.
- This technique is called **diffusion-weighted imaging (DWI)**

Diffusion MR Imaging (3)

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Diffusion Tensor Imaging (DTI, DT-MRI)

The minimal set of measurements for diffusion MRI data that can detect anisotropies in all possible directions consists of seven measurements, leading to a field of positive definite 3×3 symmetric matrices (i.e. elements of a six-dimensional data range).

- Each symmetric matrix represents a **diffusion tensor**. The method is therefore called **diffusion tensor imaging (DTI)** or **diffusion tensor MRI (DT-MRI)**
- Provided diffusion properties are homogeneous within the measured voxel, the diffusion tensor D indicates that

$$G(x; D, t) = \frac{1}{\sqrt{(4\pi t)^3 \det(D)}} \exp\left(-\frac{x^{\mathrm{T}} D^{-1} x}{4t}\right)$$

  is the probability density for a water molecule to move from $x = 0$ at $t = 0$ to point x in time t.

Diffusion MR Imaging (4)

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- Measurements for diffusion MRI:
  - one proton density measurement b_0 for reference
  - diffusion-weighted measurements $b_1, \ldots, b_6$ in six directions (given by unit vectors $\mathbf{e}_i$, $i = 1, \ldots, 6$)
- Diffusion intensity w_i in direction $i = 1, \ldots, 6$ can be computed from

$$\frac{b_i}{b_0} = \int\limits_{\mathbf{R}^3} G(x; D, t)(\mathbf{e}_i^{\mathrm{T}} x)\,\mathrm{d}x = \mathrm{e}^{t \cdot \underbrace{\mathbf{e}_i^{\mathrm{T}} D \mathbf{e}_i}_{w_i}}$$

- From diffusion intensities $w_1, \ldots, w_6$, the elements of the diffusion tensor are obtained by solving a linear system of equations.

Diffusion MR Imaging (5)

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- Typical choice of directions (unit vectors, symmetrically arranged on the sphere):

$$\mathbf{e}_1 = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\\0\end{pmatrix}, \qquad \mathbf{e}_2 = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\\1\end{pmatrix}, \qquad \mathbf{e}_3 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\1\end{pmatrix},$$

$$\mathbf{e}_4 = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\\0\end{pmatrix}, \qquad \mathbf{e}_5 = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\0\\-1\end{pmatrix}, \qquad \mathbf{e}_6 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\-1\end{pmatrix}$$

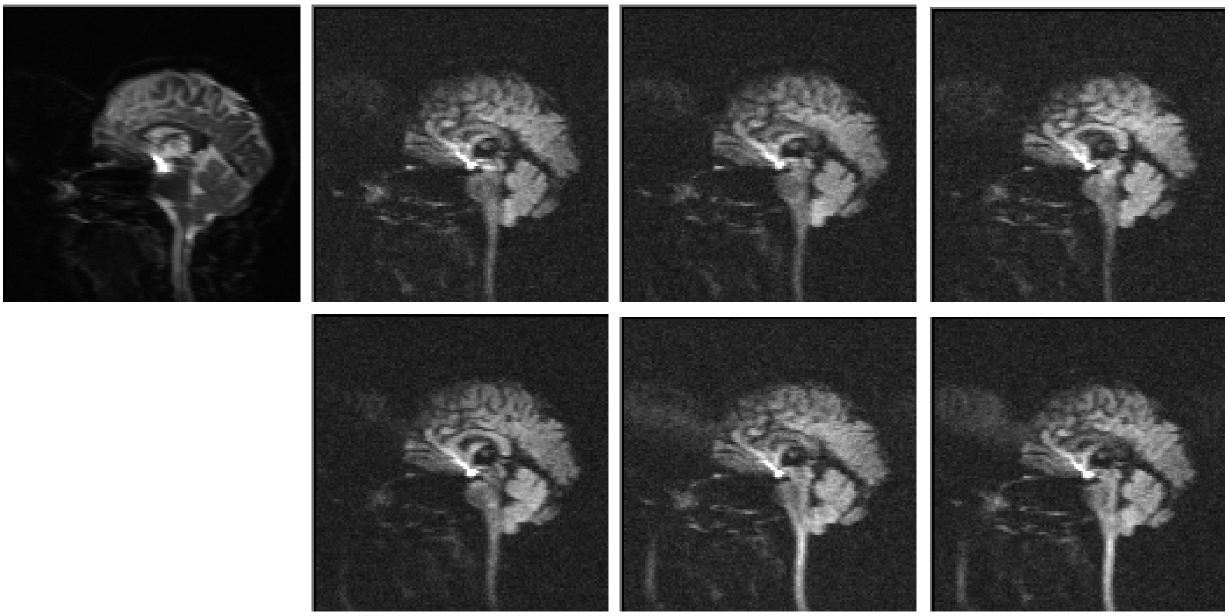
- The components of the diffusion tensor are then

$$d_{11} = \frac{1}{2}(w_1 + w_2 - w_3 + w_4 + w_5 - w_6), \qquad d_{12} = d_{21} = \frac{1}{2}(w_1 - w_4),$$

$$d_{22} = \frac{1}{2}(w_1 - w_2 + w_3 + w_4 - w_5 + w_6), \qquad d_{13} = d_{31} = \frac{1}{2}(w_2 - w_5),$$

$$d_{33} = \frac{1}{2}(-w_1 + w_2 + w_3 - w_4 + w_5 + w_6), \qquad d_{23} = d_{32} = \frac{1}{2}(w_3 - w_6)$$

Example Measurement Data



b_0 (top left) and six directional diffusion weighted images $b_1, \ldots, b_6$ for DT-MRI. Diffusion directions correspond to those given on the previous slide, though not necessary in the same order. *(Data measured by group of Oliver Gruber, Saarland University Hospital, Homburg)*

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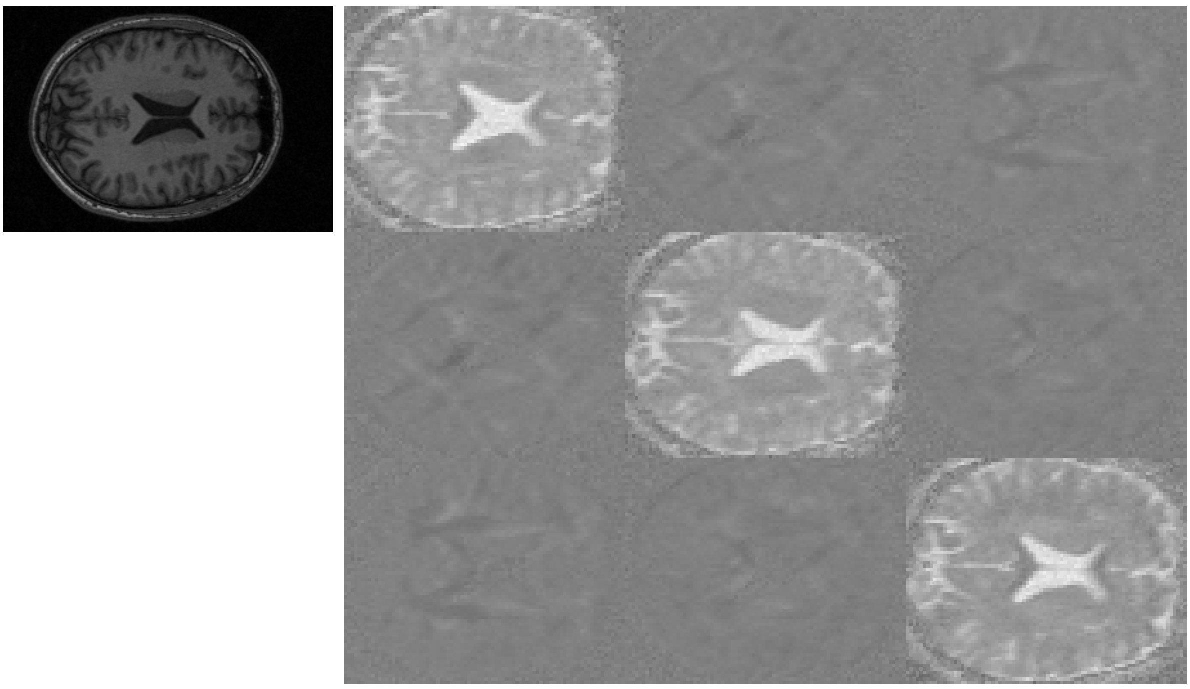
Example Diffusion Tensor Image



Main image: One transaxial slice from a DTI data set of a human head, represented componentwise, with middle grey depicting zero. Spatial resolution of this data set: $2\,\mathrm{mm} \times 2\,\mathrm{mm} \times 2\,\mathrm{mm}$. **Top left:** Slice 154 from the data set shown on Slide 2, which corresponds to approximately the same section. *(Data measured by group of Oliver Gruber, Saarland University Hospital, Homburg)*

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Diffusion MR Imaging (8)

Visualisation by Ellipsoids

- Any positive definite symmetric 3×3 matrix D can be represented by the ellipsoid

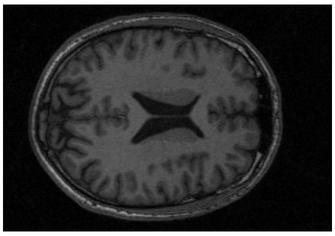
$$x^{\mathrm{T}} D^{-2} x = 1$$

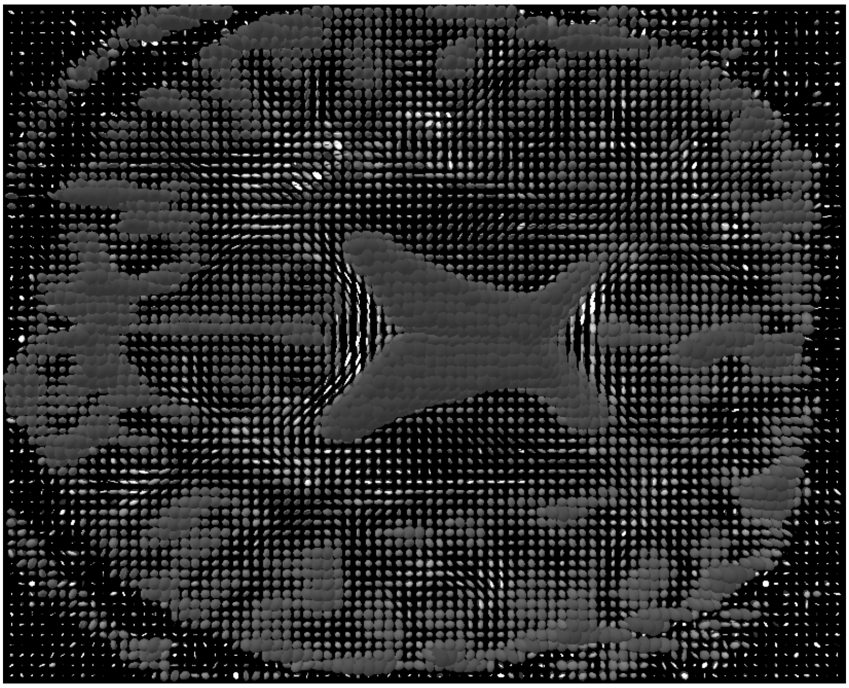
whose principal axes point into the directions of the eigenvectors of D and have the eigenvalues of D as their lengths.

Remark: If one would choose the ellipsoid $x^{\mathrm{T}} D^{-1} x = 1$, one would have directly an isosurface of the aforementioned probability density. However, visualisation of anisotropy would be less pronounced then.

Diffusion MR Imaging (9)

Ellipsoid Visualisation Example





Same transaxial slice from a DTI data set as on Slide 16, represented by ellipsoids. *(Visualisation software written by Stephan Didas, Luis Pizarro, and Stephan Zimmer.)*

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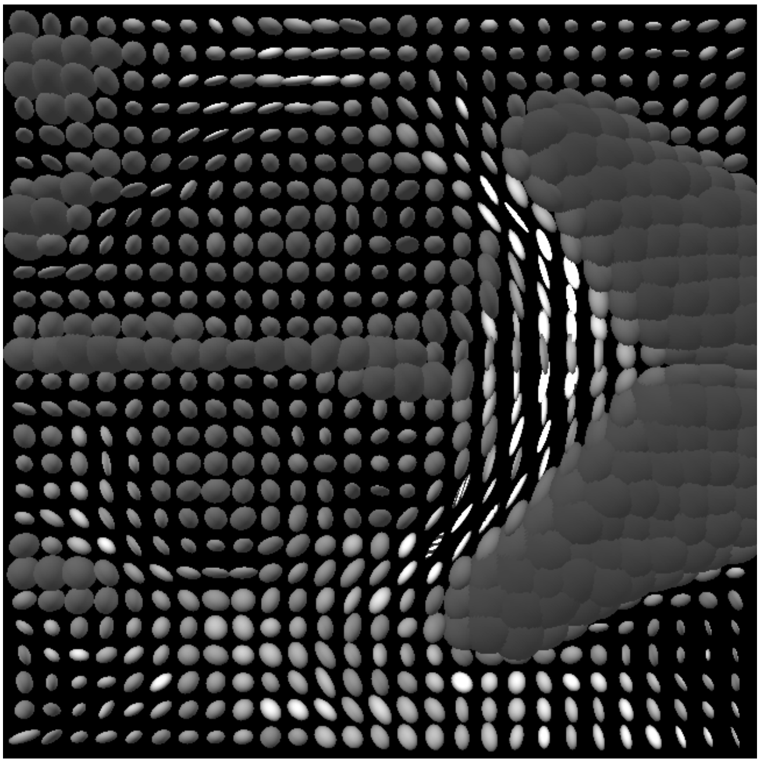
Ellipsoid Visualisation Example



Clipping from the DTI slice from the previous slide (corpus callosum and ventricle region).

MIA 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

Resolution and Diffusion Time Scale

- Voxels are typically $\geq (1\,\mathrm{mm})^3$ in size.
- Axon (neuron fibre) diametres range from below $1\,\mu\mathrm{m}$ to about $25\,\mu\mathrm{m}$.
- The diffusion time in DTI measurements is typically $10\,\mathrm{ms}$, corresponding to displacements of molecules in the order of one micrometre

Remarks on Interpretation of Brain DTI Data

- Homogeneous fibre bundles lead to needle-like elongated ellipsoids.
- Crossing fibre bundles within one voxel lead to pancake-like flattened ellipsoids. Disambiguation of fibre crossings is problematic in DTI data processing.

High Angular Resolution Diffusion Imaging

- Goal: Represent diffusion properties more precisely than just with one symmetric matrix
- Method: Measure diffusion in a larger number of directions (typically 80 directions). This procedure is called **high angular resolution diffusion imaging (HARDI)**.
- In processing HARDI data, one often aims at processing directional data immediately, instead of transforming them into a tensor-like structure.
- However, also representations by e.g. tensors of higher order are under investigation.

Summary

- The MR resolution depends on the magnetic field intensity.
- Image distortions include motion artifacts, chemical shifts, and wrap-around artifacts.
- Functional MRI (fMRI) measures the oxigen consumption in the brain. This is an indication of neural activity.
- Diffusion MRI allows to measure the diffusivity properties of water molecules.
- Diffusion tensor MRI (DT-MRI, DTI) is a sophisticated variant that can detect anisotropies. The diffusion tensors can be visualised by ellipsoids.

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