Magnetic Resonance Imaging

What it is and how it is used as a research tool.

PHD TRIAL LECTURE

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IMMIV

UNIVERSITAS OSLOENSIS MDCCCXI

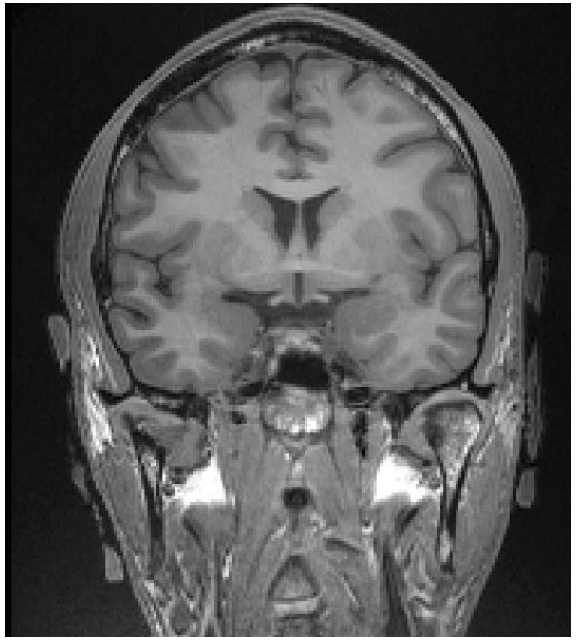
Contents

1. How Magnetic Resonance Imaging (MRI) works
   1. The different parts of an MRI system
   2. Basic principles of MRI
2. Different imaging techniques & how they are used in research
   1. T1-weighted
   2. T_2-weighted
      - FLAIR
   3. T_2*-weighted
      - Diffusion MRI
      - Functional MRI
3. Discussion

The goal of MRI

- Goal: produce signal which reflects the structure or anatomy and biochemical processes of what is imaged
  - E.g., images of the healthy human brain
- Allows in-vivo imaging
  - Comparably good resolution
  - Many contrasts
  - No ionised radiation

T_1-weighted image

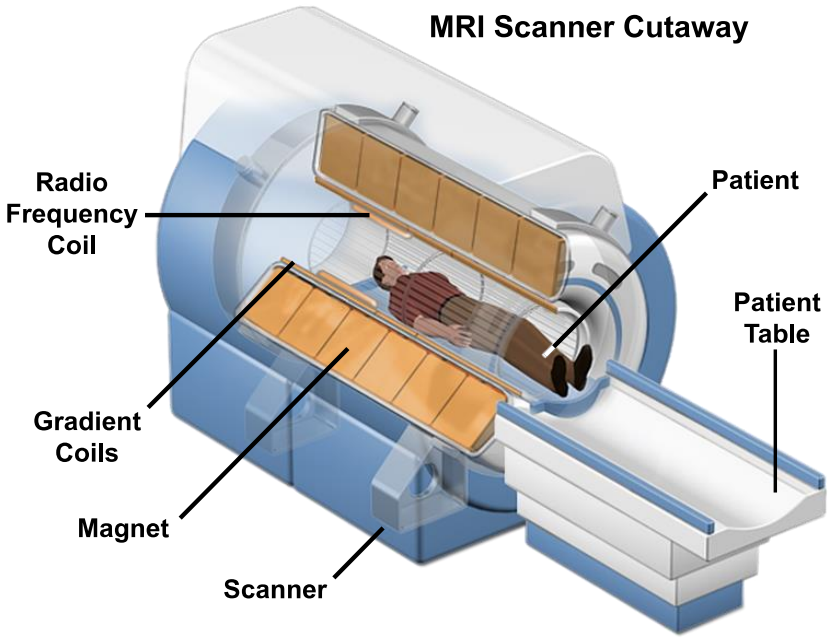


Wang et al. (2022). Front.Hum.Neurosci. 16 (1021503) / my brain

How MRI works

The different parts of an MRI system

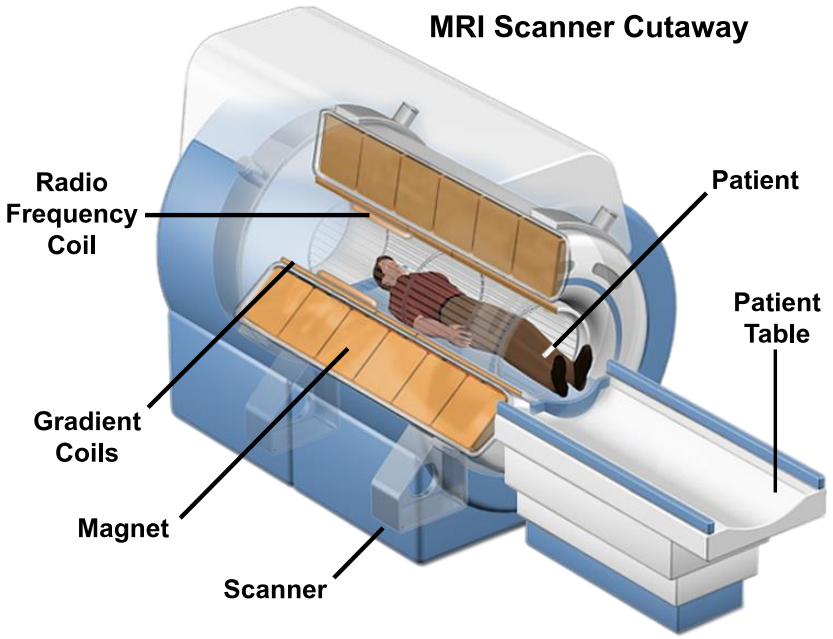
- **Magnet** is at the heart of the system (B_0)
- Today, often at 1.5T-3T
- As a comparison: The earth's magnetic field = 0.05mT



https://nationalmaglab.org/magnet-academy/read-science-stories/science-simplified/mri-a-guided-tour/

The different parts of an MRI system

- **Magnet** is at the heart of the system (B_0)
- Today, often at 1.5T-3T
- As a comparison: the earth's magnetic field = 0.05mT
- Different types of magnets used in MRI
  - **superconducting magnets** – typically with fields of 1.5 or 3 T
  - permanent magnets – capable of sustaining fields up to about 0.3 T
  - electromagnets – capable of fields up to about 0.6 T



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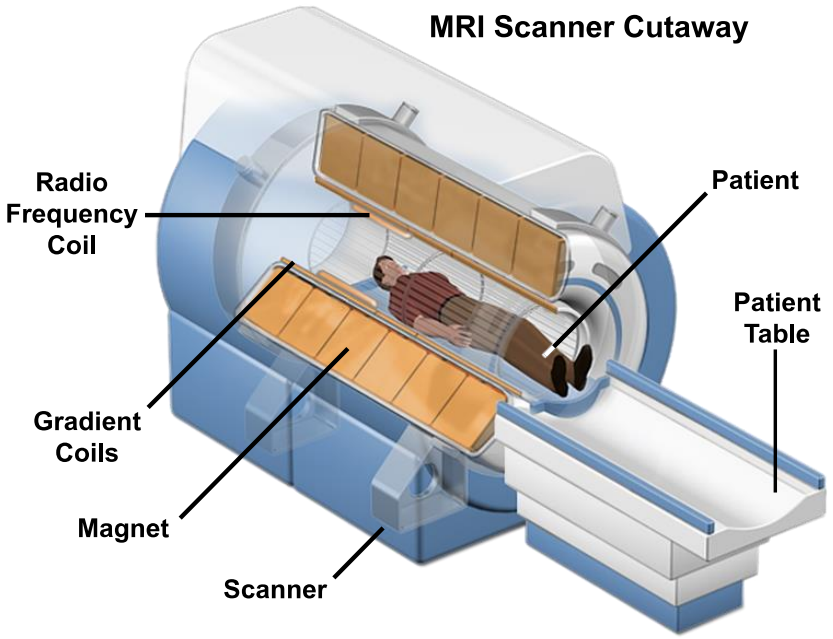
The different parts of an MRI system

- **Radiofrequency Coils**
  - **Signal from tissue** is generated in **response to radiofrequency (RF) pulses** (B_1)
  - Transmitter coils generates the radiofrequency pulse
  - Receiver coils record the signal



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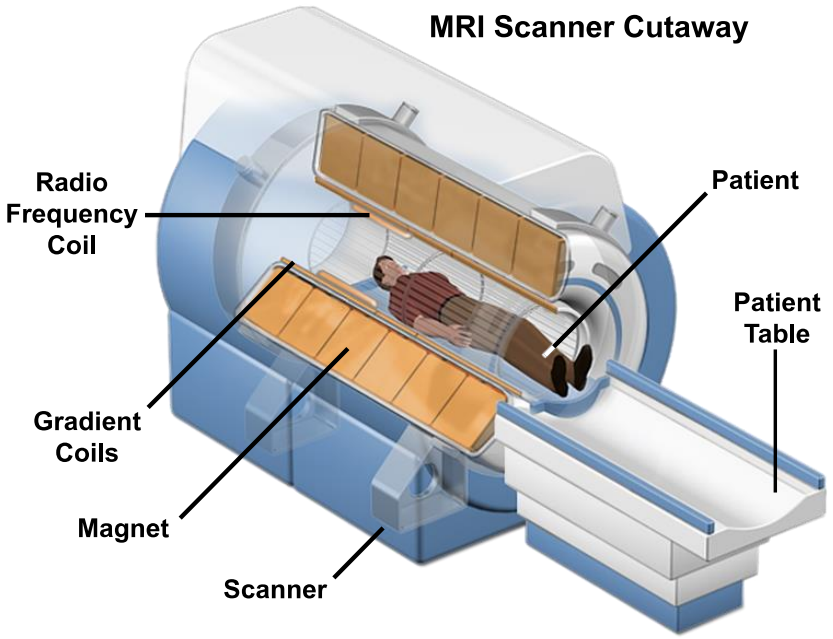
- **Faraday's cage** / Shielding
  - MRI signal is weak and sensitive to electrical interference
  - Hence, scanner room needs electromagnetic shielding

Example of a Faraday's cage: Static electricity (such as lightning) only effects the outside of a cage made of conductive material

https://lifeonthebluehighways.com/2013/04/20/faradays-cage/

The different parts of an MRI system

- **Gradient Coils**
  - Generate short-term variations in magnetic field across the body, called imaging gradients
  - Serve to **localise the signal** in space (3 planes)



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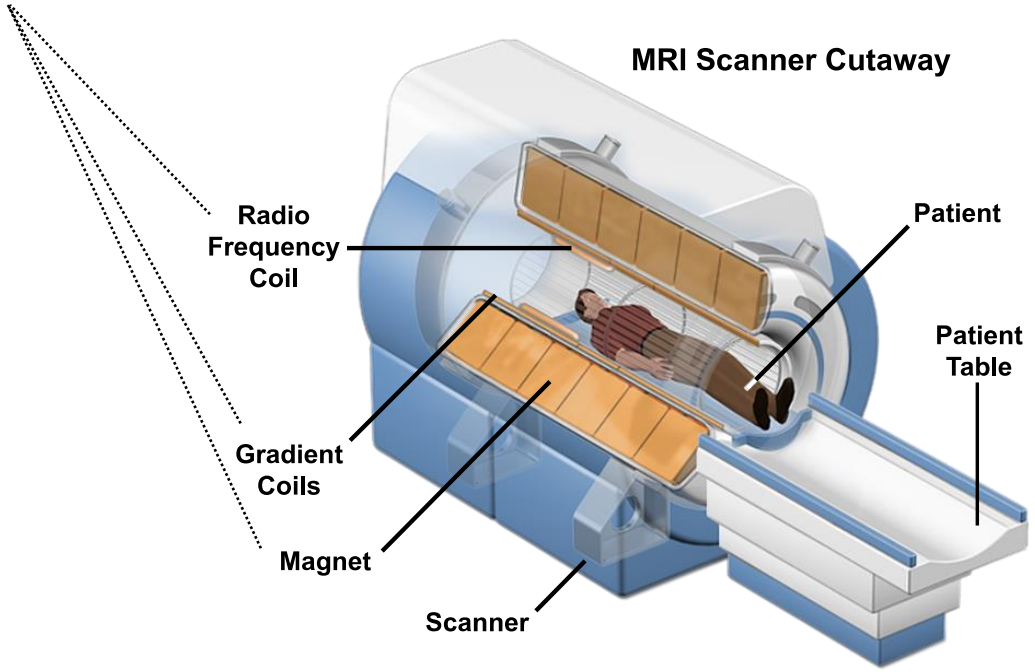
The different parts of an MRI system

- We utilize several magnetic fields in the scanner to leverage the magnetic properties of different atomic nuclei



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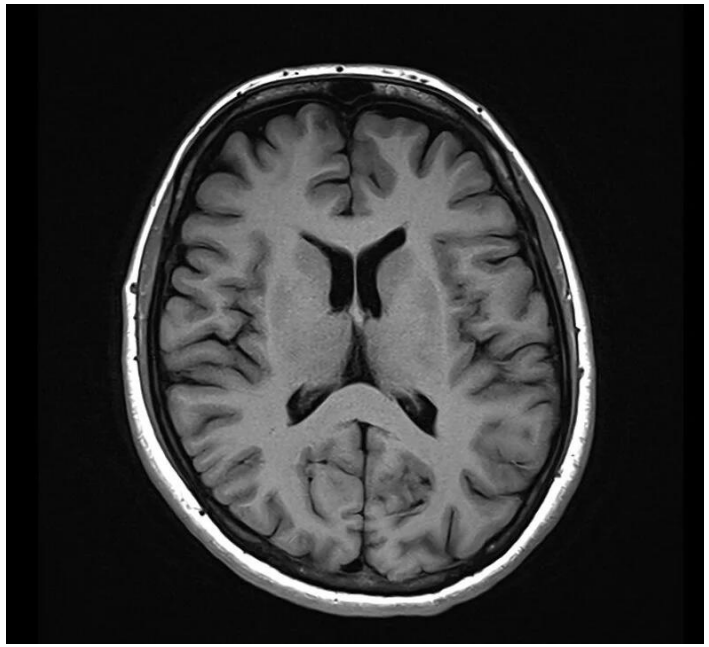
The different parts of an MRI system

- We utilize several magnetic fields in the scanner to leverage the magnetic properties of hydrogen nuclei
- **Pulse sequences** allow to produce different contrasts
- Pulse sequences are several radiofrequency (RF) pulses in a row

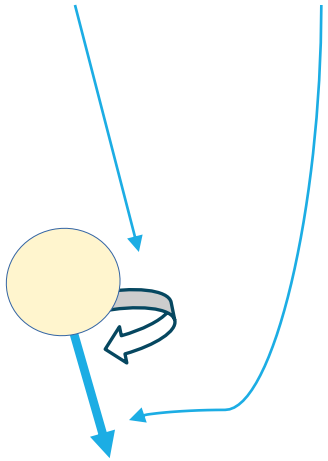
T_1-weighted image



McRobbie et al. (2017). MRI from Proton to Picture.

Basic principles: MRI physics

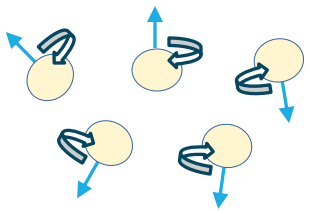
- Main principle
  - Protons possess spin and orientation



Basic principles: MRI physics

- Main principle
  - Protons possess spin and orientation
  - These are at random outside the scanner (a)

a) No magnetic momentum, out-of-phase spin



Basic principles: MRI physics

- Main principle
  - Protons possess spin and orientation
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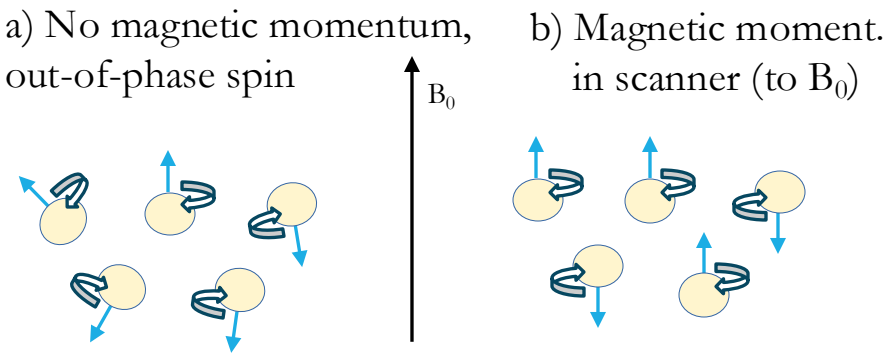
  - Protons obtain magnetic momentum in magnetic field (b)



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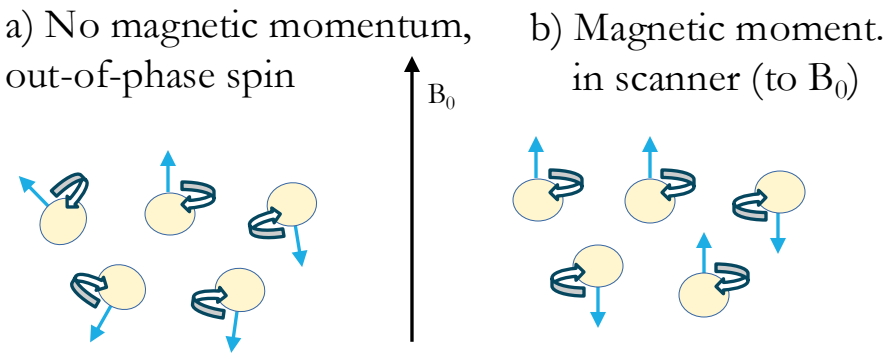

$$\omega = \gamma B_0$$

Larmor frequency in MHz

Gyromagnetic ratio, in $MHzT^{-1}$

Strength of the static magnetic field in T

Basic principles: MRI physics

- Main principle
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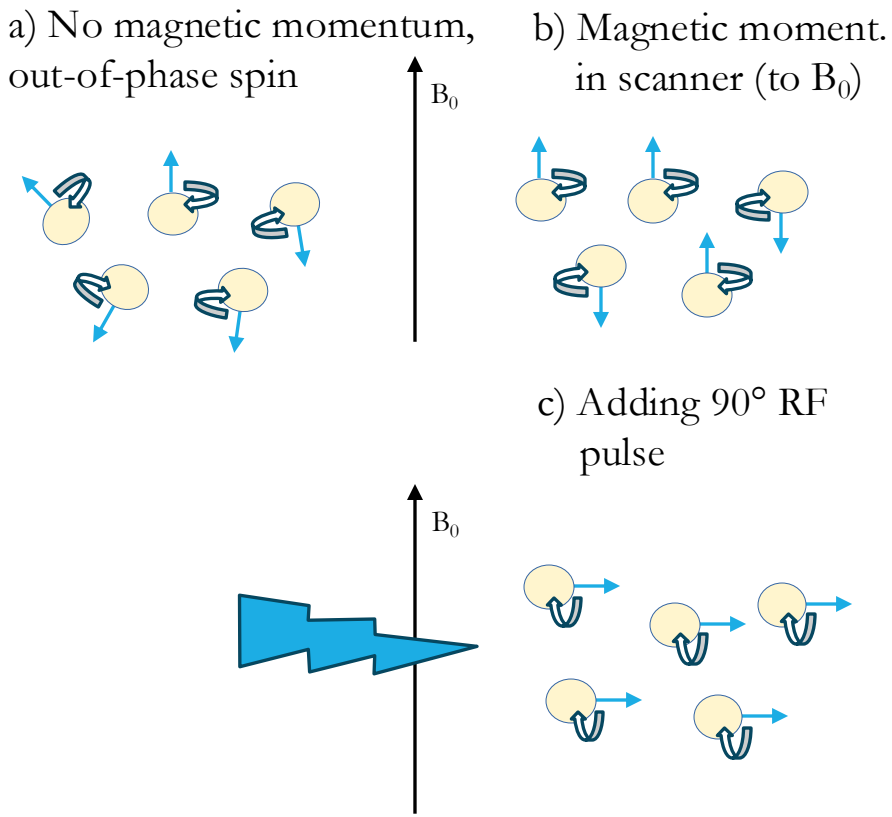
  - Protons obtain magnetic momentum in magnetic field (b)
  - Radio frequency (RF, resonating with protons of interest) allows to flip magnetisation vector and in-phase spin (c)



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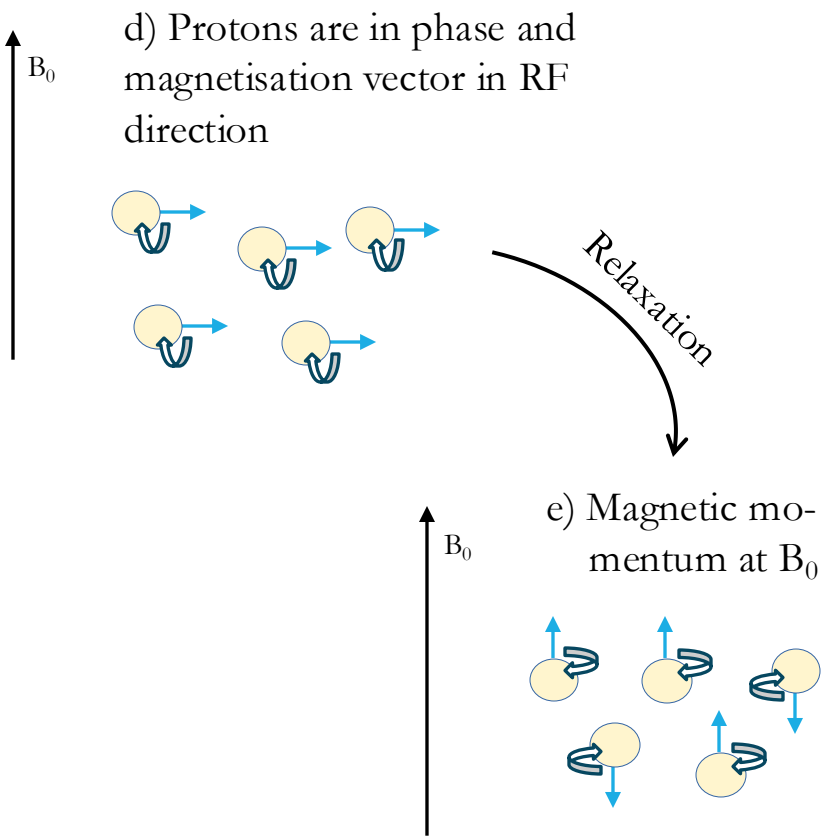
  - Protons presessing out of phase and their magnetisation vector moving back to their equilibrium at B_0 forms signal (d-e)



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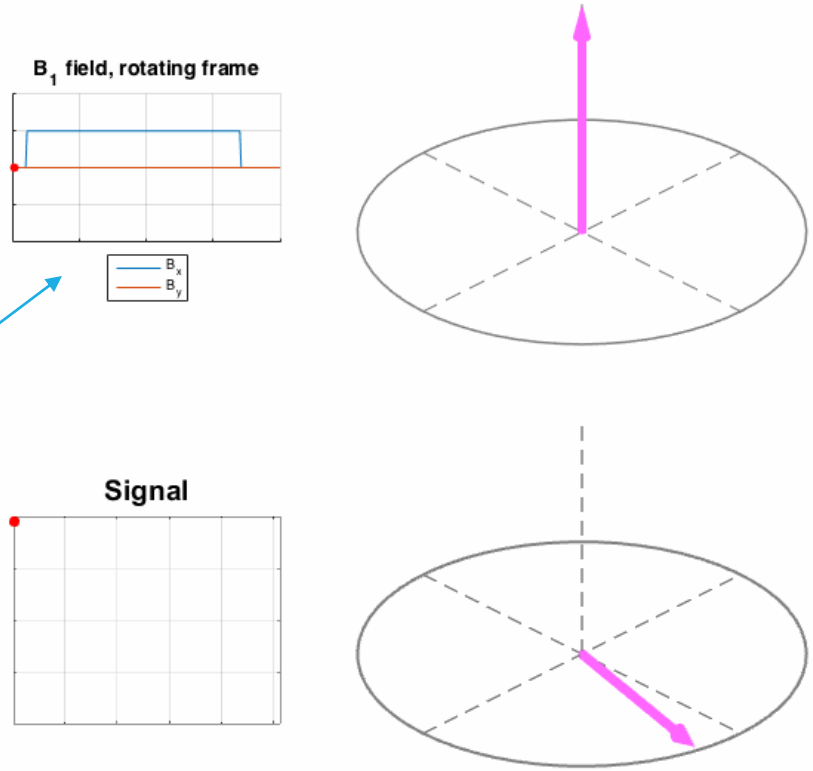
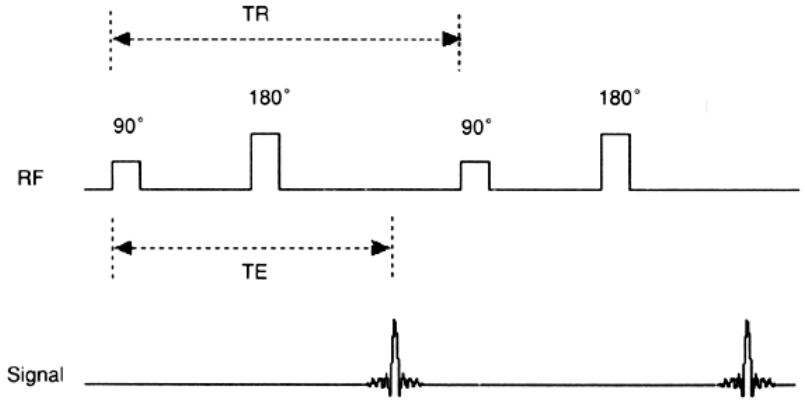


http://mriphysics.github.io/teaching-mri-intro.html

Basic principles: key paramters

- Repetition (TR) and echo time (TE)
  - TR: amount of time between successive pulse sequences applied to the same slice
  - TE: time between the delivery of the radio frequency (RF) excitation pulse and the peak signal induced in the coil

f) Diagram of spin echo sequence



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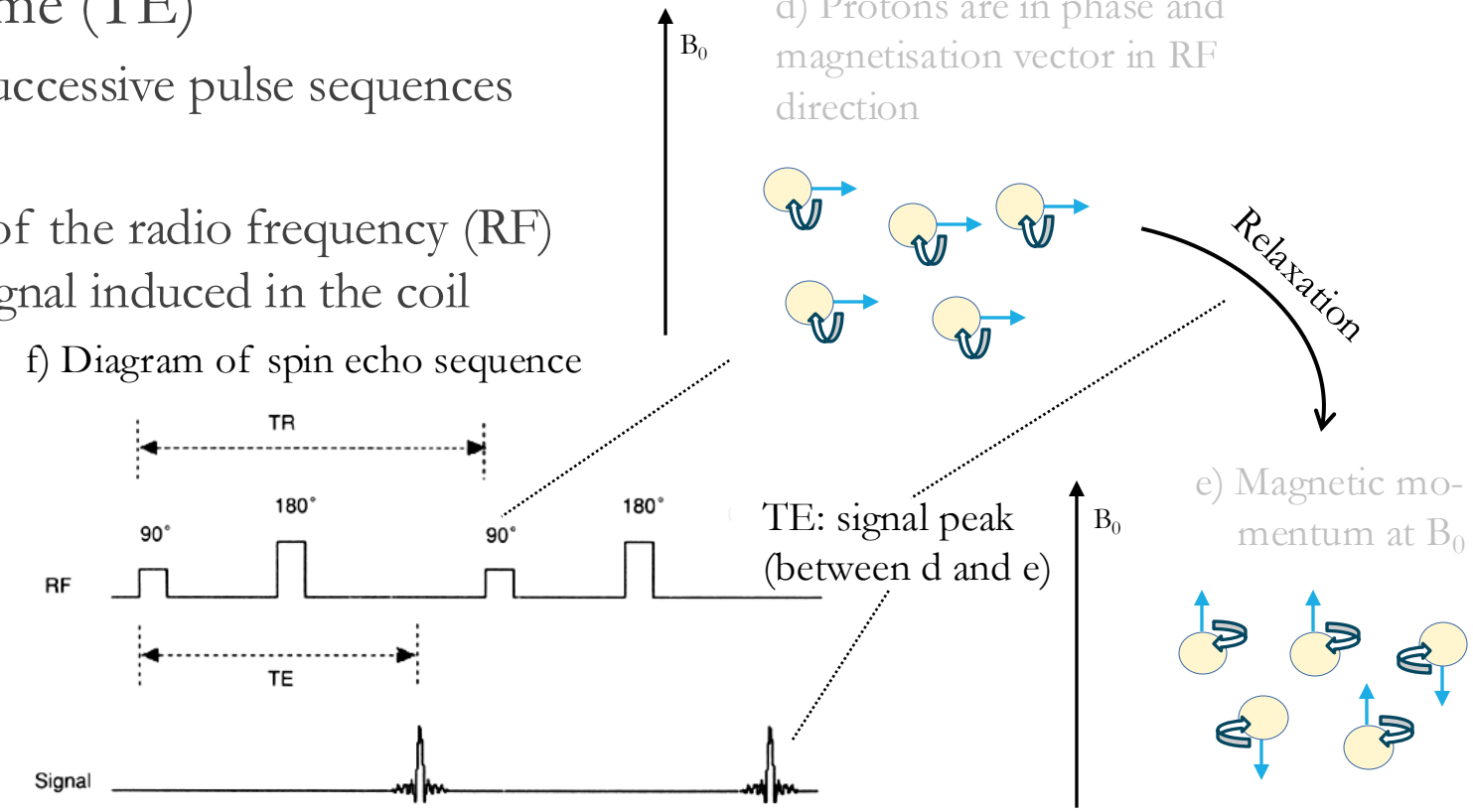
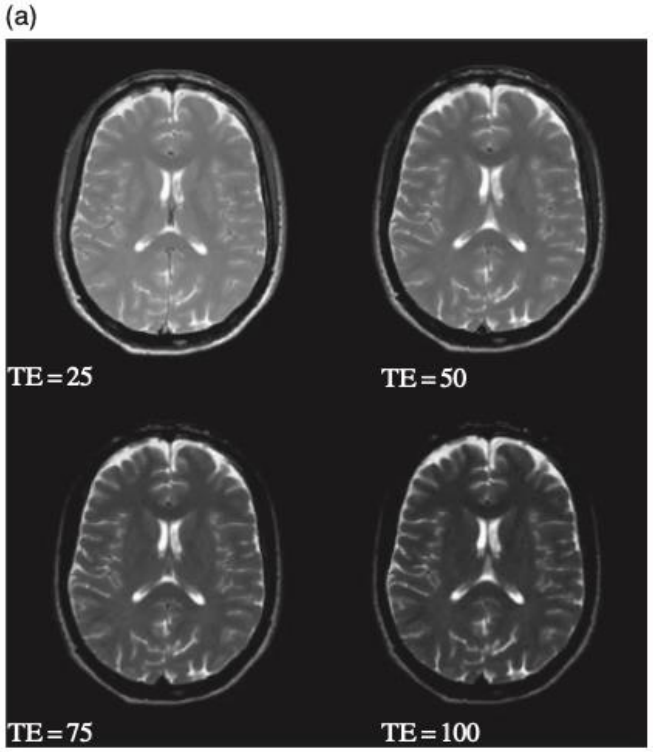
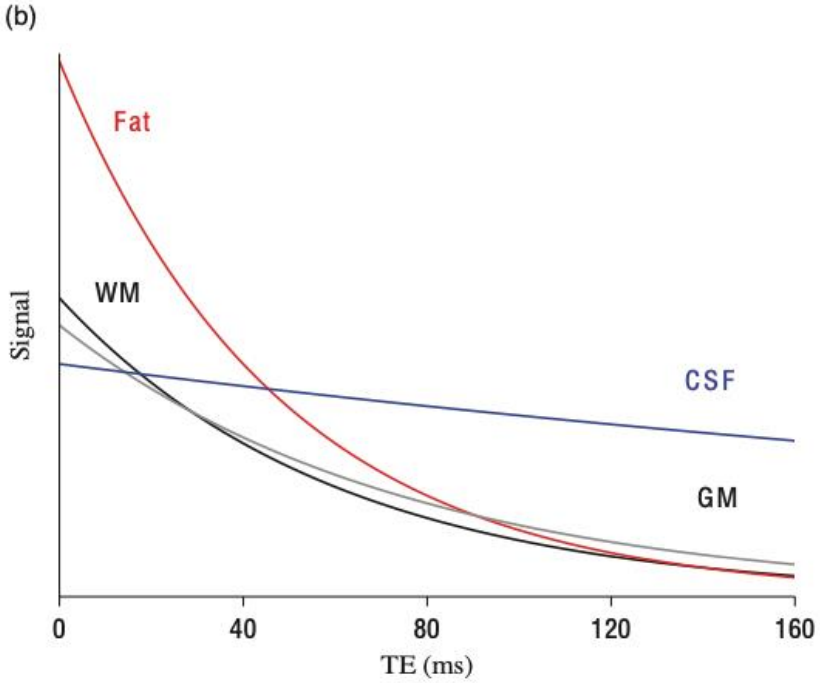


McRobbie et al. (2017). MRI from Proton to Picture.

Basic principles: key paramters

- Different TEs and TRs produce different contrasts as tissues' relaxation times vary
- Example (right): Varying TE while keeping TR constant at 1500 ms
- Signal *decay* over time





McRobbie et al. (2017). MRI from Proton to Picture.

Basic principles: key paramters

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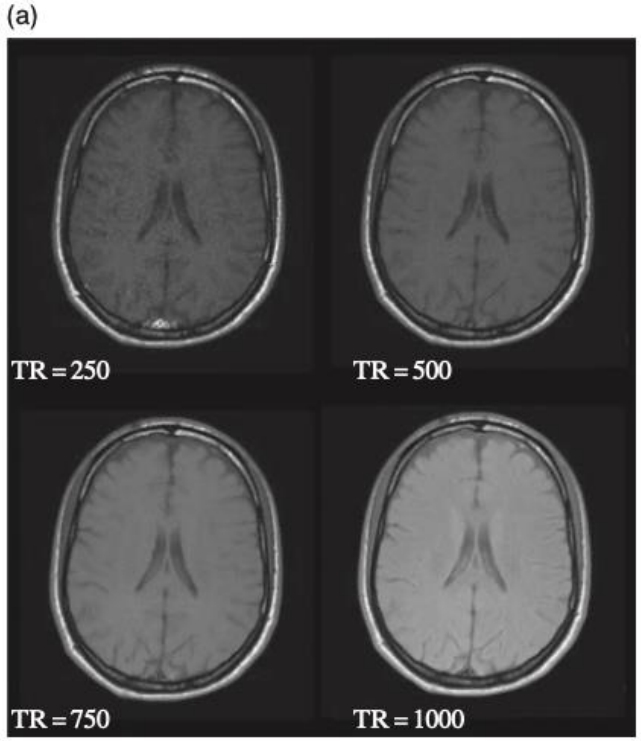
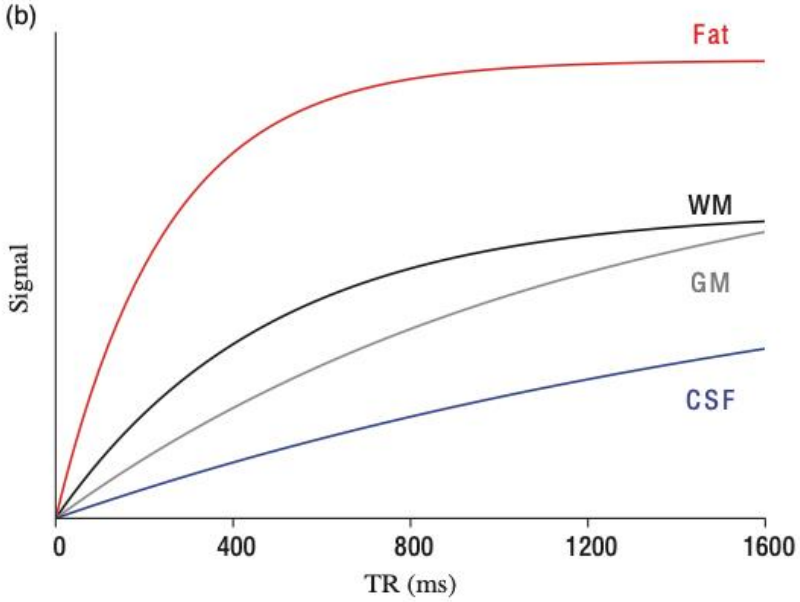
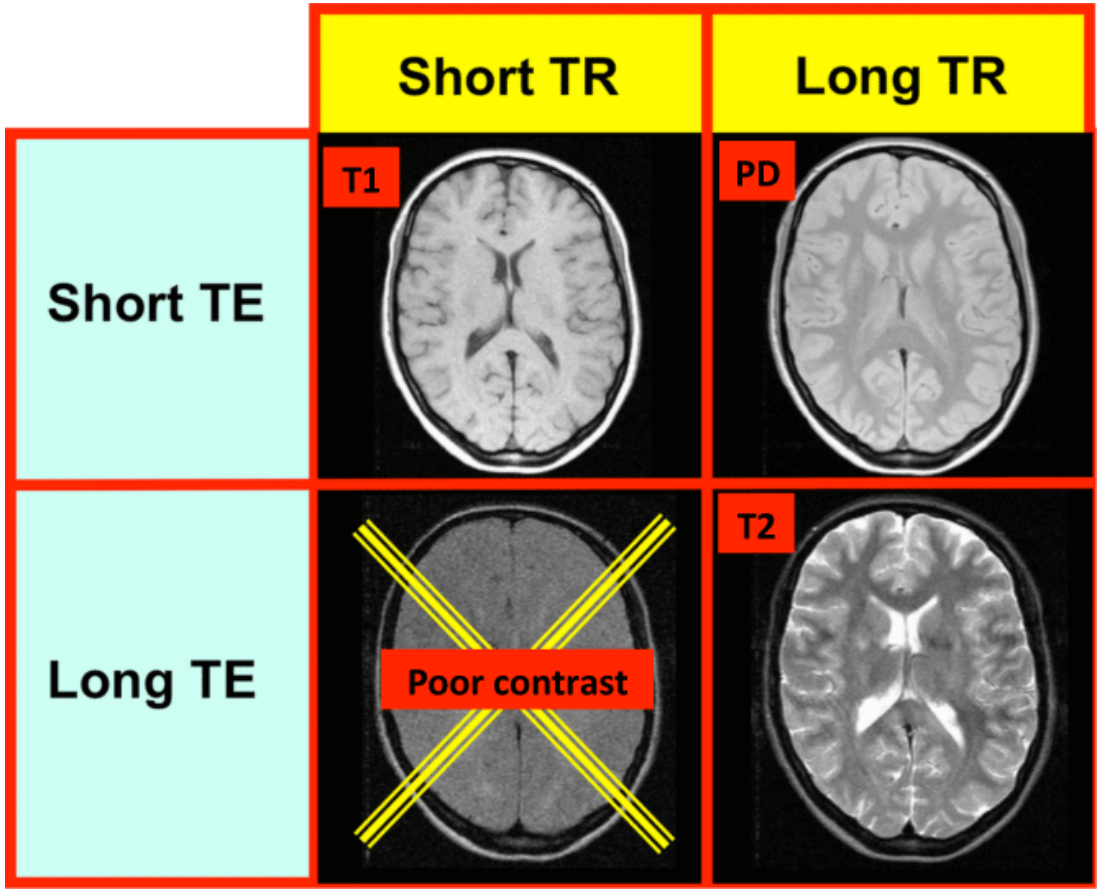
- Example (right): Varying TR while keeping TE constant at 10 ms
- Signal *increase* over time





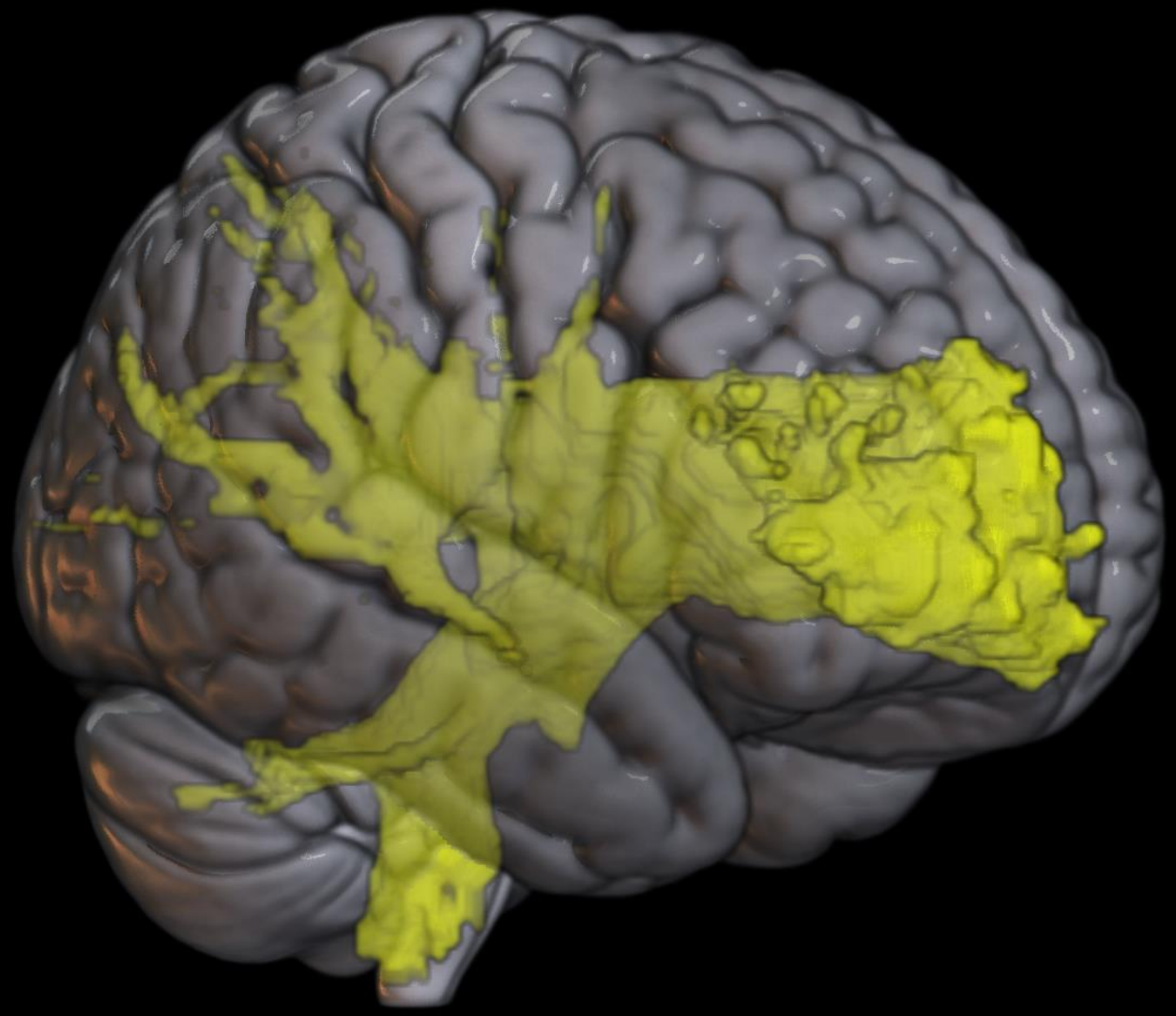
McRobbie et al. (2017). MRI from Proton to Picture.

Varying echo and repition times

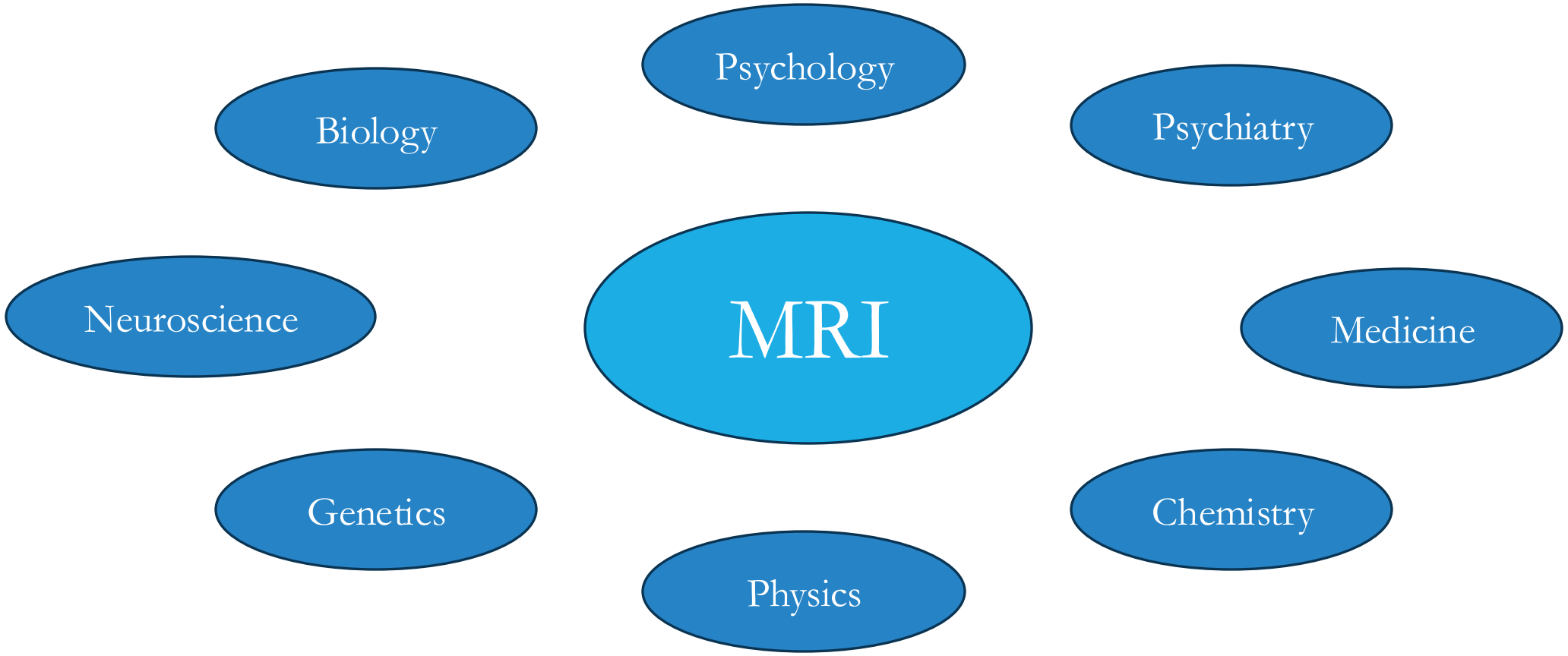


https://mriquestions.com/image-contrast-trte.html

Different imaging techniques & how they are used in research



MRI is applied in multiple fields



Imaging techniques used in research

- MRI possible for the entire body, here, I will focus on the brain
- Most research focuses on quantifyable markers, such as:
  - signal intensity,
  - or more processed features /estimates of tissue properties, e.g. cortical thickness
- These biological markers are used to describe phenomena such as ageing, disorders, or their development

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Imaging techniques used in research

- Only most recently: availability of population scale brain MRI
  - Exploration of small and variable effects is now possible

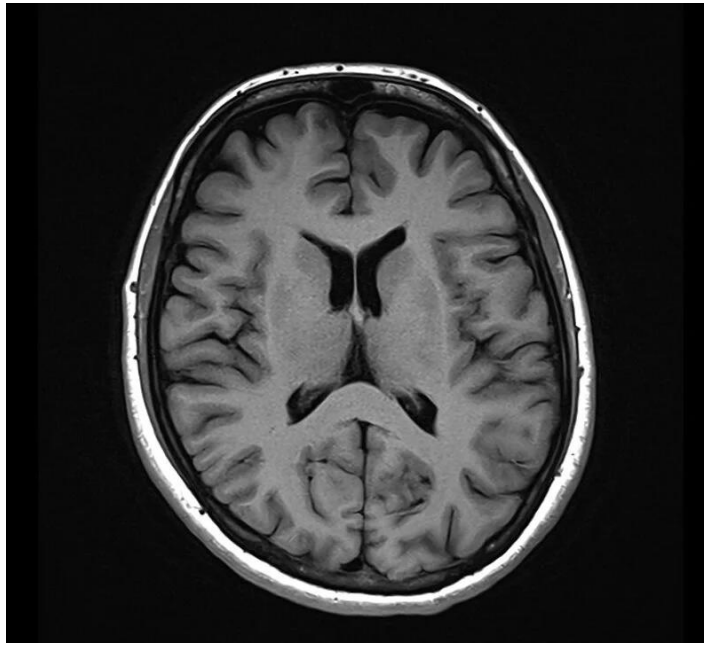
Usually small effects: genetics

Variable effects: psychiatric disorders

Images generated with NightCafe

Imaging: T_1-weighted

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting



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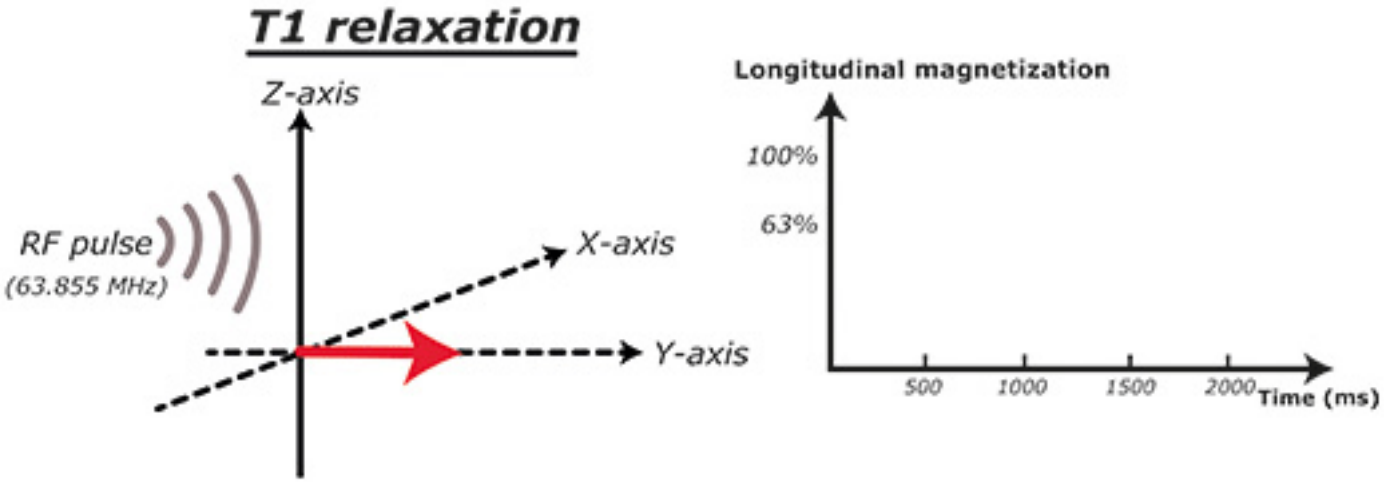
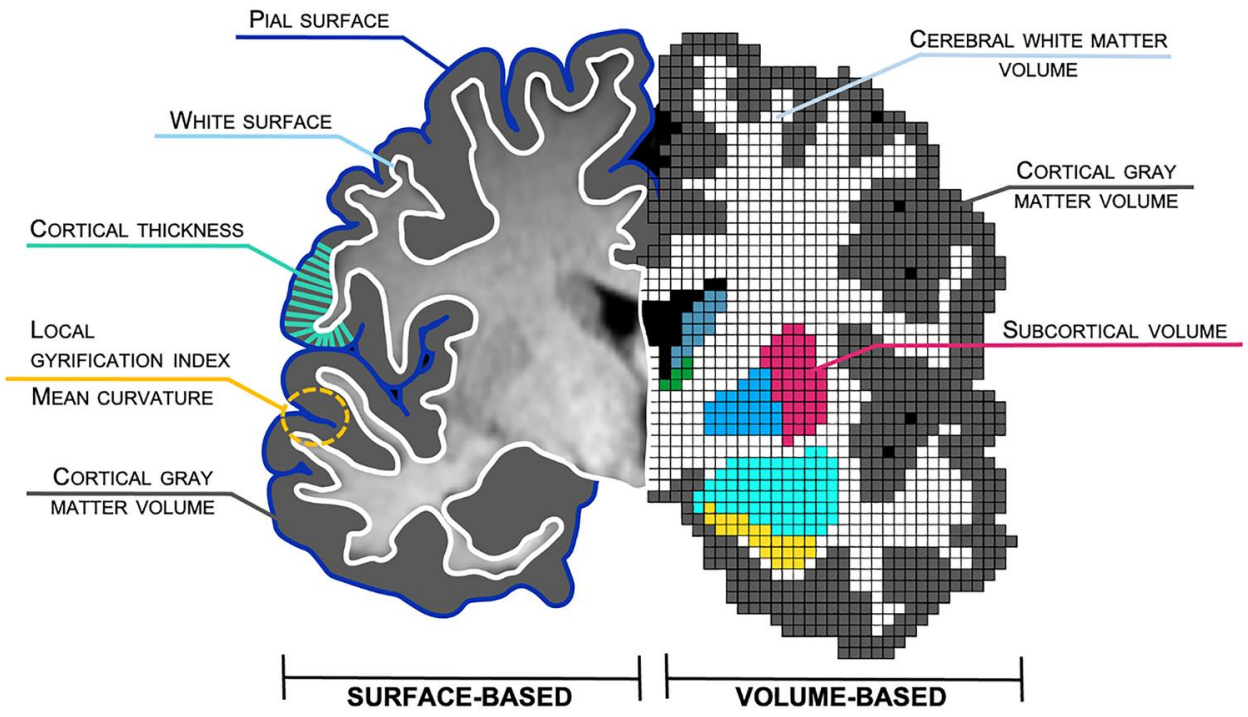


https://www.radiology.expert/en/modules/mri-technique-introduction/mri-technique/

Imaging: T_1-weighted

- Research application:
  1. Image reconstruction
  2. Feature extraction
  3. Computation of statistics
     - Voxel to whole brain level



Backhausen et al. (2021), Neuropsy Rev, 32 (2)

Imaging: T_1-weighted

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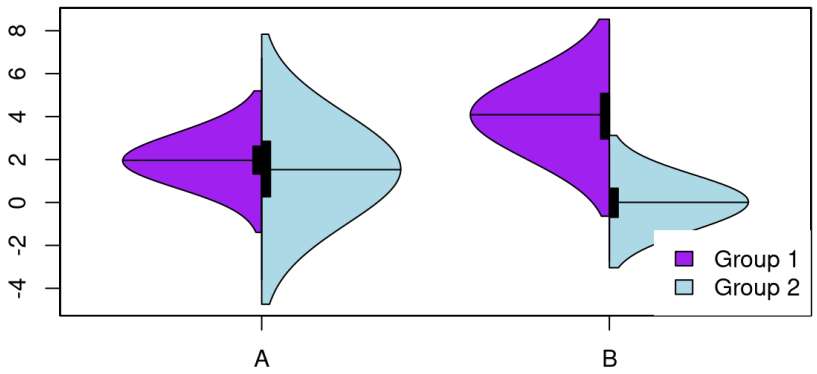
Group differences in a single feature



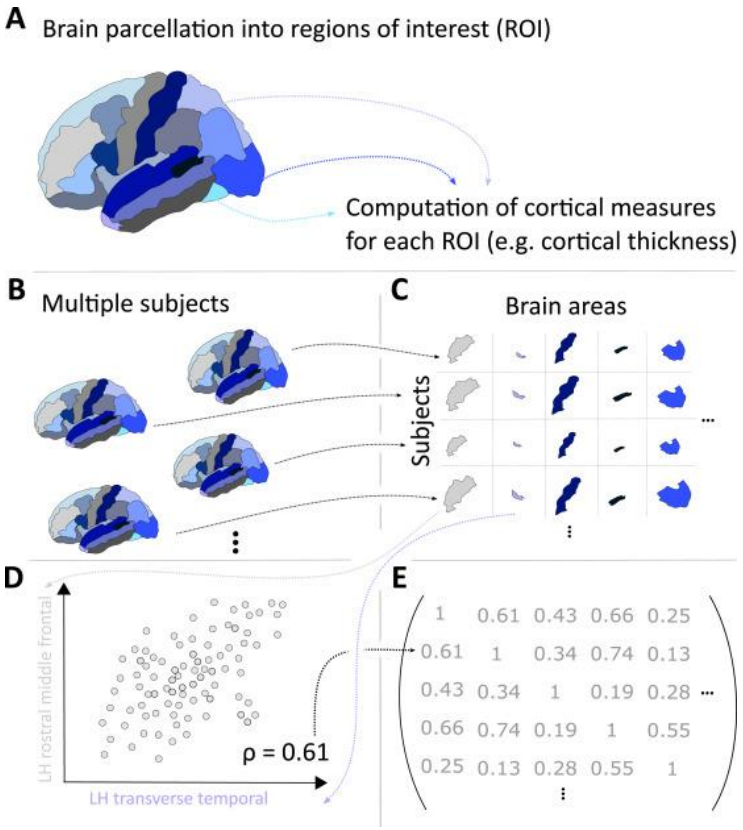
https://github.com/mbjoseph/mbjoseph.github.io

Voxel-level analysis highlighting significant clusters on the cortical surface

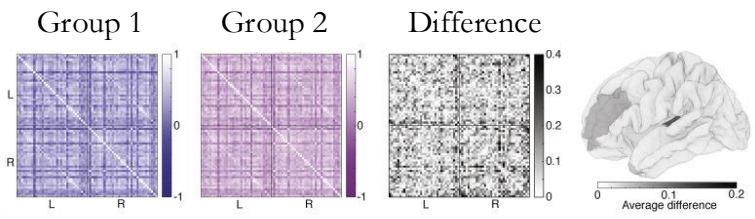
Roe et al. (2023), eLife, 12 (e84685)

Imaging: T_1-weighted

1. Estimation of covariance matrices



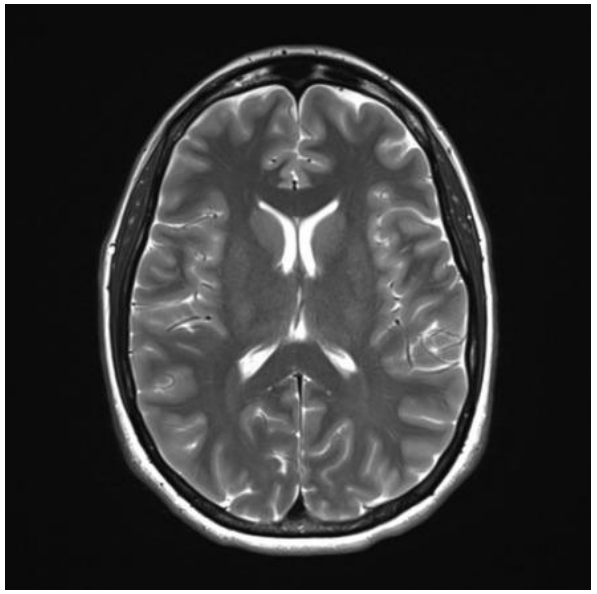
2. Examining overlaps of matrices



Carmon et al. (2023), NeuroImage, 220 (117104)

Imaging: T_2-weighted

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting



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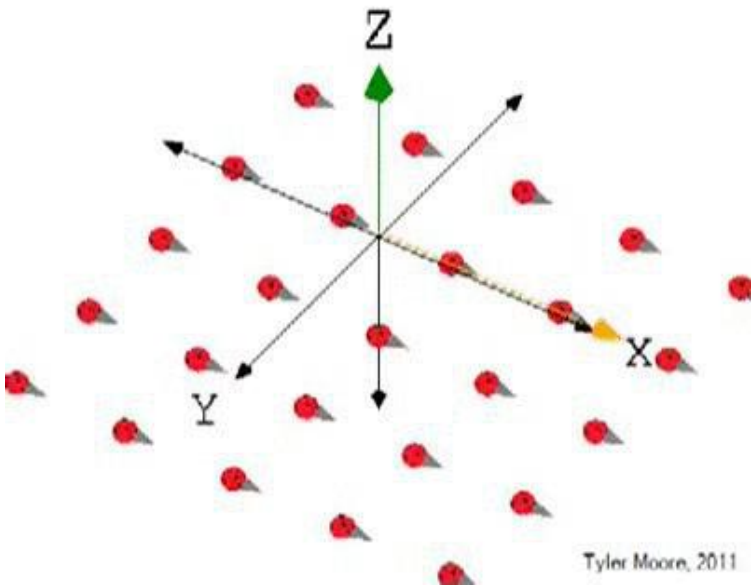
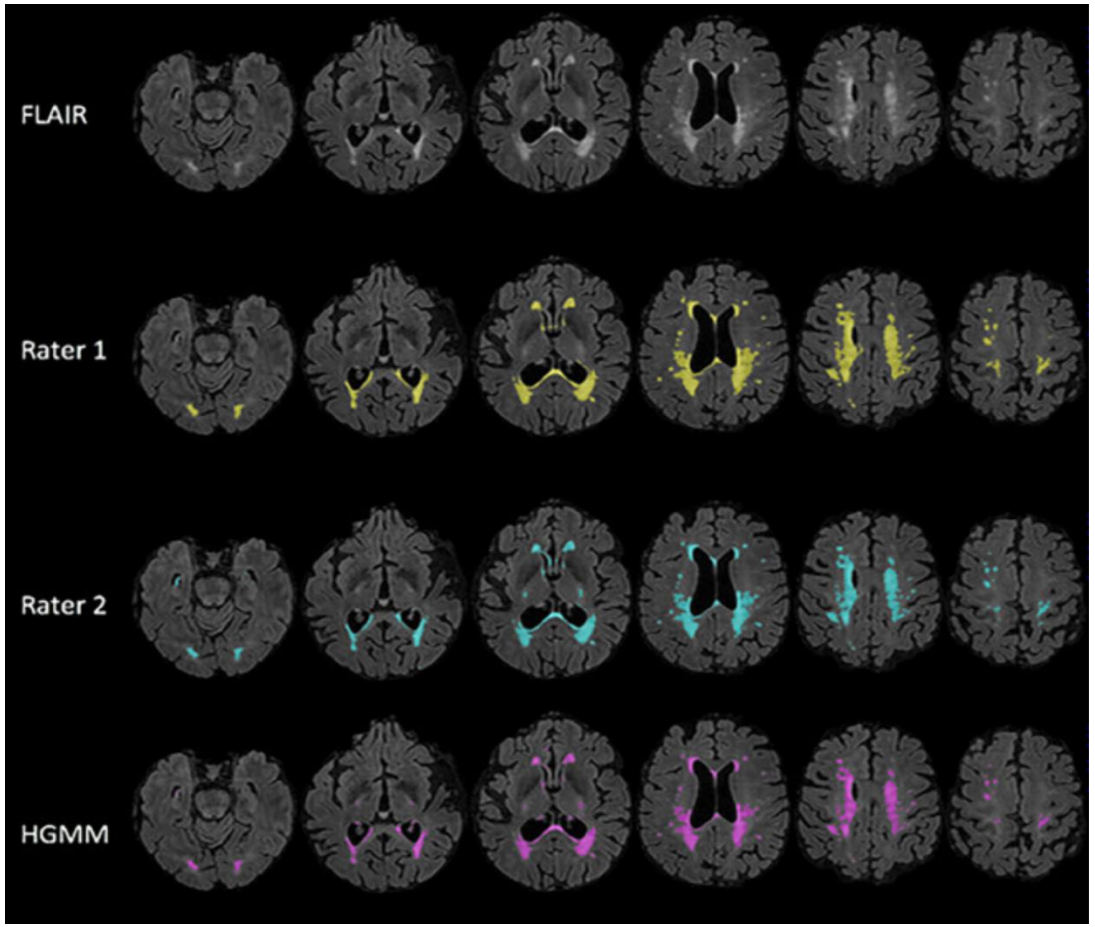


Imaging: T_2-weighted

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
    - Fluid attenuated inversion recovery (FLAIR) MRI
- Algorithms applied to FLAIR allows to automatically quantify white matter hyperintensities
  - Hyperintensities can be interpreted as lesions



Igwe et al. (2022) IJPSR, 13(2)

Imaging: T_2-weighted

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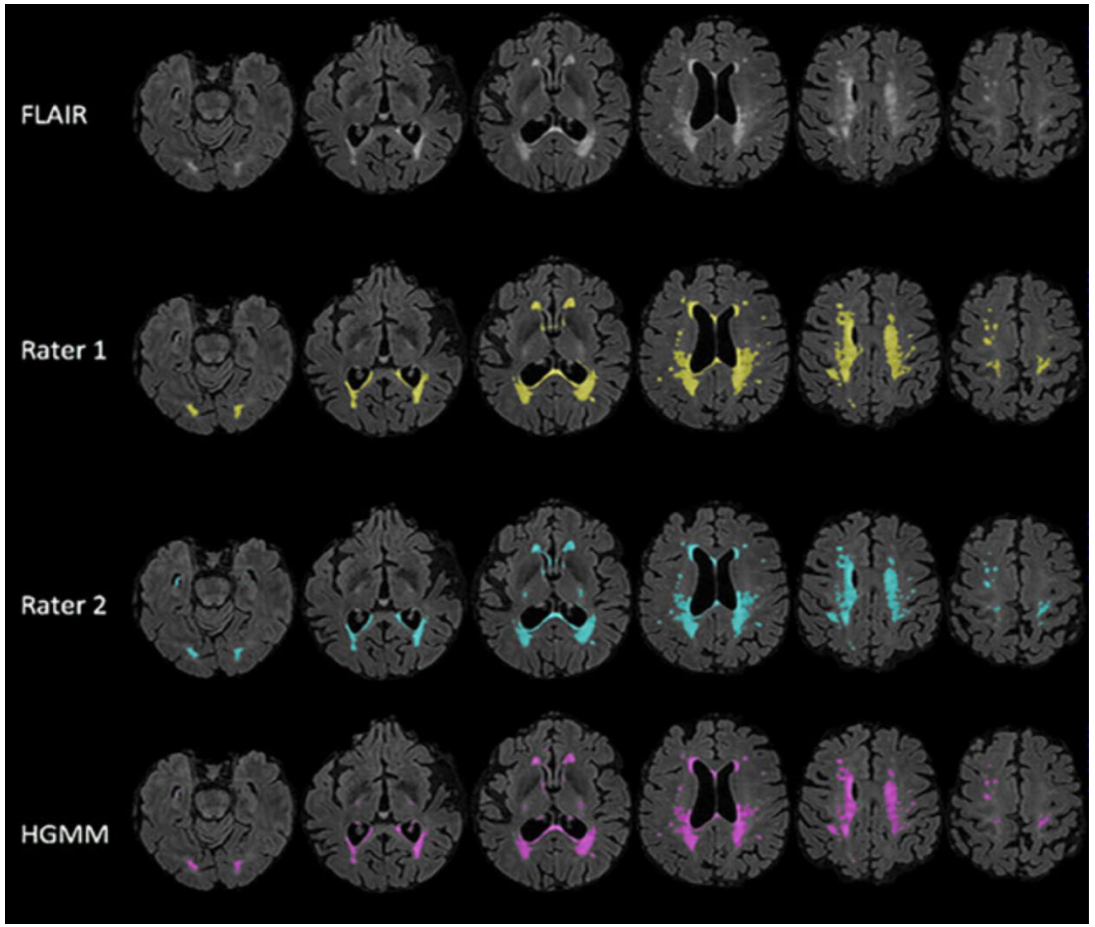
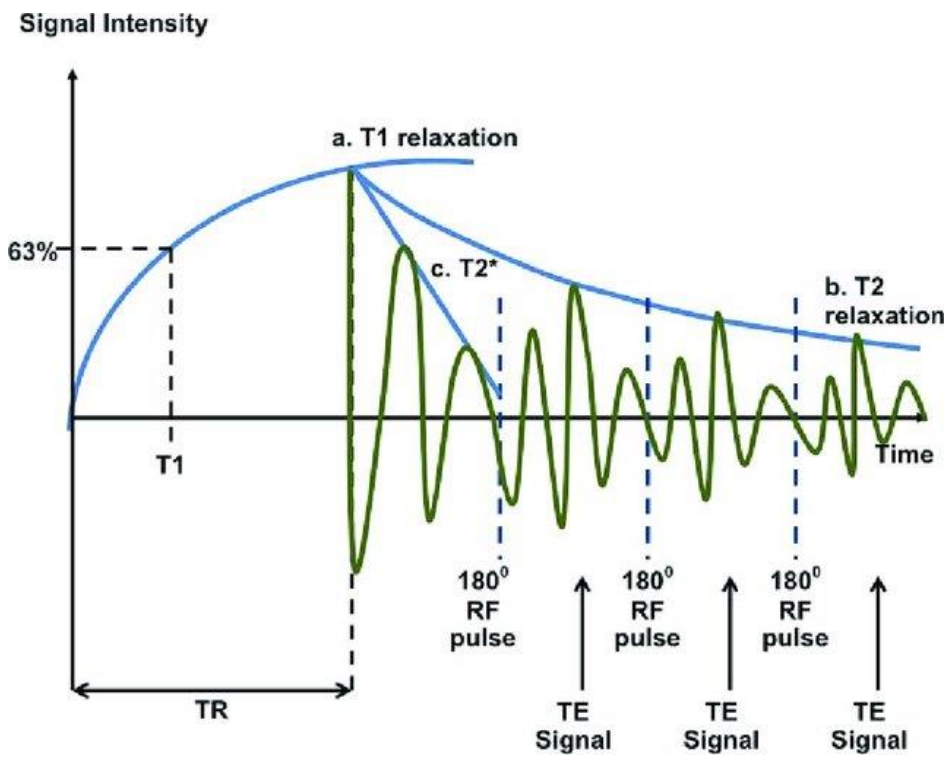


Igwe et al. (2022) IJPSR, 13(2)

Imaging: T_2*-weighted

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting



Currie et al. (2012) Postgr. Med. J., 89 (1050)

Imaging: T_2*-weighted

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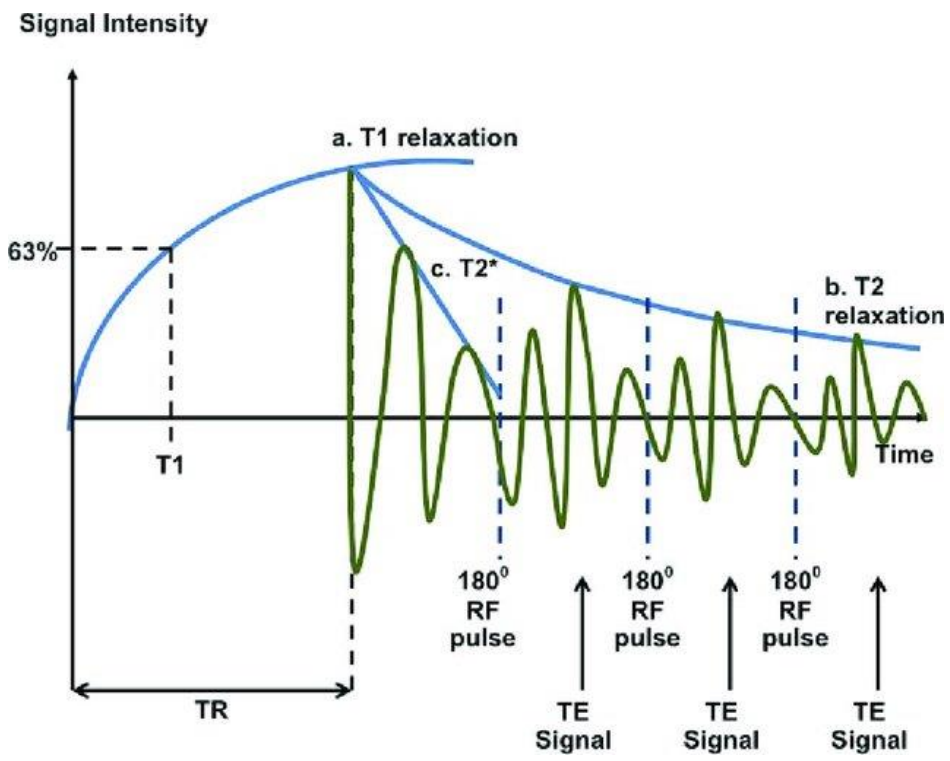
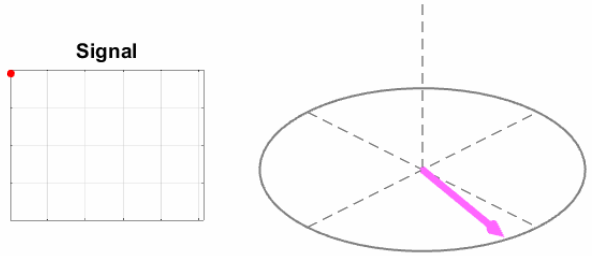
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting



Single pulse



http://mriphysics.github.io/teaching-mri-intro.html

Currie et al. (2012) Postgr. Med. J., 89 (1050)

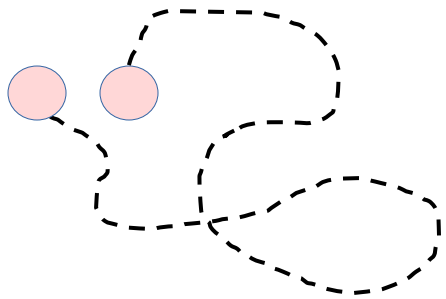
Imaging: T_2*-weighted

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI

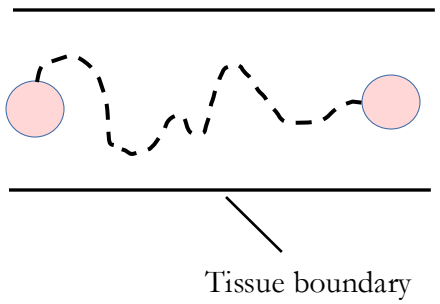
Imaging: diffusion-weighted (T_2*)

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI

a) Isotropic diffusion

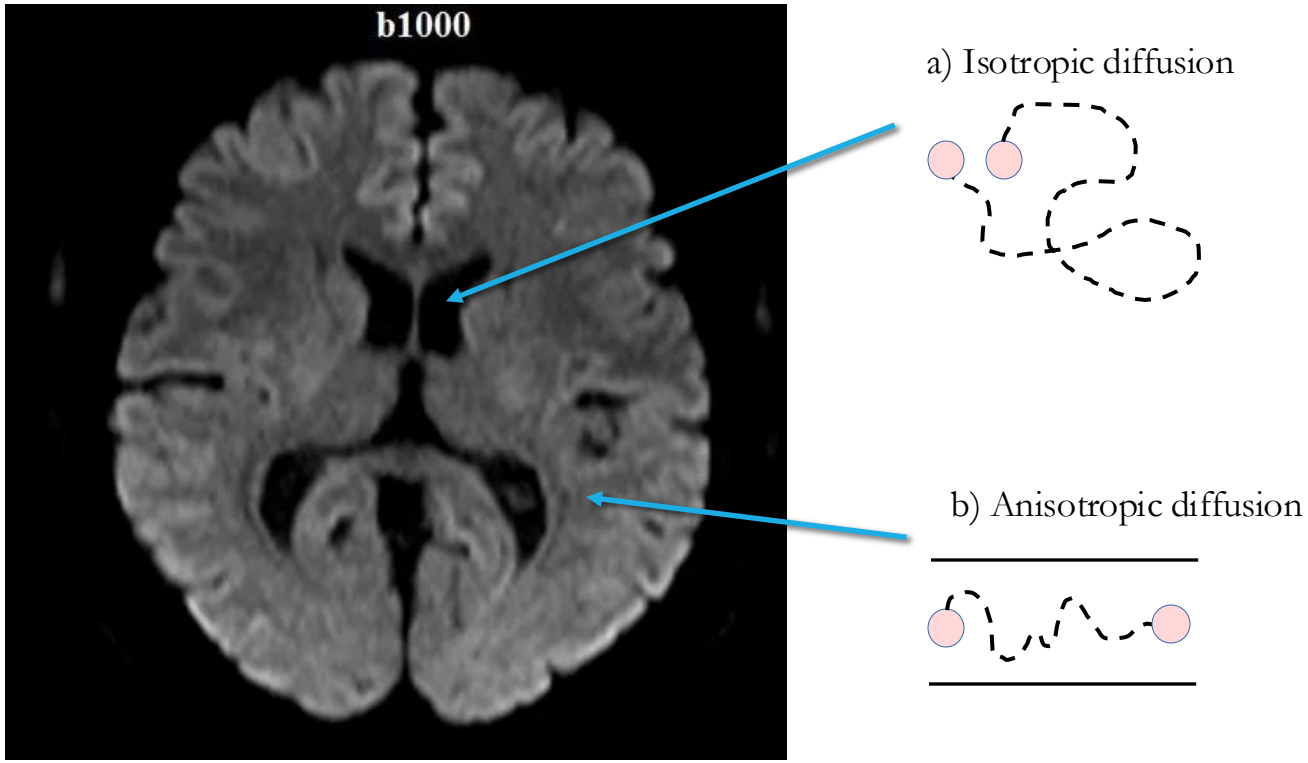


b) Anisotropic diffusion



Imaging: diffusion-weighted (T_2*)

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI



https://mrimaster.com/characterise-image-dwi/

Imaging: diffusion-weighted (T_2*)

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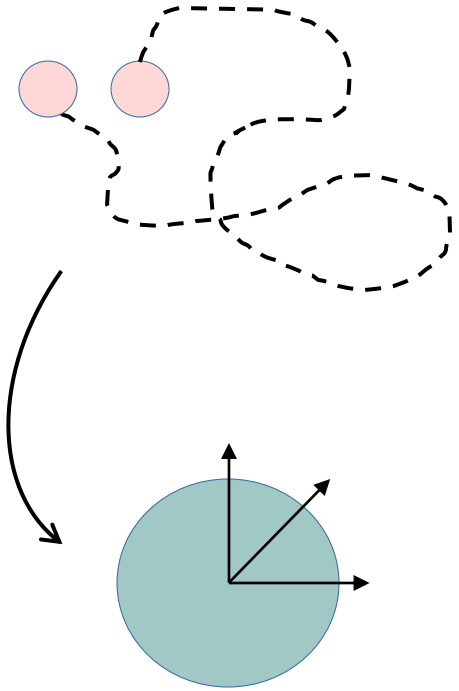
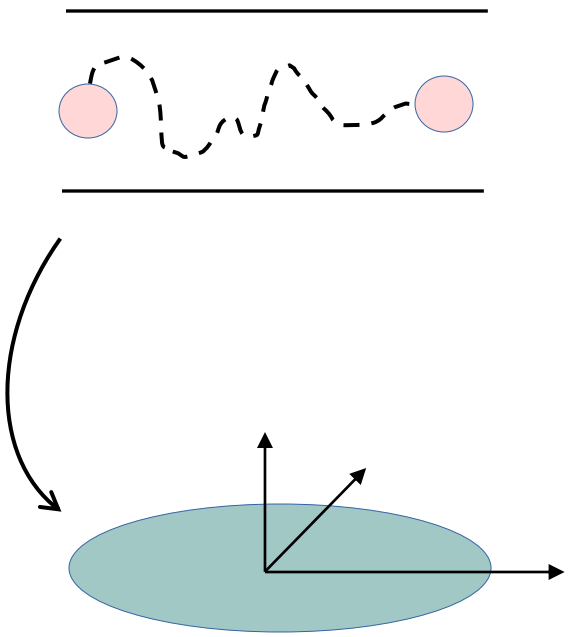
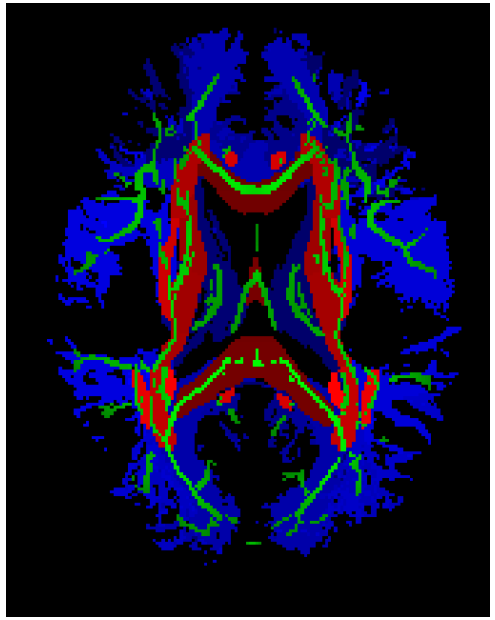


b) Anisotropic diffusion



c) Fractional anisotropy voxel map(s)



Korbmacher et al. (2023) HBM, 44 (10)

Imaging: diffusion-weighted (T_2*)

- TE and TR configurations can be used to obtain different contrasts
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  - T_2-weighting
  - T_2*-weighting
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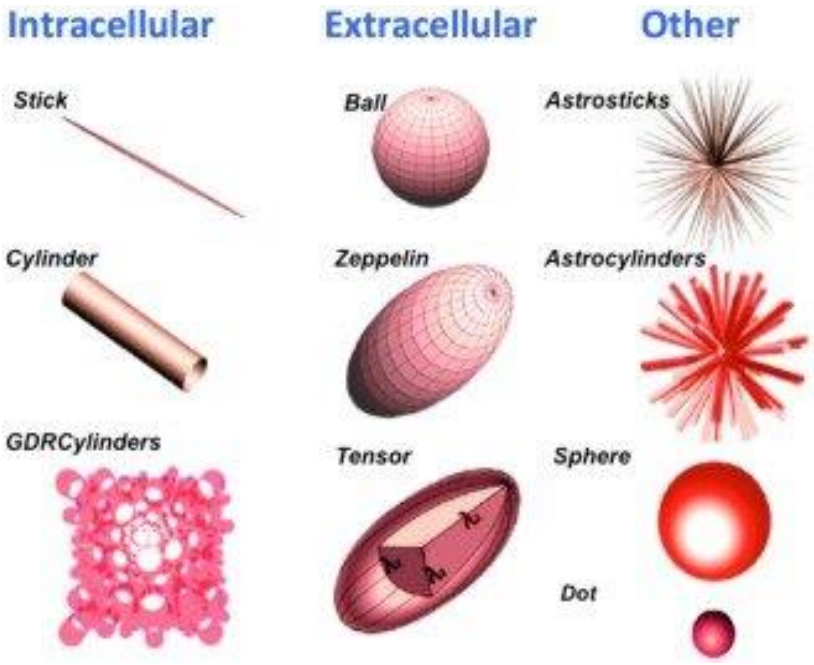
a) Multicompartment diffusion approaches



Ferizi et al. (2013), MRM, 72 (6)

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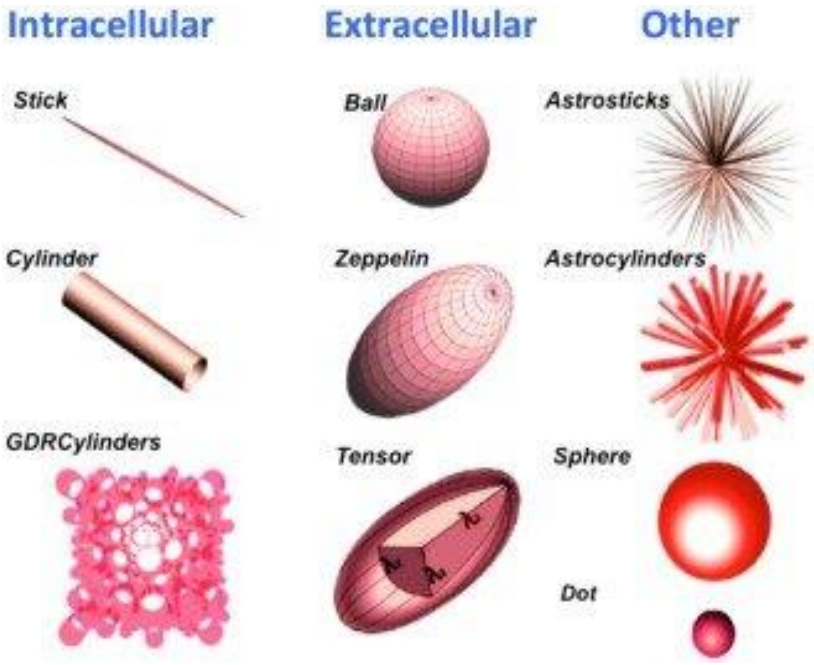
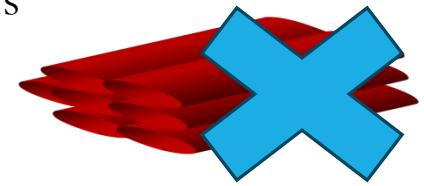


Ferizi et al. (2013), MRM, 72 (6)

White matter is not a collection of cylinders



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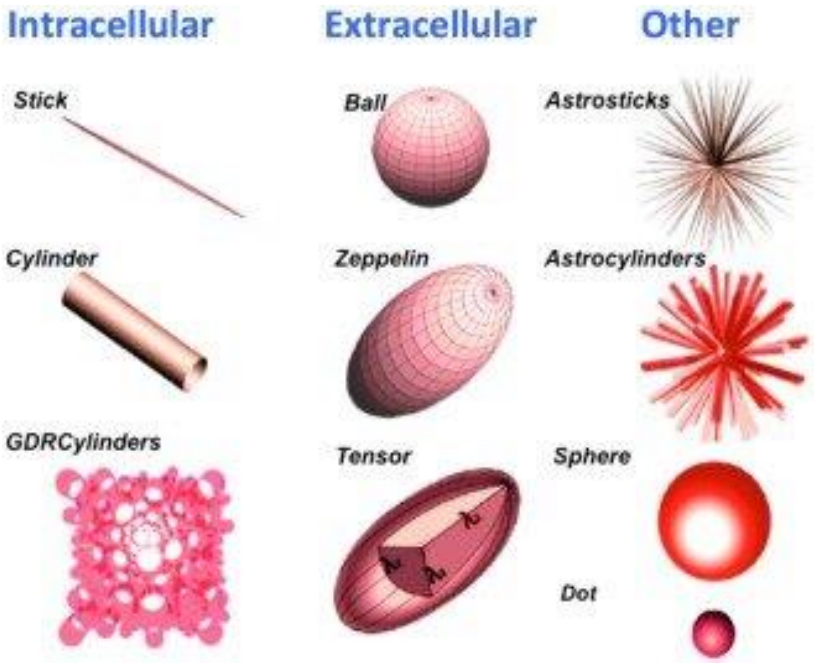

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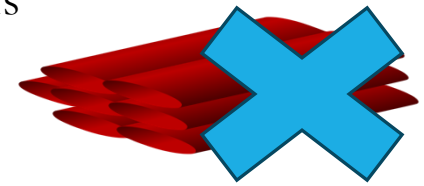
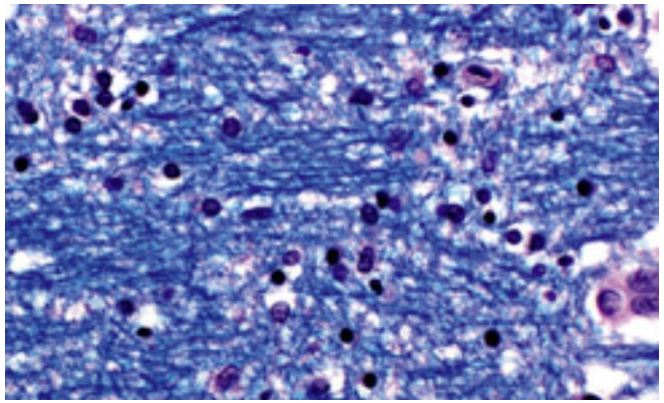


White matter histology



https://radiologykey.com/white-matter/

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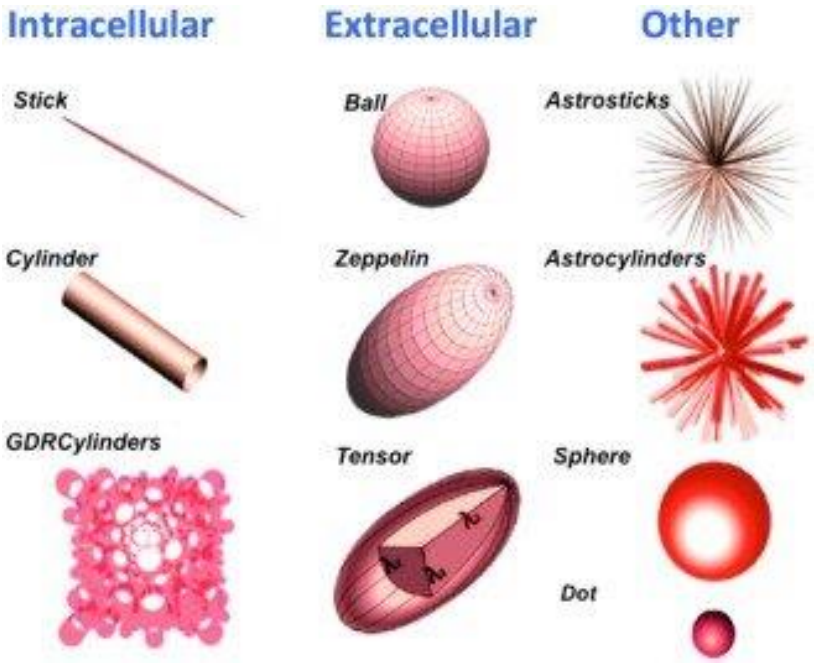

Ferizi et al. (2013), MRM, 72 (6)

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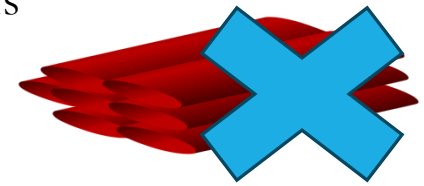
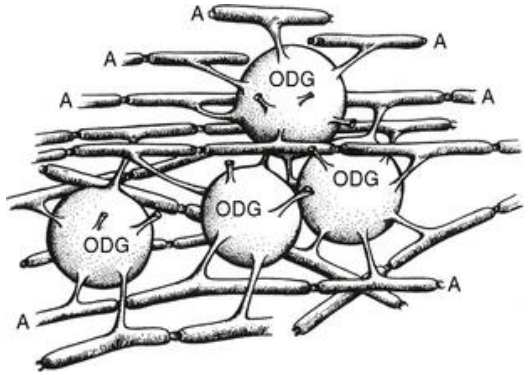


Oligodendroglial embedded in axons



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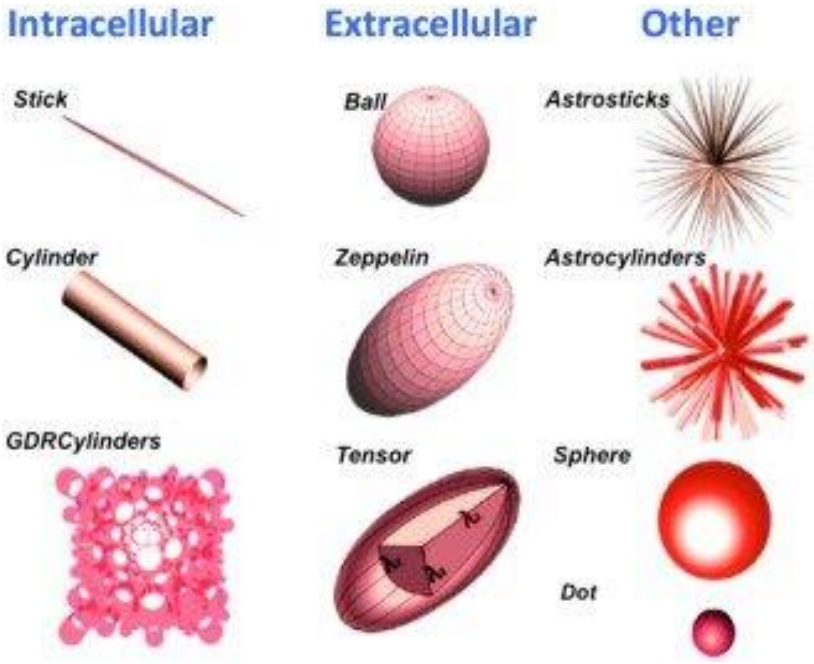
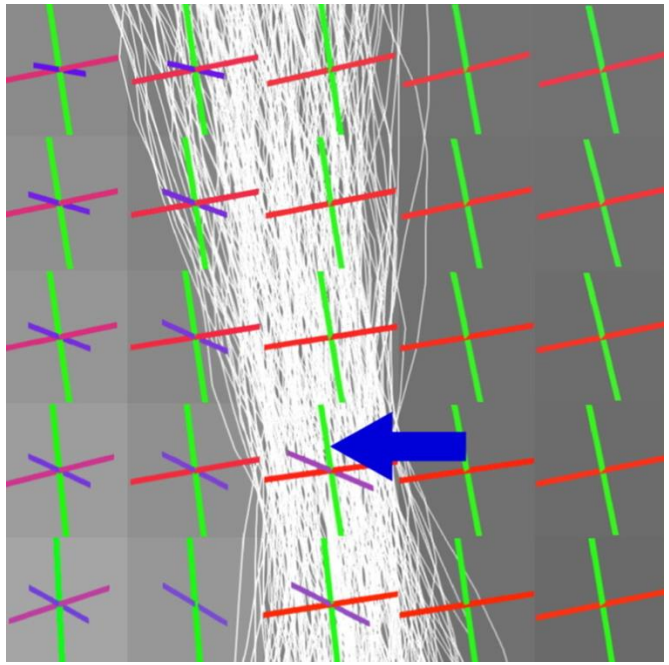


Ferizi et al. (2013), MRM, 72 (6)

b) Fixel approach



Raffelt et al. (2015), NeuroImage, 117

Imaging: diffusion-weighted (T_2*)

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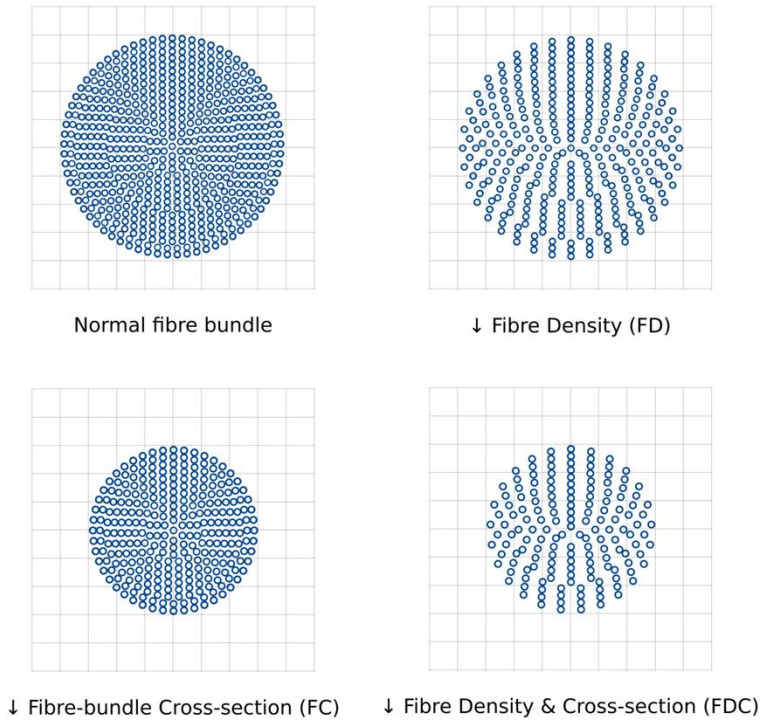

Petersen et al. (2022), Sci.Rep., 12 (1581)

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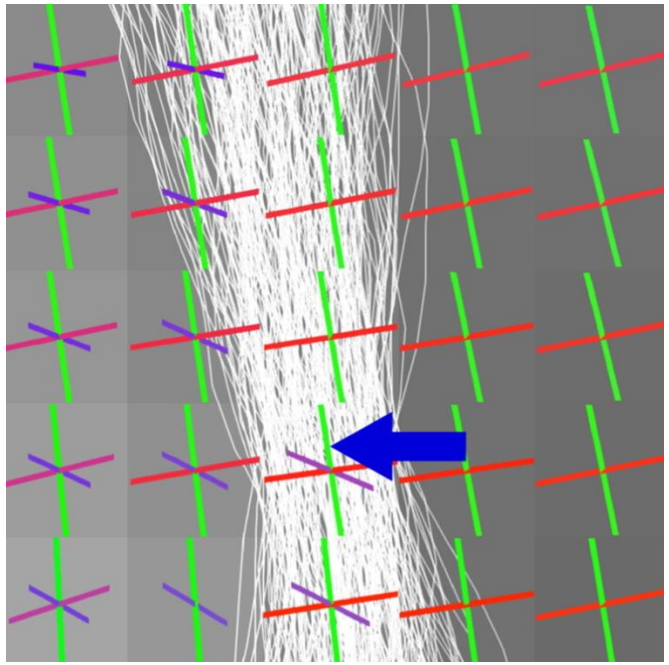

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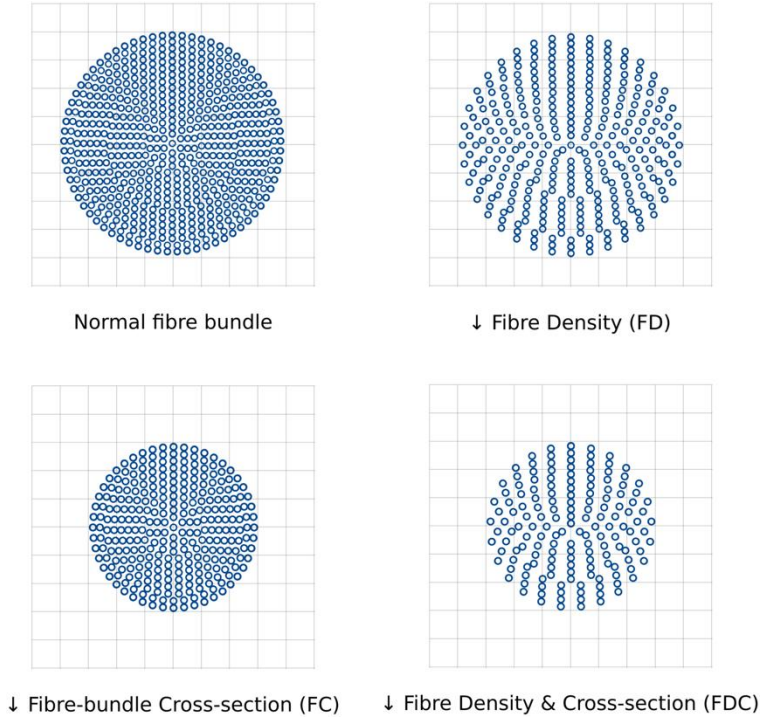

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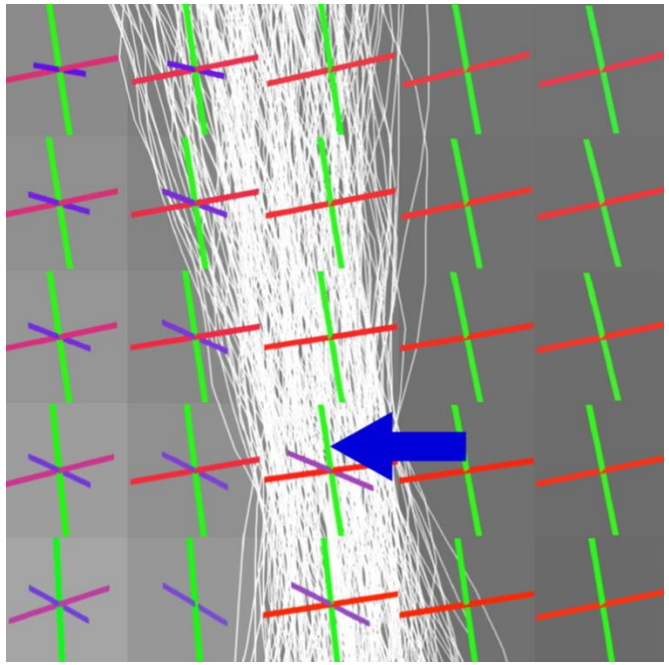

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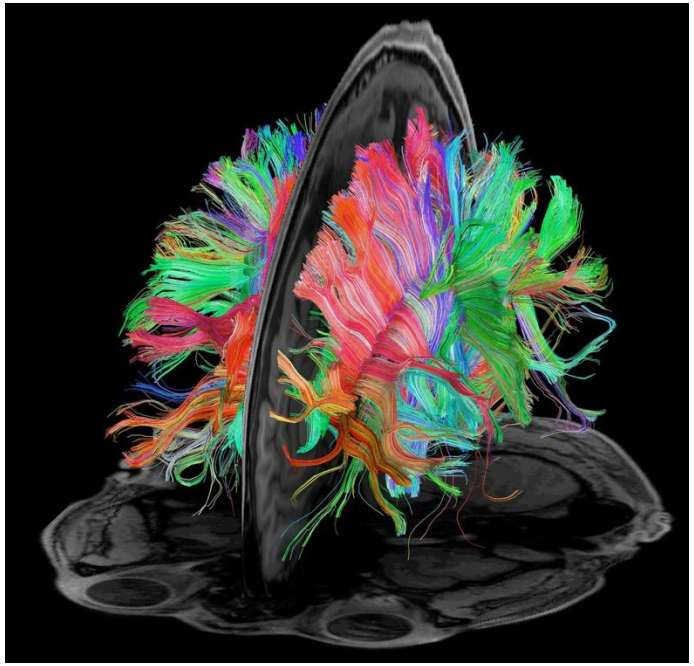
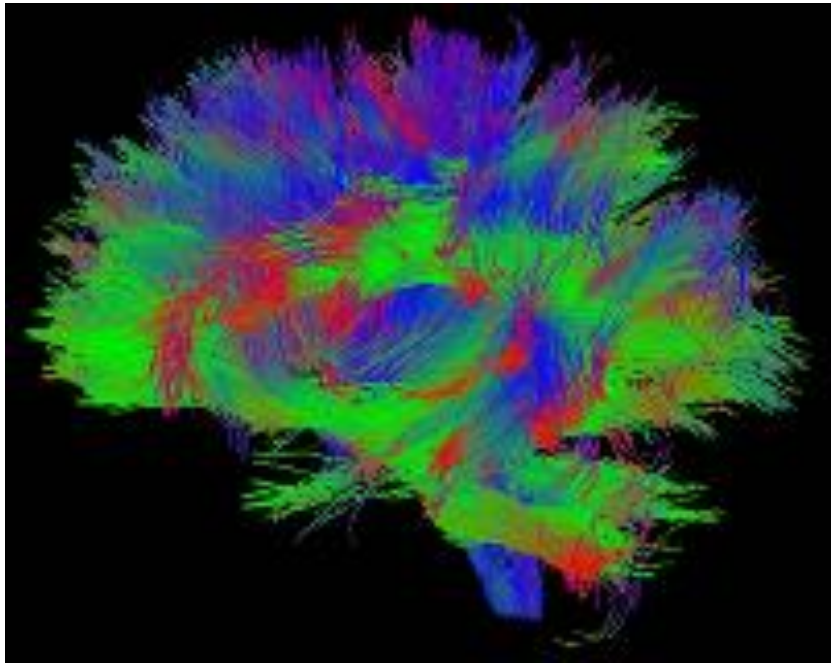


@Vilavaite (Twitter/X)



https://www.uniklinik-freiburg.de/mr-en/research-groups/postprocessing/global-tractography.html

Imaging: diffusion-weighted (T_2*)

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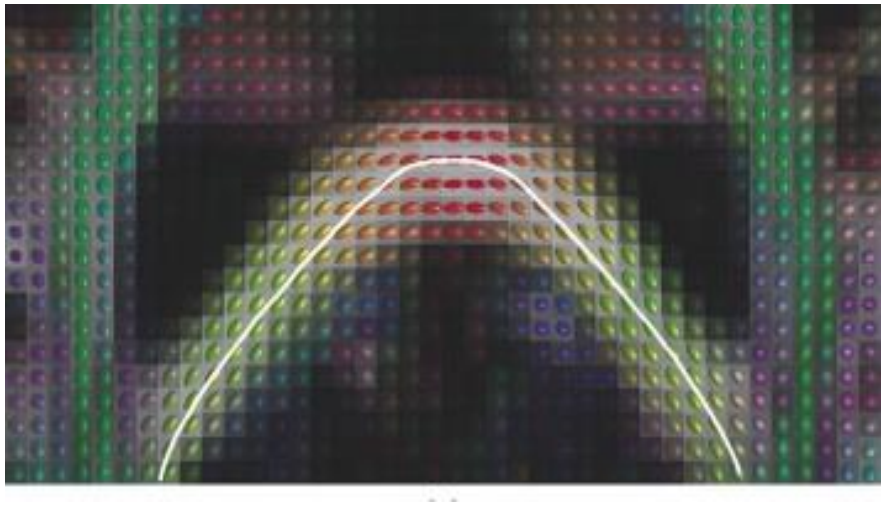

Johansen-Berg & Behrens (2009). Diffusion MRI.

Imaging: diffusion-weighted (T_2*)

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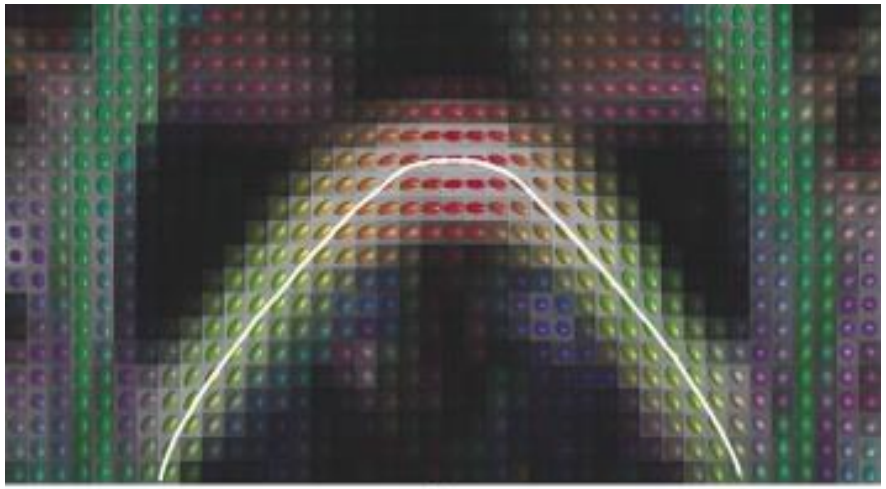
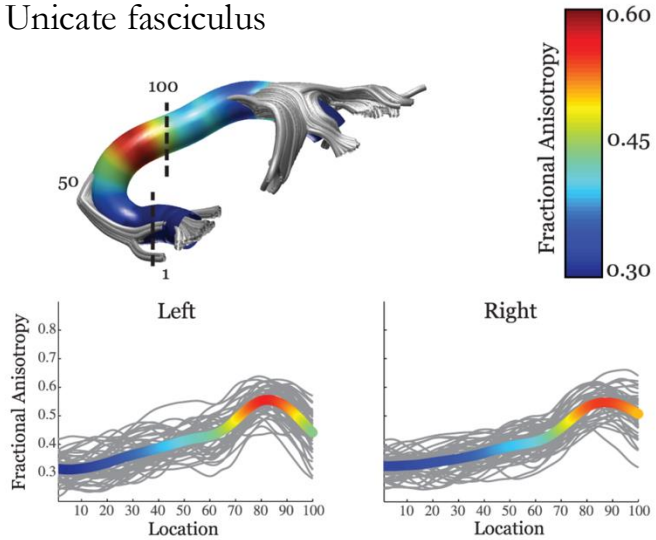


Johansen-Berg & Behrens (2009). Diffusion MRI.

a) Tract profiles



Yeatman (2012), PLOS, 7 (11)

Imaging: diffusion-weighted (T_2*)

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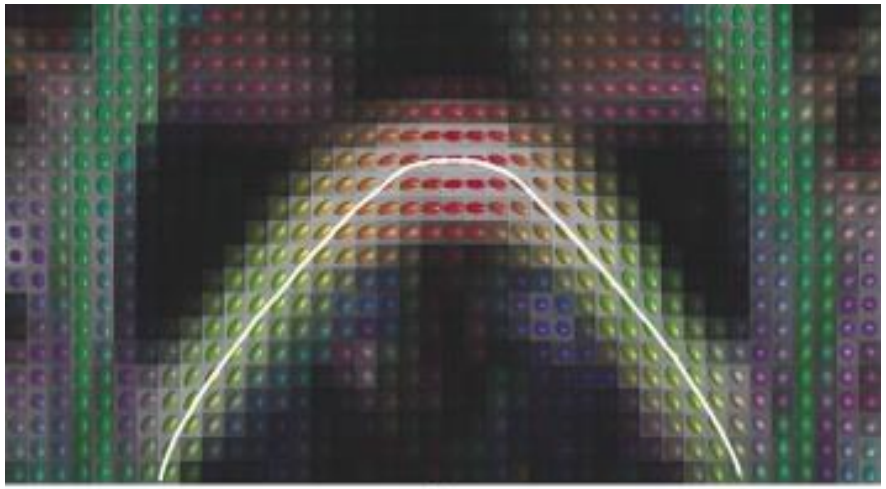
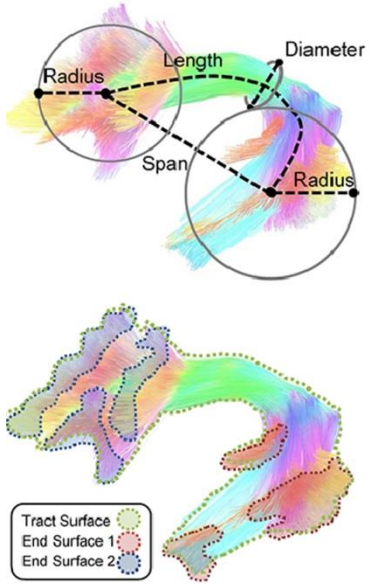


Johansen-Berg & Behrens (2009). Diffusion MRI.

b) Shape analysis



Yeh (2020), NeuroImage, 223 (117329)

Imaging: diffusion-weighted

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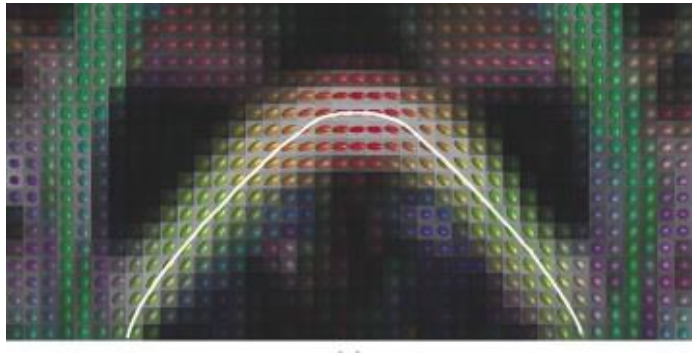
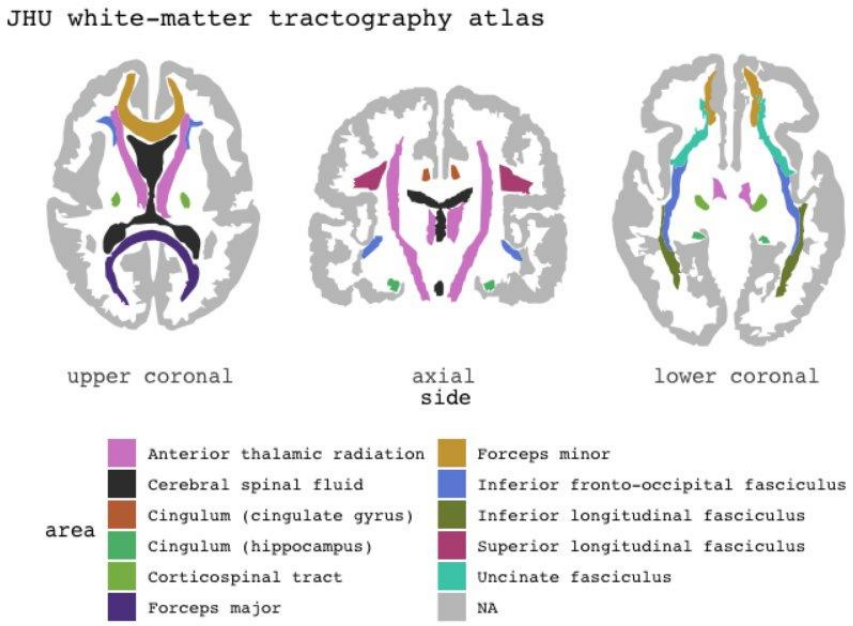


Johansen-Berg & Behrens (2009). Diffusion MRI.

c) Building tract atlases



Mowinckel & Vidal-Piñeiro (2020), Adv. Meth. & Pract. Psych. Sci. 3 (4)

Imaging: functional MRI (T_2*)

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
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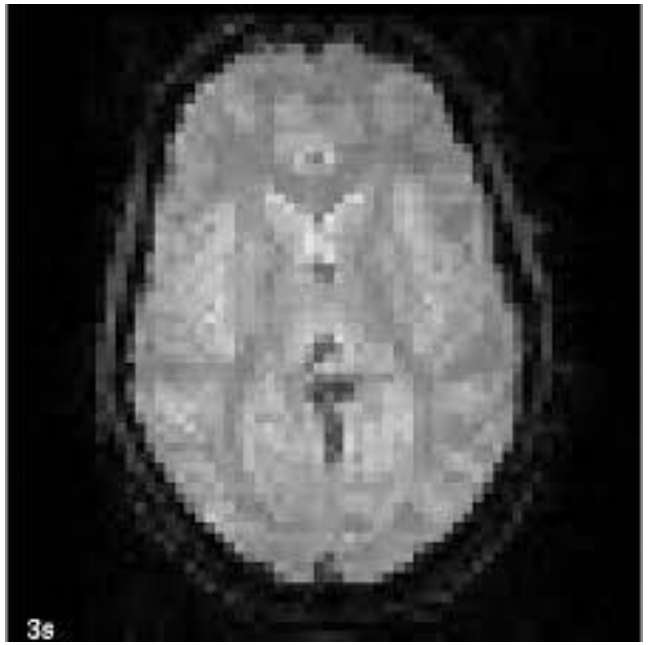
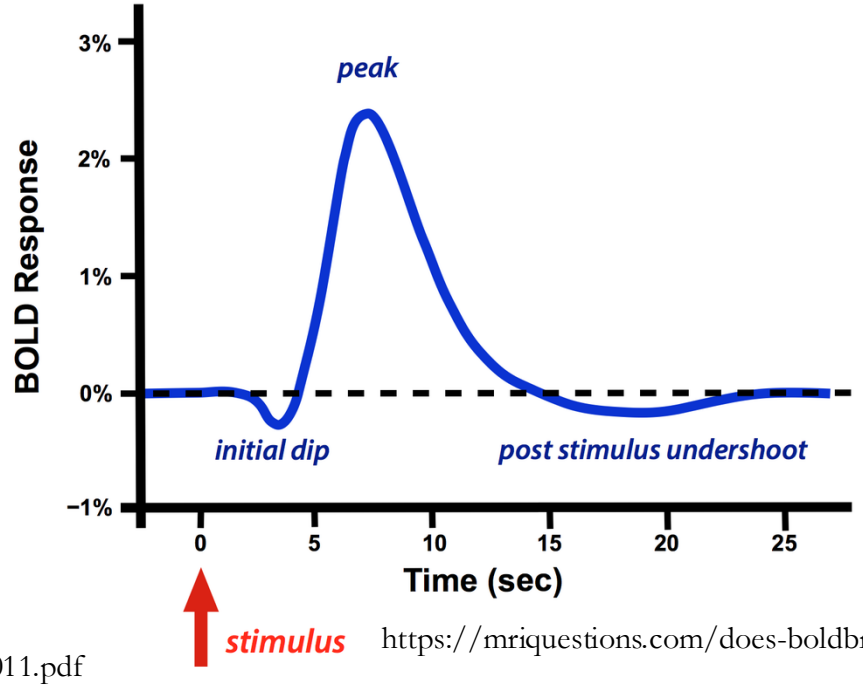
  - T_2*-weighting
    - diffusion-weighting
    - fMRI

a) Functional MRI slice



https://ftp.nmr.mgh.harvard.edu/pub/docs/SavoyfMRI2014/fmri.april2011.pdf

b) Hemodynamic response function



https://mriquestions.com/does-boldbrain-activity.html

Imaging: functional MRI (T_2*)

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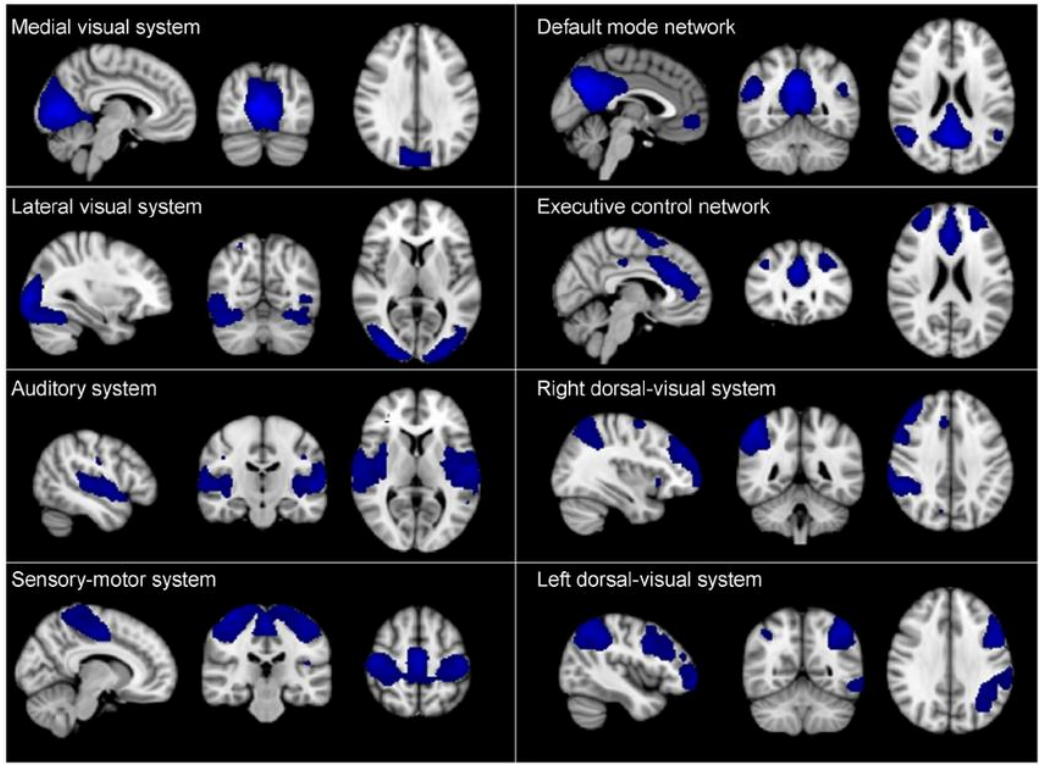

Adriannse et al. (2014) PLOS, 9 (7)

Imaging: functional MRI (T_2*)

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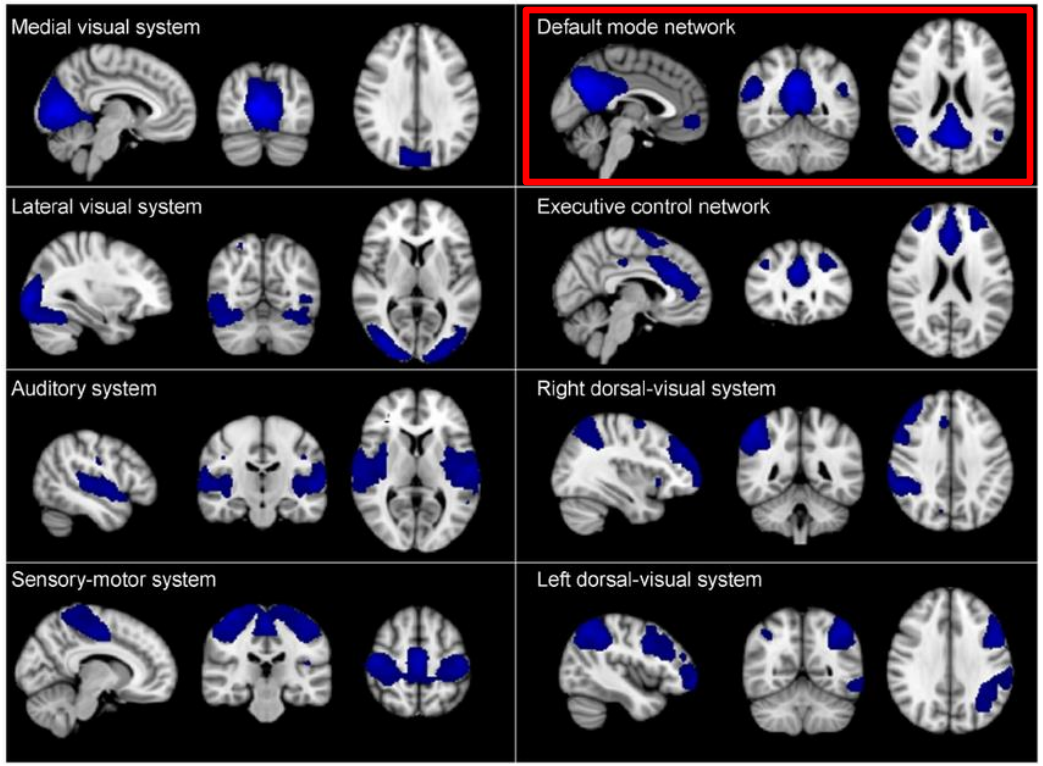
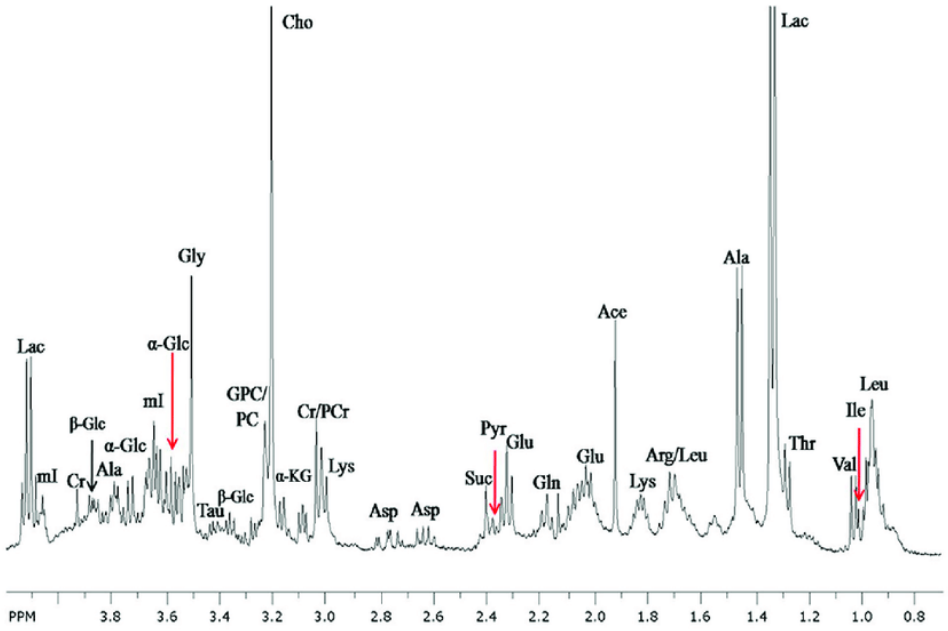


Adriannse et al. (2014) PLOS, 9 (7)

Imaging: spectroscopy

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy

Spectroscopy



Imaging: proton density

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy
  - proton density

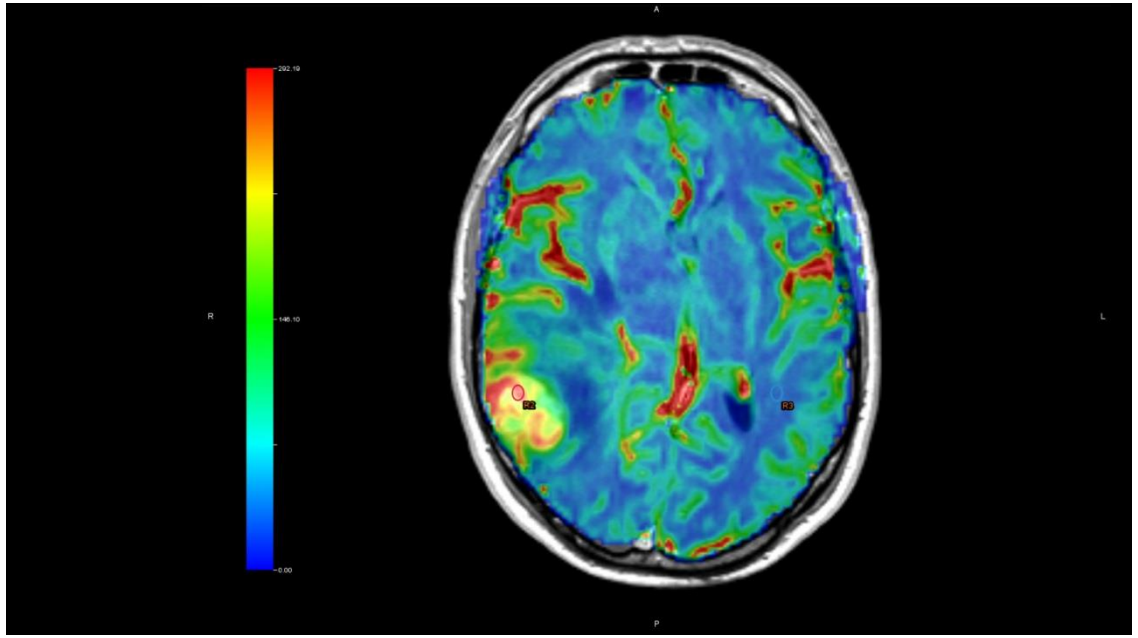
Proton density MRI

https://webpath.med.utah.edu/HISTHTML/NEURANAT/MRIPRA21.html

Imaging: perfusion

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy
  - proton density
  - perfusion

Perfusion imaging

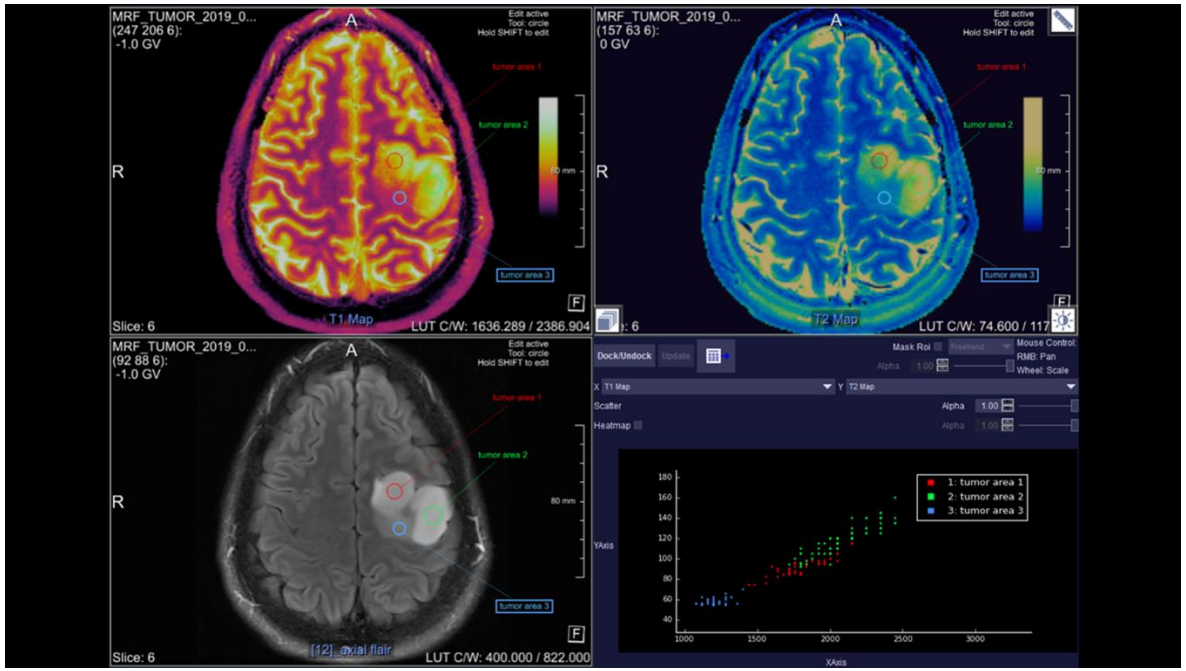


https://www.imagilys.com/perfusion-imaging-MRI

Imaging: fingerprinting

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy
  - proton density
  - perfusion
  - fingerprinting

MR Fingerprinting



https://www.siemens-healthineers.com/magnetic-resonance-imaging/options-and-upgrades/clinical-applications/mr-fingerprinting

Practical Study Example

- A multimodal study linking brain anatomy and function to Parkinson's disease outcomes
  - Motor tasks stimulating basal ganglia & motor putamen
    - e.g., direct hand movement (BOLD fMRI)
  - Substantia nigra assessment
    - grey matter imaging and segmentation (T1w)
  - WM lesions assessment (T2 FLAIR)
  - Substantia nigra near tract assessment (dMRI)

Discussion: Limitation, solutions, future directions

Limitations & Solutions

- MRI provides *approximations* of biological phenomena
- Biological phenomena are complex
  - Better models suitable for clinical data?
  - Call for multimodal MRI?
- Challenges with the signal

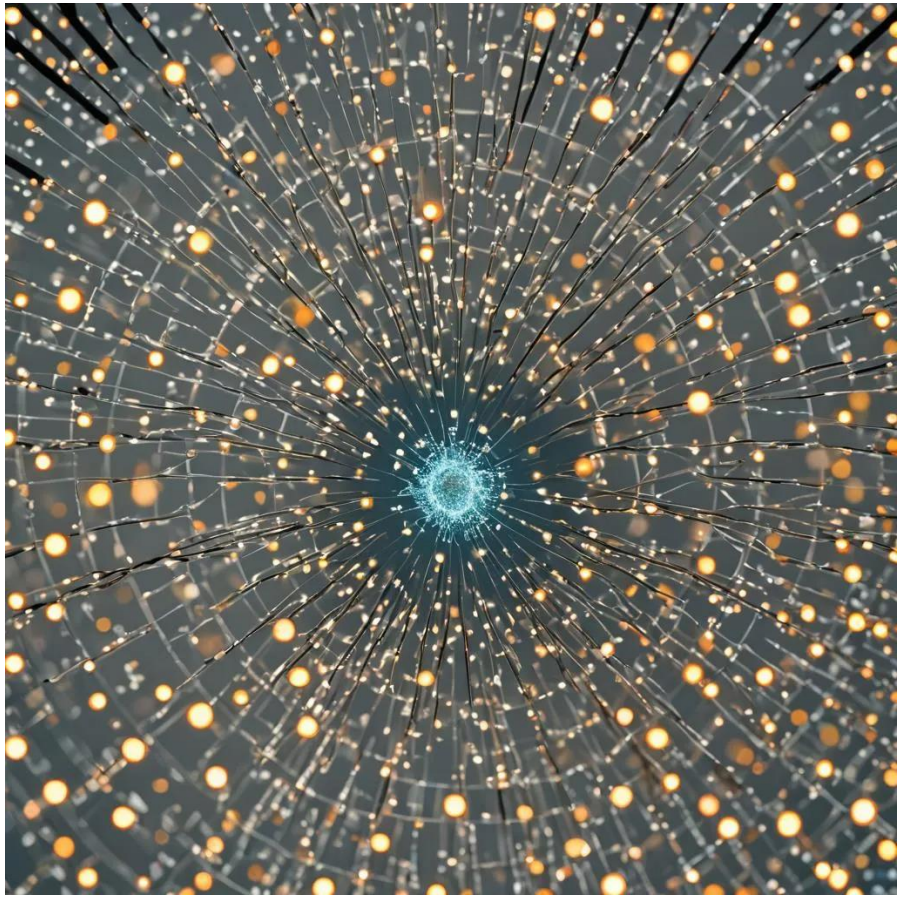


Image generated with NightCafe

Limitations & Solutions

- Reliability, replicability and even reproducibility issues (particularly fMRI)
  - The many decision points during the research process
  - Individual differences, variability
- A few solutions
  - Open Science
  - Large samples
  - Streamlined analyses
  - Multiverse analyses

Image generated with NightCafe

Future directions

- Portable, affordable low field scanners

Ultra-low field MRI magnet

https://www.nature.com/articles/d41586-023-00759-x

Future directions

- Portable, affordable low field scanners
- Ultrahigh fields & stronger gradients

Ultra-high field MRI magnet (10.4T)

https://twin-cities.umn.edu/news-events/worlds-largest-imaging-magnet-arrives-u-ms-center-magnetic-resonance

Future directions

- Portable, affordable low field scanners
- Ultrahigh fields & stronger gradients
- Treatment & diagnostic aid
  - MRI guided magnetic or current stimulation
  - Better surgical mapping
  - Automated diagnostic flagging

Transcranial Magnetic Stimulation (TMS)

https://awarehub.com.au/resources-2/transcranial-magnetic-stimulation/

Future directions

- Portable, affordable low field scanners
- Ultrahigh fields & stronger gradients
- Treatment & diagnostic aid
  - MRI guided magnetic or current stimulation
  - Better surgical mapping
  - Automated diagnostic flagging
- Surrogate markers of MRI

Pupillometry as MRI surrogate marker?

https://www.uio.no/ritmo/english/research/labs/fourms/online-courses/pupillometry/

Future directions

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- Surrogate markers of MRI
- Understanding basic phenomena such as ageing

Yet not fully understood phenomenon: ageing

Night Cafe

Future directions

- Portable, affordable low field scanners
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  - Better surgical mapping
  - Automated diagnostic flagging
- Surrogate markers of MRI
- Understanding basic phenomena such as ageing
- Biologically founded understanding of psychiatric (or generally) disease

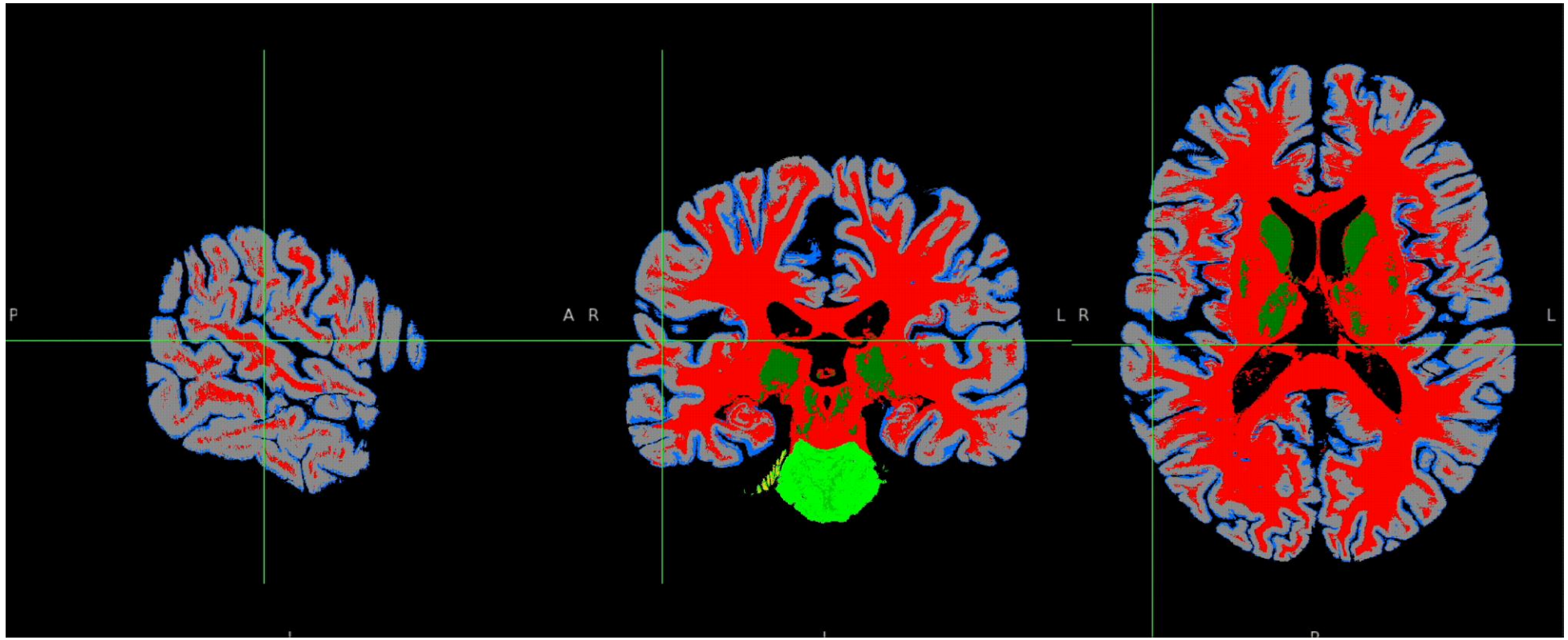
Our understanding of the biology of different disorders is yet limited

Night Cafe

Summary

- Chemical properties of tissue allow us to image the human body leveraging the magnetic resonance effect
- There are many sequences which provide proxies for more or less static phenomena (cellular structure vs blood flow)
  - Mesostructure: grey matter thickness, volume, area
  - Microstructure: in white matter
  - Proxies for neural activity: BOLD fMRI / blood flow
- These phenomena are extensively studied in different research fields

Thank you for your attention!



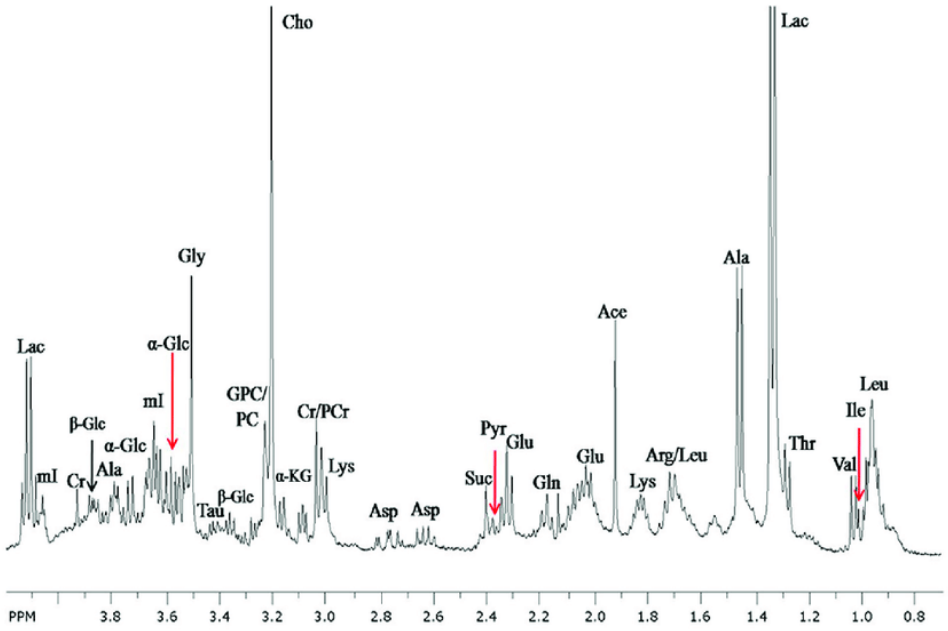
Data available from https://bigbrain.loris.ca

Supplement

Imaging: spectroscopy

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy

Spectroscopy



Imaging: proton density

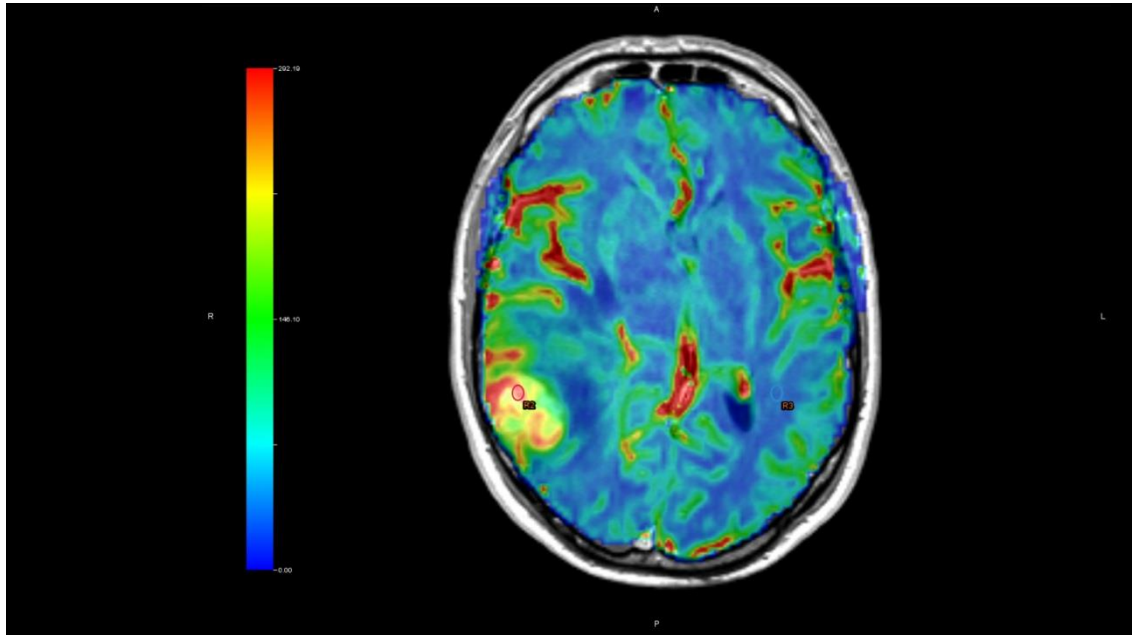
- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy
  - proton density

Proton density MRI

Imaging: perfusion

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy
  - proton density
  - perfusion

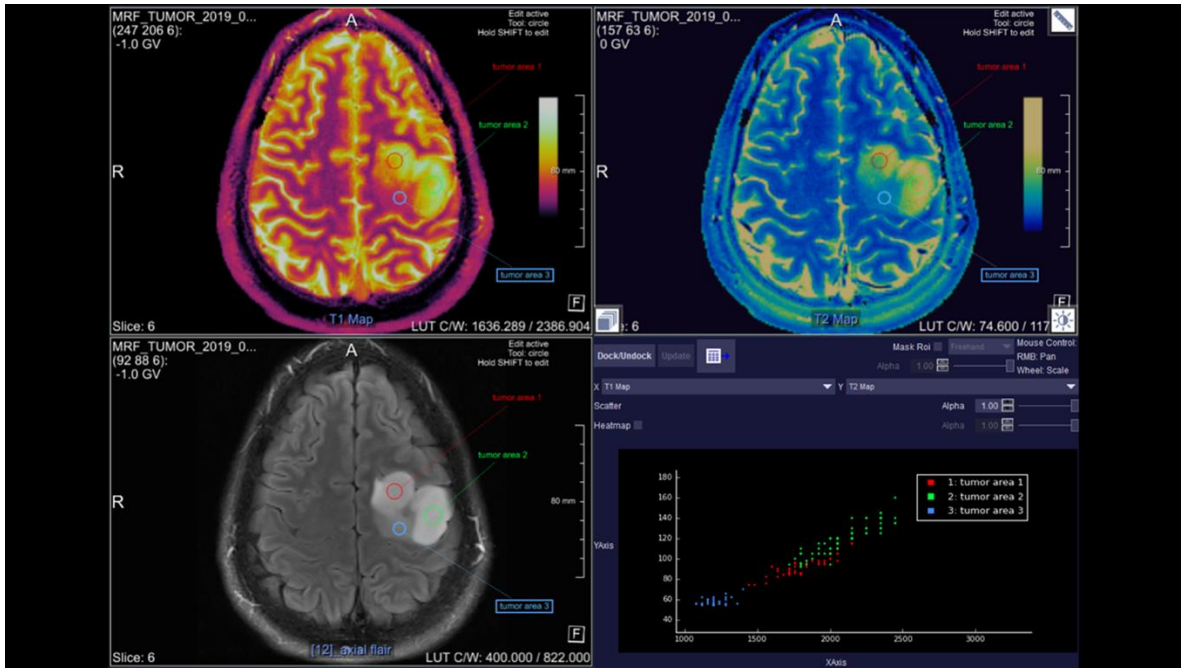
Perfusion imaging



Imaging: fingerprinting

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI
  - spectroscopy
  - proton density
  - perfusion
  - fingerprinting

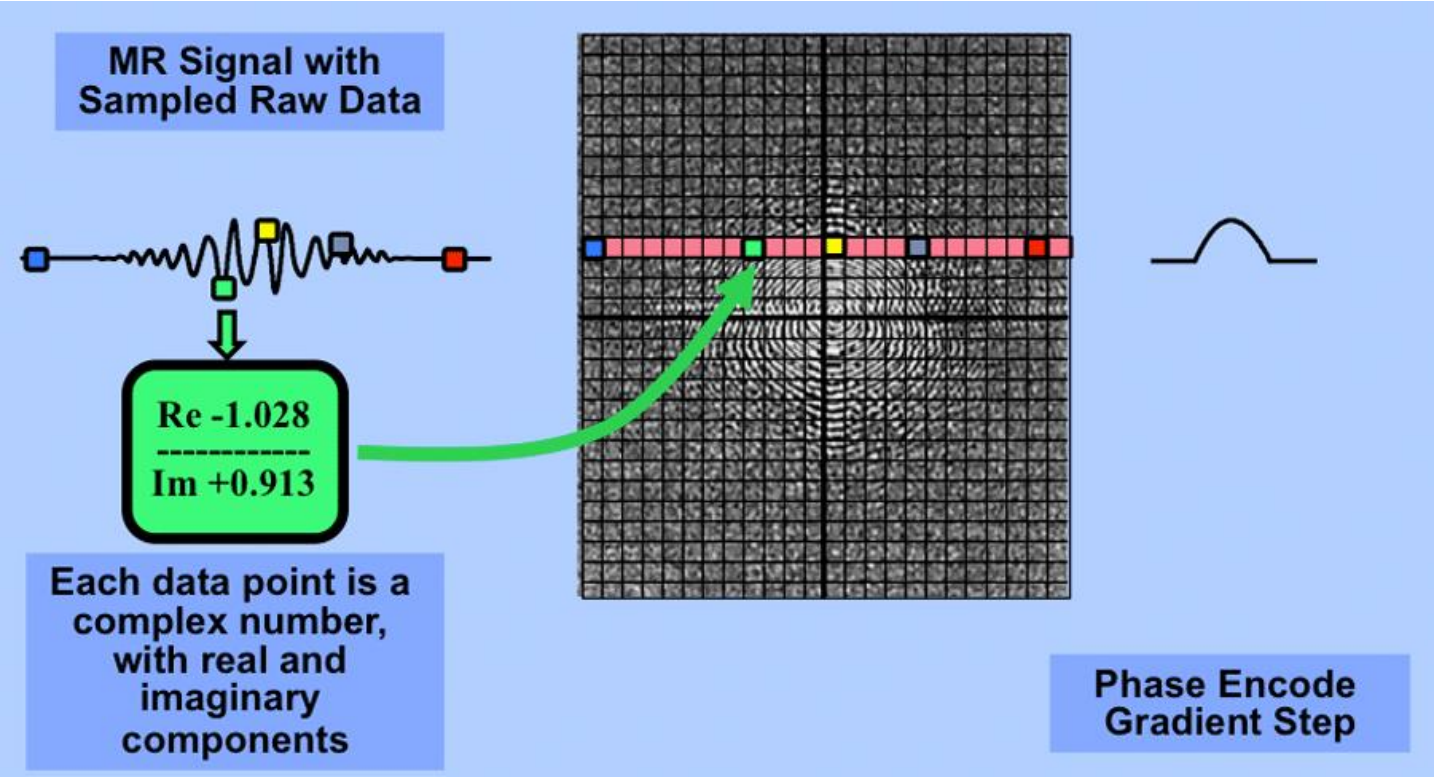
MR Fingerprinting



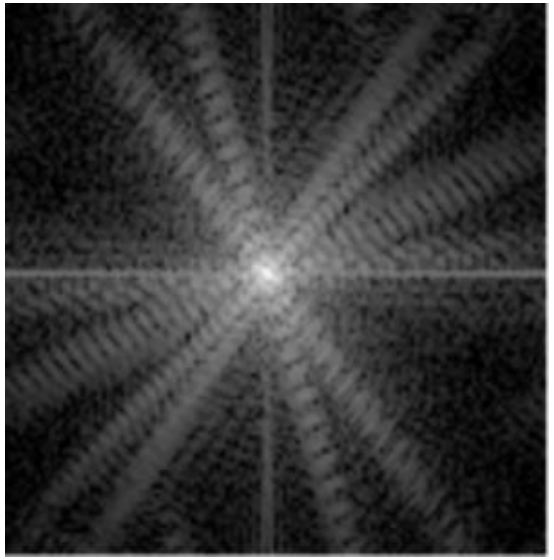
https://www.siemens-healthineers.com/magnetic-resonance-imaging/options-and-upgrades/clinical-applications/mr-fingerprinting

Fourier Transform

From signal to K-space



Kspace



https://mriquestions.com/why-signal-harr-k-space.html

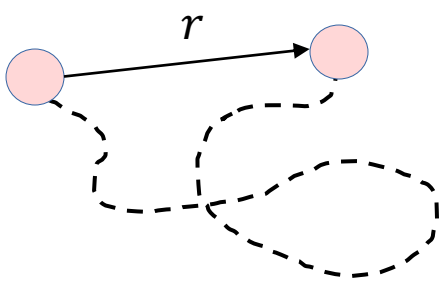
Diffusion: background

$$MSD(t) = 1/N*(r_1^2(t) + r_2^2(t) + \cdots + r_n^2(t)$$

Mean square displacement

Number of particles

Time dependent



Isotropic diffusion

Brown (1827) Edinburgh New Philosophical Journal;
Einstein (1905). Annalen der Physik

Diffusion: background

$$MSD(t) = 1/N*(r_1{}^2(t) + r_2{}^2(t) + \cdots + r_n{}^2(t)$$

$$MSD(t) = 6\mathrm{Dt}$$

Constant depending on the dimensions, here 3

$D_{iso} = 3\mu m^2/ms$

Example: Diffusion length: L(t) = sqrt(6Dt)

For t = 20ms: L = sqrt(6*3*20) = 19μm

Brown (1827) Edinburgh New Philosophical Journal;
Einstein (1905). Annalen der Physik

Diffusion: background

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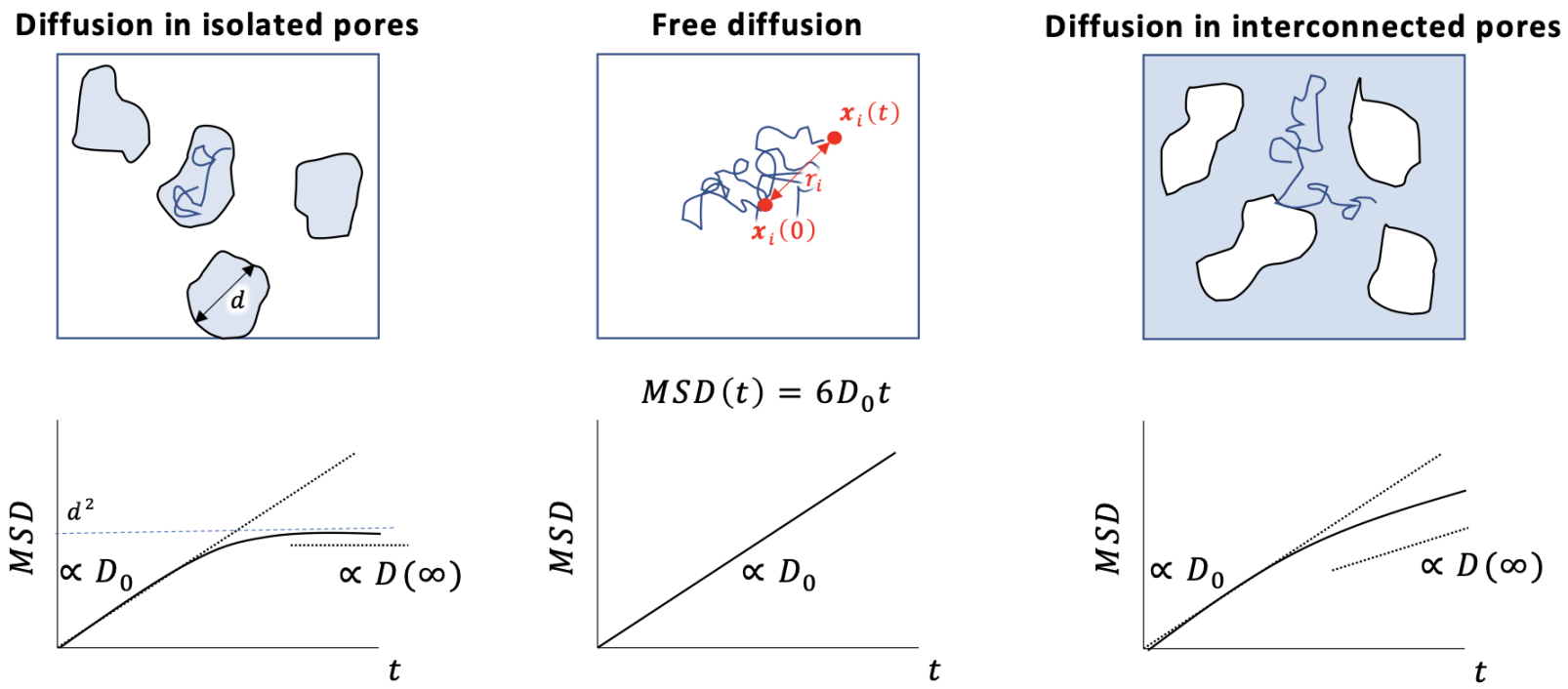

Callaghan (2011) Diffusion MRI

Diffusion signal

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    - fMRI

Estimating diffusion signal

$$S = S_0 e^{-bD}$$

Signal

Signal at baseline

b-value

Diffusion coefficient (area/time)

Stejskal & Tanner (1965). J Chem Phys

Equivalent to

$$D = -1/b * ln(S_{DWI}/S_0)$$

Diffusion coefficient

b-value

Signal of isotropic diffusion

Signal at baseline

$$b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3)$$

Gyromagnetic ratio

Amplitude

Gradient application time

Duration between gradients

Diffusion signal

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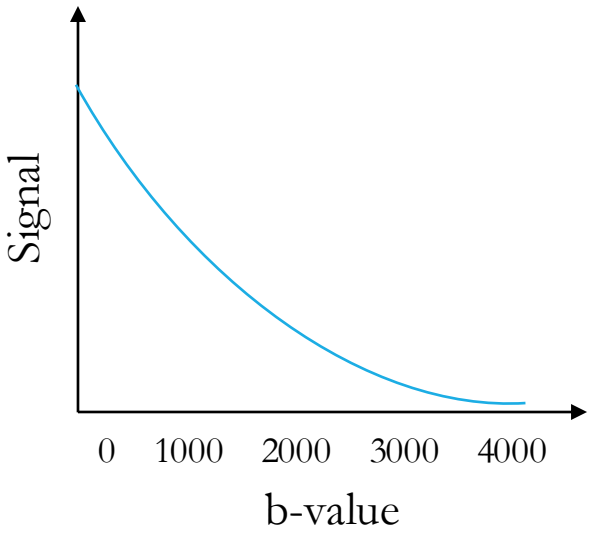

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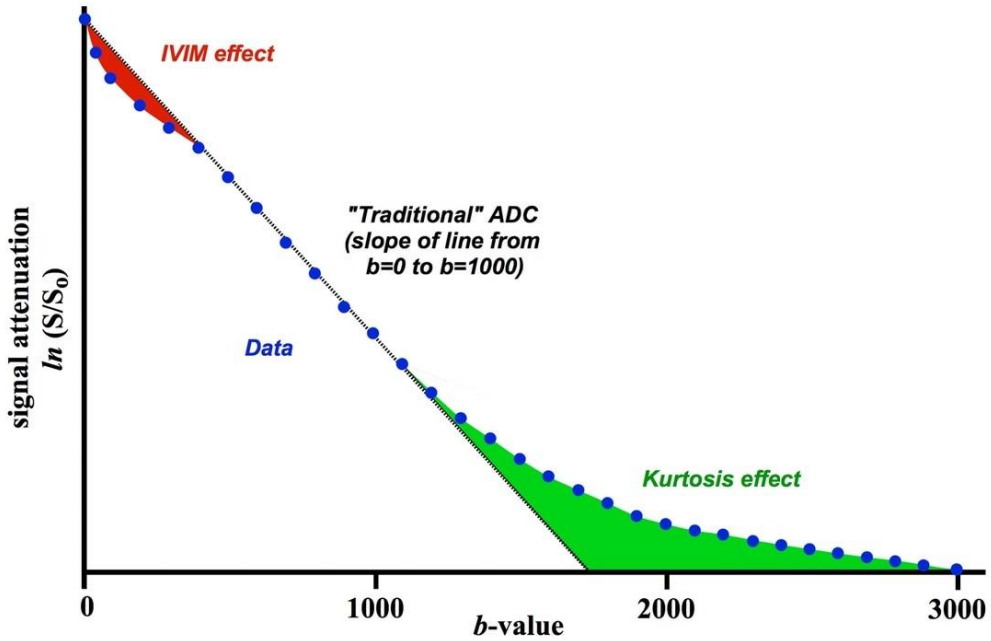


https://mriquestions.com/diffusion-kurtosis.html

b-value parametrisation

- TE and TR configurations can be used to obtain different contrasts
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI

$$b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3)$$

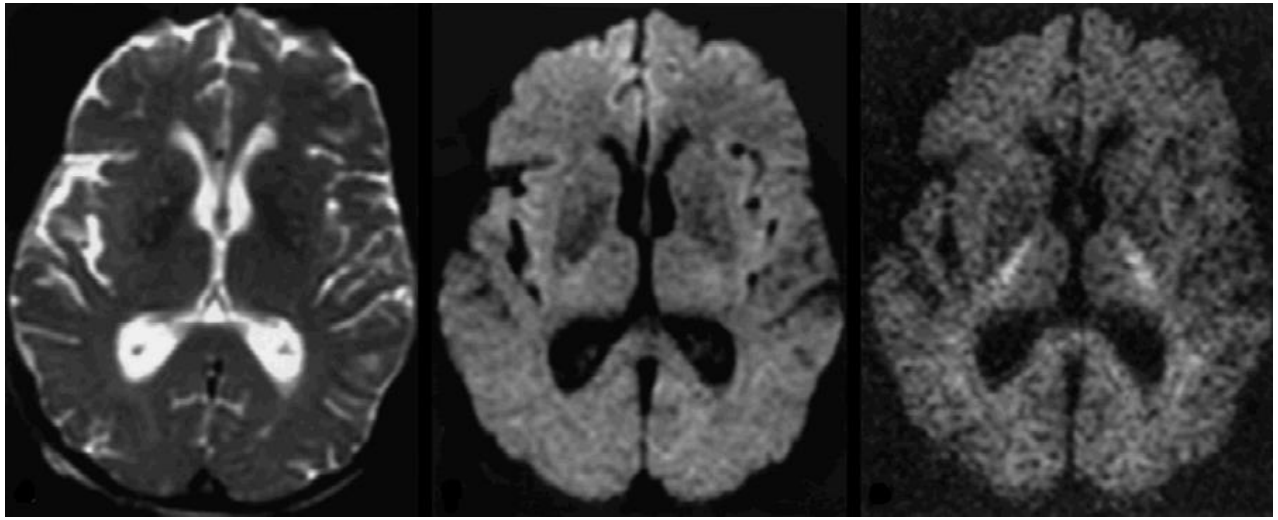
Gyromagnetic ratio

Amplitude

Gradient application time

Duration between gradients

b = 0, b = 1,000, b = 2,000



https://mriquestions.com/what-is-the-b-value.html

b-value parametrisation: *more practical*

- Imaging techniques
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI

0) Basic formula

$$b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3)$$

Gyromagnetic ratio

Amplitude

Gradient application time

Duration between gradients

1) For sinusoidal pulses

$$b = 4\gamma^2 G^2 \delta^2 (\Delta - \delta/4)/\pi^2$$

2) For trapezoidal pulses (ξ is the rise time)

$$b = \gamma^2 G^2 [\delta^2 (\Delta - \delta/3) + \xi^3/30 - \delta\xi^2/6]$$

3) For single long gradient G

$$\gamma^2 G^2 TE^3/12$$

4) Fast spin echo with n echoes

$$b = \gamma^2 G^2 TE^3/12n^2$$

b-value parametrisation: *more practical*

- Imaging techniques
  - T_1-weighting
  - T_2-weighting
  - T_2*-weighting
    - diffusion-weighting
    - fMRI

Introducing kurtosis into the diffusion equation

$$\ln S(b) = \ln S_o - bD + 1/6 b^2 D^2 K + \ldots$$

Future direction for dMRI

- Double diffusion encoding
- Stronger gradients, e.g., Connectome scanner