



Magnetic Resonance Imaging

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

PHD TRIAL LECTURE
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University of
Applied Sciences



- Respected members of the committee, institute leader, dear colleagues and friends.
- I will now present to you the trial lecture entitled “Magnetic Resonance Imaging: what it is and how it is used as a research tool”

Contents

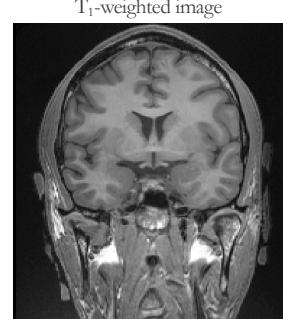
1. How Magnetic Resonance Imaging (MRI) works
 1. The different parts of an MRI system
 2. Basic principles of MRI
2. Different imaging techniques & how they are used in research
 1. T1-weighted
 2. T2-weighted
 - FLAIR
 3. T₂*-weighted
 - Diffusion MRI
 - Functional MRI
3. Discussion

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- I will walk through the **different parts** of an MRI system and touch on the **basic principles** of MRI
- Then, I will present **different imaging techniques** and how they have been used as **research tools**
- I will finish with discussing limitations, future directions.

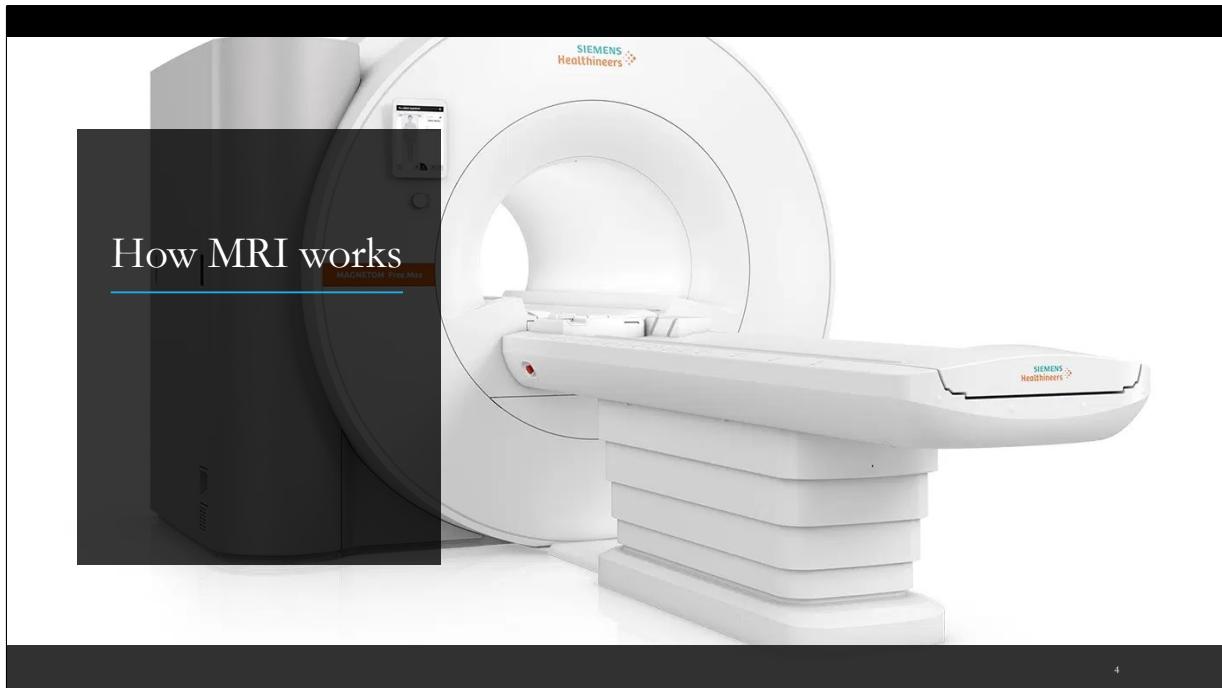
The goal of MRI

- 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



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

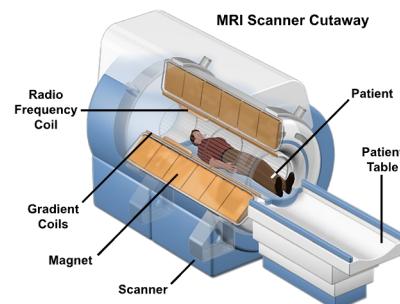
- MRI = imaging technique, used in the clinic and research
- **The goal of MRI** is to produce accurate pictures of the body and brain
- More specifically, MRI is used to establish **signal which reflect the structure or anatomy and biochemical processes of what is imaged**
 - In our case, that would be human tissue
 - As an example, see a T1w image on the right, an alrounder sequence showing good tissue contrasts
- This is **particularly useful** when attempting to image **in-vivo**, the living being
- MRI offers also **superior resolution** and many **more contrasts** compared to other techniques such as X-ray or computed tomography
- And there is **no ionised radiation** necessary, which can be harmful for humans



(Photo: Siemens MAGNETOM Free.Max 0.55T <https://www.siemens-healthineers.com/en-uk/magnetic-resonance-imaging>)

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/>

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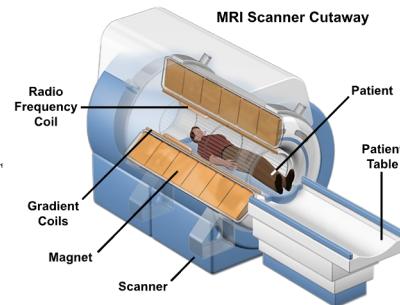
- A **strong magnet** is the heart of the MR system.
- **Static magnetic field** produced by this magnet is called **B₀**
- The size of an MR system is expressed in terms of its operating magnetic field strength
- In the clinic in the Western world, we use high field MRI at around 1.5-3T
- As a comparison: a 3T magnet is 60,000 times the strength of the earth's magnetic field
- **EXTRA INFO:**
- The scientific name of field strength is magnetic flux density or induction, and its

unit is the tesla (T).

- Another unit is gauss (G) as a measure of field strength.
- $1\text{T} = 10\,000 \text{ gauss}$, i.e. 1 G equals 0.1 mT (milli- tesla).

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



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

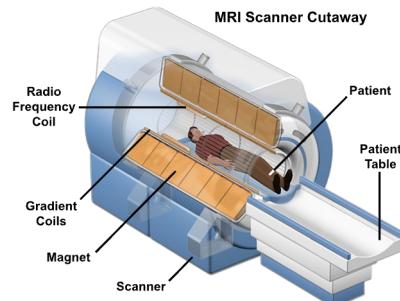
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- Different types of Magnets
 - Superconducting & permanent magnets are always on
 - Electromagnets can be turned off with electricity
 - Superconducting magnets need traditionally helium as cooling agent (for superconducting)
- If the windings heat up and the magnetic field collapses, the helium boils into gas and is released

The different parts of an MRI system

• Radiofrequency Coils

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



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

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• Radiofrequency Coils

- Signal from tissue is generated in response to radiofrequency pulses (oscillating magnetic field called B_1),
- Transmitter coils generate the radiofrequency pulse
- Receiver coils record the signal

• Specific coils for head and body, but also for other body parts such as **spine, neck, knee, wrist, shoulder, or breast**

- Tighter coils produce better signal to noise ratio

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

• 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://lifconthebluehighways.com/2013/04/20/faradays-cage/>

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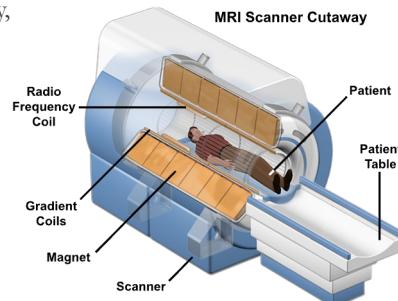
• Faraday cage / Shielding

- **MRI signal is weak** and sensitive to **electrical interference**
- Hence, scanner room needs electromagnetic **shielding**
- This can be reached using a Faraday's cage which conducts electricity towards the ground
- In the example of the scanner that would mean that no outside electromagnetic disturbances reach the receiver coil

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)



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

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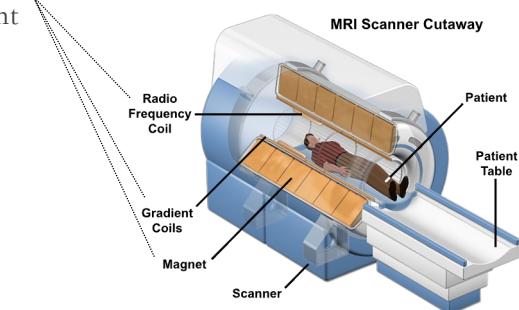
- Gradient coils

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

- **Magnitude of the gradient magnetic field** is in the region of tens of mT, **much smaller than the main static magnetic B_0 field**.
- There is **one set of gradient coils for each direction**, x, y, z, built into the bore of the magnet.
- The **gradients are applied repeatedly in a carefully controlled pulse sequence**.
- They generate loud tapping, clicking or higher pitched beeping sounds during scanning.

The different parts of an MRI system

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



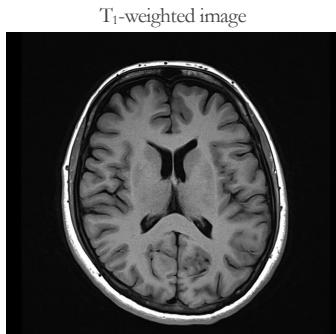
<https://nationalmaglab.org/magnet-academy/read-science-stories/science-simplified/mri-a-guided-tour/>

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- IN SUMMARY
- We utilize **several magnetic fields** in the scanner (generated by the **coils** and the **magnet**)
- With those we **leverage the magnetic properties of different atomic nuclei**,
 - >> which is why MRI was also called nuclear magnetic resonance imaging
- But more on these effects in the following slides

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



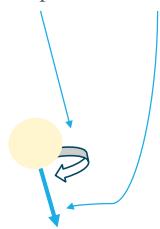
McRobbie et al. (2017). MRI from Proton to Picture.

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- Namely, we use pulse sequences to produce different contrasts
- Pulse sequences consist of several radio frequency pulses
- In the **image on the right**, you see that different tissue types are highlighted by **different contrasts**
 - for example, cerebrospinal fluid appears black
 - grey matter, the cortical ribbon, which contains the cell bodies of the neurons appears darker than white matter, which contains more fatty, myelinated axons of the neurons

Basic principles: MRI physics

- Main principle
 - Protons possess spin and orientation



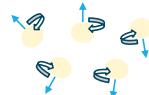
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- The reason why we use radio frequency pulses is that **protons possess spin and magnetic momentum**
- This spin or precession can be manipulated, once protons gain magnetic momentum in an external magnetic field

Basic principles: MRI physics

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

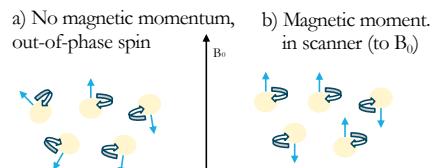
a) No magnetic momentum,
out-of-phase spin



- Outside the scanner, protons are in equilibrium
 - they spin out of phase and possess no magnetic momentum

Basic principles: MRI physics

- Main principle
 - Protons possess spin and orientation
 - These are at random outside the scanner (a)
 - Protons obtain magnetic momentum in magnetic field (b)

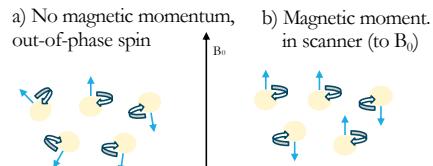


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- In the scanner, protons “align” along the scanner’s magnetic field lines and obtain magnetic momentum
 - They become microscaled dipolar magnets
 - This leads to a magnetisation vector along the magnetic field
- Protons still spin out of phase

Basic principles: MRI physics

- Main principle
 - Protons possess spin and orientation
 - These are at random outside the scanner (a)
 - Protons obtain magnetic momentum in magnetic field (b)

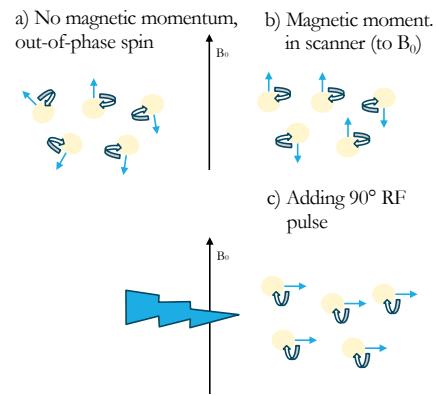


$$\omega = \gamma B_0$$

- The spin or **precession** can be described by the **Larmor equation**
 - This entails the **Larmor frequency**, the **gyromagnetic ratio**, and the **field strength**
 - Different isotopes such as hydrogen or sodium possess different gyromagnetic ratios
 - which allows different imaging
 - Once we know the protons' frequency, also called **resonance condition**, we can manipulate them with the right **radio frequency pulse**
 - Importantly different tissue types have different resonances, which allows to weight images to achieve better contrasts for certain tissue types or suppress others

Basic principles: MRI physics

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

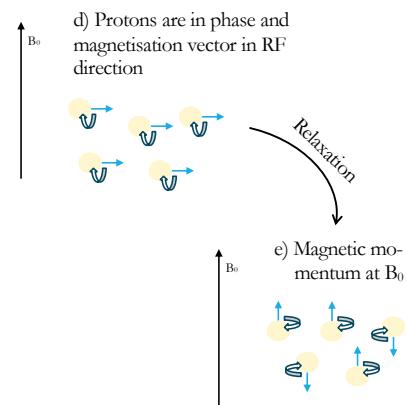


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- A 90 degree radio frequency allows to
 - flip magnetisation vector (which is the sum of the magnetisation across protons) and
 - synchronise spin (which is the resonance of protons with each other)

Basic principles: MRI physics

- Main principle
 - Protons possess spin and orientation
 - These are at random outside the scanner (a)
 - 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)
 - Protons precessing out of phase and their magnetisation vector moving back to their equilibrium at B_0 forms signal (d-e)



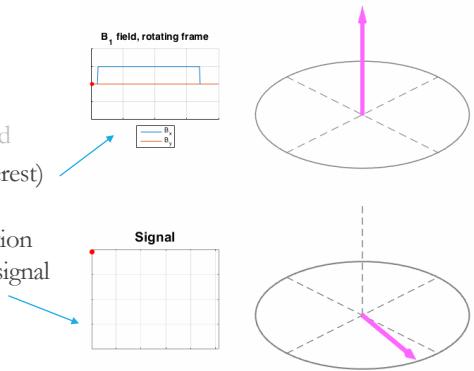
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- Then: Protons precess out of phase and their magnetisation vector moves back to B_0 , the tissue relaxes
- This process from (d-e) can be leveraged to form the signal as protons emit energy when returning to equilibrium (both in terms of spin and magnetisation)
- Additionally, **protons do so differently when being free or bound in different tissues**, leading to **different tissue relaxation times**

Basic principles: MRI physics

- Main principle

- Protons possess spin and orientation
- These are at random outside the scanner
- Protons obtain magnetic momentum in magnetic field
- Radio frequency (RF, resonating with protons of interest) allows to flip magnetisation vector and in-phase spin
- Protons precessing out of phase and their magnetisation vector moving back to their equilibrium at B_0 forms signal (d-e)



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

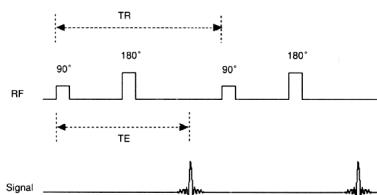
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- Importantly, this process does not only happen in 2 dimension, but 3.
- The actual influence of the RF pulse in the net magnetisation vector looks like this

Basic principles: key parameters

- 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

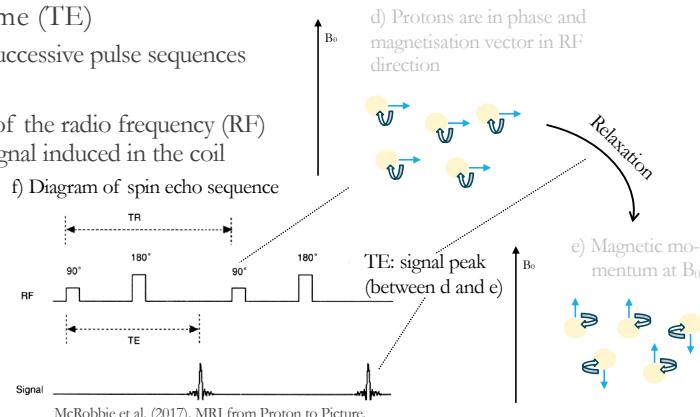


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- To control these processes we use two key parameters of sequences
- This means, we are talking not talking about single pulses anymore, but a sequence, which can be seen below
 - We see the sequence of pulses in the top row and signal in the bottom
- 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

Basic principles: key parameters

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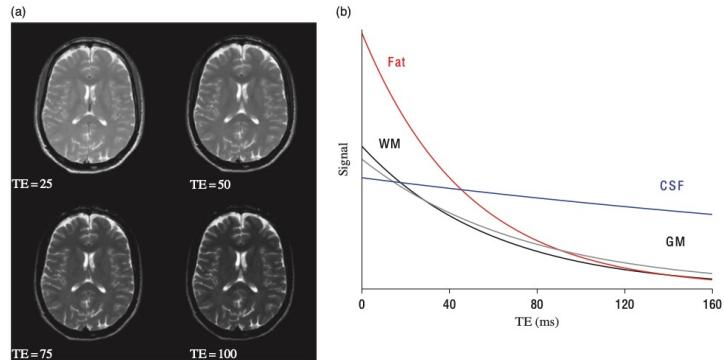


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- Practically speaking, when applying a 90 degrees radio frequency pulse, we then flip the magnetisation vector 90 degrees
 - We can do that several times
 - The time in between excitation pulses is the repetition time (here we see in addition 180 degree refocusing pulses)
 - The time from excitation pulse to peak signal is the echo time

Basic principles: key parameters

- 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



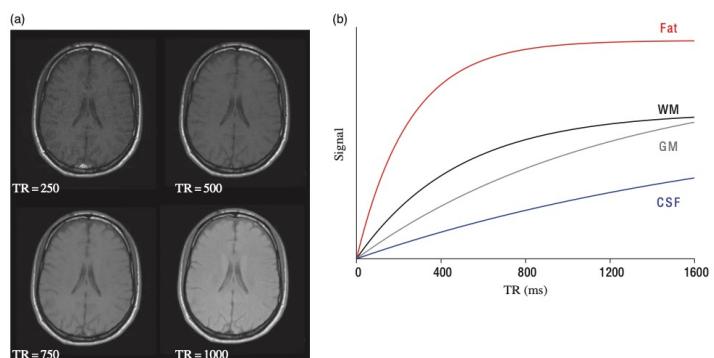
McRobbie et al. (2017). MRI from Proton to Picture.

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- Different TEs and TRs produce different contrasts as tissues' relaxation times vary
- Here we see that when holding the repetition time constant at TR = 1500ms, signal intensities decay with higher TE
- That is described by
 - signal intensity changes in a slice on the left
 - and a graph with the signal strength on the y and TE on the x axes
- WM = white matter
- GM = grey matter
- CSF = cerebrospinal fluid

Basic principles: key parameters

- Different TEs and TRs produce different contrasts as tissues' relaxation times vary
- Example (right): Varying TR while keeping TE constant at 10 ms
- Signal *increase* over time

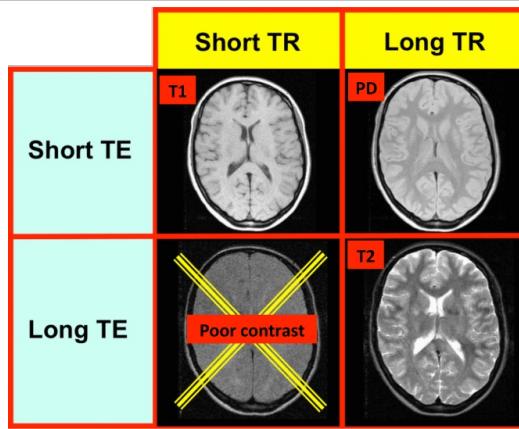


McRobbie et al. (2017). MRI from Proton to Picture.

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- When holding TE constant at 10ms instead, we see the signal increase with increasing repetition time across tissue types

Varying echo and repetition times

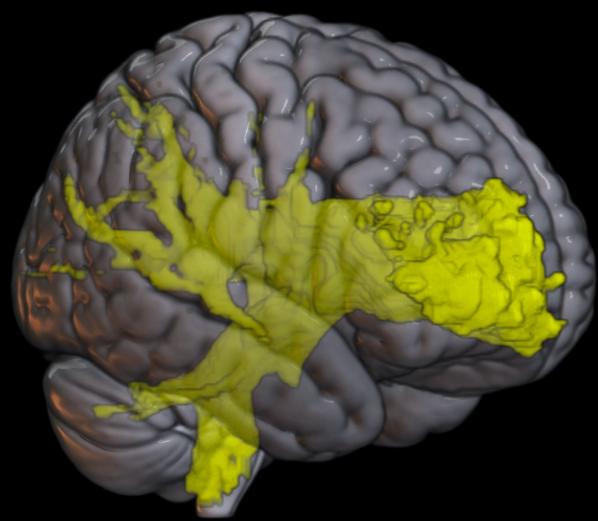


<https://mriquestions.com/image-contrast-trte.html>

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- Just a simplified overview, when varying the length of TE and TR, we can establish different contrasts by weighting signal
- So, here you see some of the most commonly used sequences

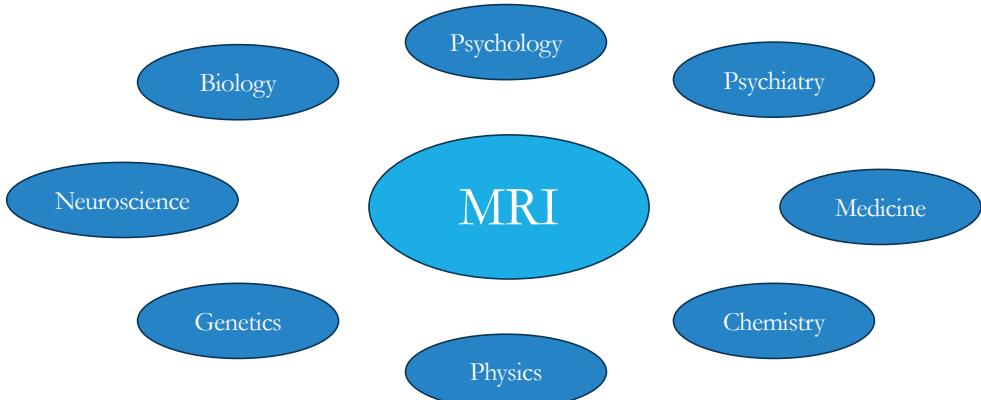
Different imaging
techniques & how
they are used in
research



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- Now, let's take a closer look at some of the more commonly used imaging techniques used in research

MRI is applied in multiple fields



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- MRI is being used in multiple fields and has contributed to a deeper understanding of multiple phenomena in fields from genetics to medicine

Imaging techniques used in research

- MRI possible for the entire body, here, I will focus on the brain
- Most research focuses on quantifiable 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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- MRI possible for the entire body, here, I will focus on the brain
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 - or more processed features /estimates of tissue properties, e.g. cortical thickness
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Imaging techniques used in research

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 - 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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- This usually requires different processing steps, including
 - the removal of noise and artifacts
 - Bringing the images into a standardized space and warping them to make them comparable across participants

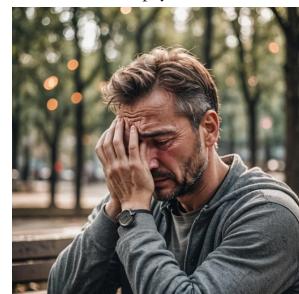
Imaging techniques used in research

- 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

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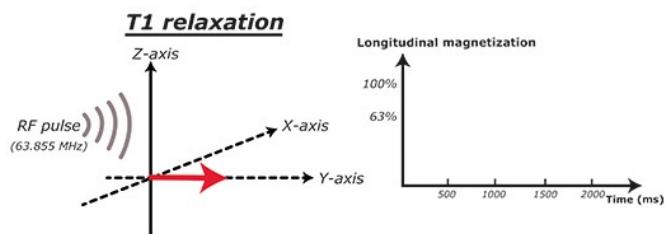
- Only most recently, population scale brain MRI is available
 - That means, that we can now start exploring small effects or effects which show large variability
 - Genetics
 - Different psychiatric disorders
 - Etc.
- In the following, I will present some of the most commonly used imaging techniques and some state-of-the-art analysis approaches used on the resulting data
- Note that this is not an extensive list of neither imaging techniques nor respective studies

Imaging: T₁-weighted

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting



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



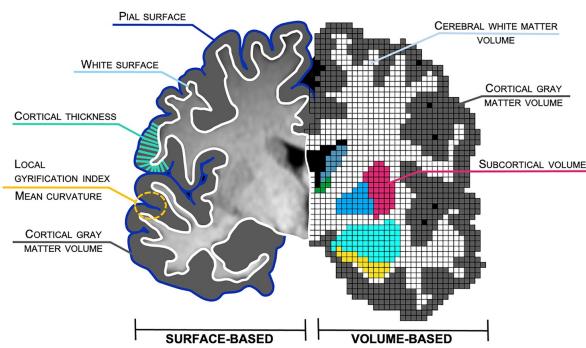
<https://www.radiologyexpert/en/modules/mri-technique-introduction/mri-technique/>

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- As mentioned, TE and TR configurations can be used to obtain different contrasts
 - These depend on which relaxation times are emphasised
 - We can start with T₁ weighted imaging, see an example on the left
 - Water has low signal, high-density tissue high signal (as shown in the figure on the left)
 - Here we are interested in the net magnetisation vector which is flipped from B₀, the static magnetic field from the z- to the y-axis
 - (let this be the result of a 90 degree RF pulse)
 - The magnetisation vector can be seen graphically on the left part of the right figure
 - The time course of this process on the right
 - The vector then recovers by protons returning to their equilibrium
 - 1 T₁ has passed at 63% recovery >> Why 63%? This is because the relaxation proceeds slower and slower, so 63% is a useful measurement time

Imaging: T₁-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)

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- As a next step after image acquisition and corrections, for example for motion artefacts ...
- Most commonly, images are being reconstructed using either surface or volume based methods
- Surface-based estimations are based on the surfaces of the grey and white matter (left half of figure)
 - Allow to estimate:
 - Surface area
 - Thickness
 - Volume
- For volumetric measures (right half of the figure)
 - 1) segment different tissue types and
 - 2) estimate then the volume of these regions

Imaging: T₁-weighted

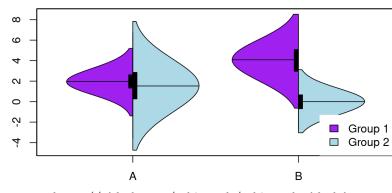
- Research application:
 1. Image reconstruction
 2. Feature extraction
 3. Computation of statistics
 - Voxel to whole brain level

Voxel-level analysis highlighting significant clusters on the cortical surface



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

Group differences in a single feature



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

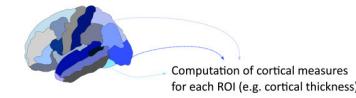
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- Now, one can compute statistics,
 - such as simple group differences in a metric averaged across a region or the whole brain, as in the top right
 - For example, we can compare the cortical volume (on an arbitrary scale on y-axis) of patient groups receiving different treatments (on the x-axis)
 - Another approach is to create voxel-level analyses based surface maps of significant voxels
 - These voxels could show significant brain asymmetries or differences between two groups of subjects

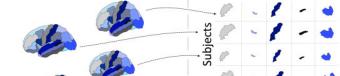
Imaging: T₁-weighted

1. Estimation of covariance matrices

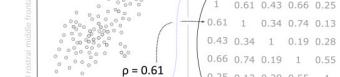
A Brain parcellation into regions of interest (ROI)



B Multiple subjects



C Brain areas



D



$$\rho = 0.61$$

E

$$\begin{pmatrix} 1 & 0.61 & 0.43 & 0.66 & 0.25 \\ 0.61 & 1 & 0.34 & 0.74 & 0.13 \\ 0.43 & 0.34 & 1 & 0.19 & 0.28 \\ 0.66 & 0.74 & 0.19 & 1 & 0.55 \\ 0.25 & 0.13 & 0.28 & 0.55 & 1 \end{pmatrix}$$

2. Examining overlaps of matrices

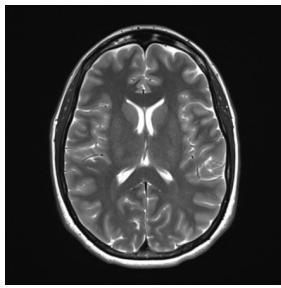
Carmon et al. (2023), NeuroImage, 220 (117104)

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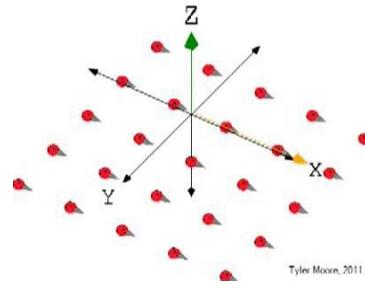
- Another way to look at the data are covariance matrices
- Here we treat each brain region as a column and each subject as a row in a matrix
- For the matrices, we can estimate the covariance
- We can do this for different samples
 - For example healthy controls vs dementia patients
- From the resulting matrices, we hope to learn something about the differences in structural integrity
- Yet, the biological meaning of these analyses is still discussed

Imaging: T₂-weighted

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting



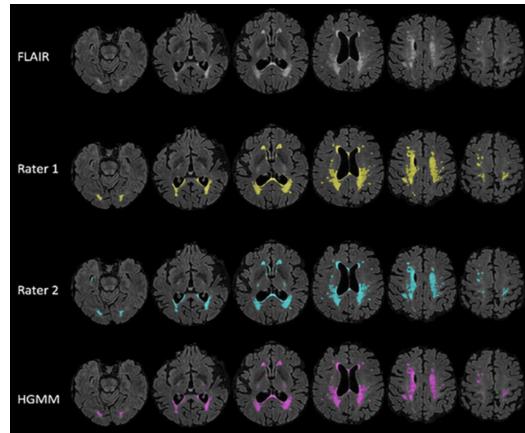
McRobbie et al. (2017), MRI from Proton to Picture.



- T₂ focusses on protons spinning out of phase, with one T₂ indicating that the **transverse magnetization dropped to 37% of its initial size**
- After the RFpulse the protons spin in phase and then slowly get out of phase (as shown in the figure on the right)
- Water has high signal, high density tissue such as the WM has low signal (as shown in the figure on the left)

Imaging: T₂-weighted

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - Fluid attenuated inversion recovery (FLAIR) MRI
- Algorithms applied to FLAIR allows to automatically quantify white matter hyperintensities
 - Hyperintensities can be interpreted as lesions



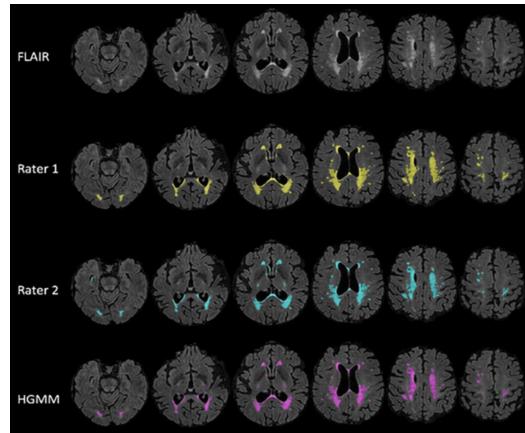
Igwe et al. (2022) IJPSR, 13(2)

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- Research example for T₂-weighted MRI is fluid attenuated inversion recovery (FLAIR) MRI
 - The **long inversion time** allows to **suppress cerebrospinal fluid**, making **fluids appear dark**, and **GM brighter than WM**
- **several algorithms** have now been established to **automatically quantify white matter hyperintensities** from FLAIR images
 - Hyperintensities can be indicative of lesions
 - Lesions appear in several disorders, such as epilepsy and multiple sclerosis
 - Also useful to identify **strokes, tumours or abscesses**
 - Also part of ageing

Imaging: T₂-weighted

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - Fluid attenuated inversion recovery (FLAIR) MRI
- Algorithms applied to FLAIR allows to automatically quantify white matter hyperintensities
 - Hyperintensities can be interpreted as lesions



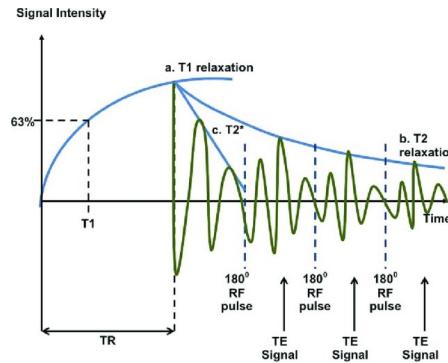
Igwe et al. (2022) IJPSR, 13(2)

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- On the right you can see the labelling performance of an algorithm
- hyperintensities in the bottom row, compared to experts in the rows above
- The top row shows the raw image
- The number and volume of the hyperintensities can be used to compute statistics

Imaging: T_2^* -weighted

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



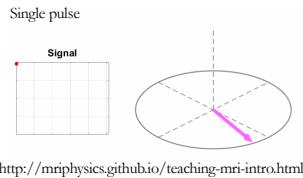
Currie et al. (2012) Postgr. Med. J., 89 (1050)

36

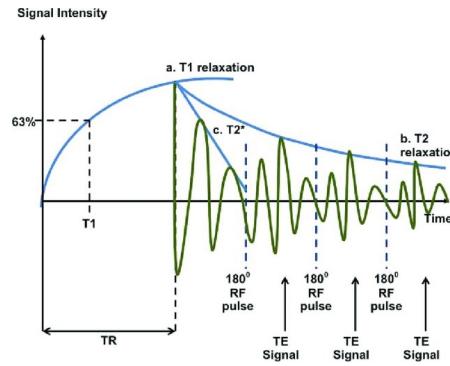
- Similar to T_2 -weighting, one can also weight the immediate T_2 signal decay to obtain T_2^*
- Let's look at the signal in a pulse sequence
- This is useful as the signal decreases exponentially right after the initial RF pulse
- So, what we see here on the right are the tissue relaxation curves indicated by the signal intensity on the y-axis and time on the x
 - A) T_1 curve
 - B) T_2 curve
 - C) T_2^* curve when not using 180 degree refocussing pulses

Imaging: T_2^* -weighted

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



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



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

- To put this into context, we can again look at single pulse, where we see the makeup of the signal

Imaging: T₂*-weighted

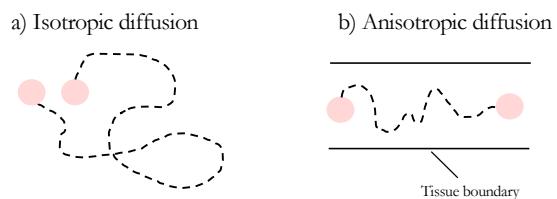
- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI

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- With T₂*-weighted imaging, one can focus on fluid dynamics:
 - Diffusion MRI
 - map cellular structures
 - especially microstructure is interesting
 - Susceptibility and functional MRI
 - map e.g. blood flow

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



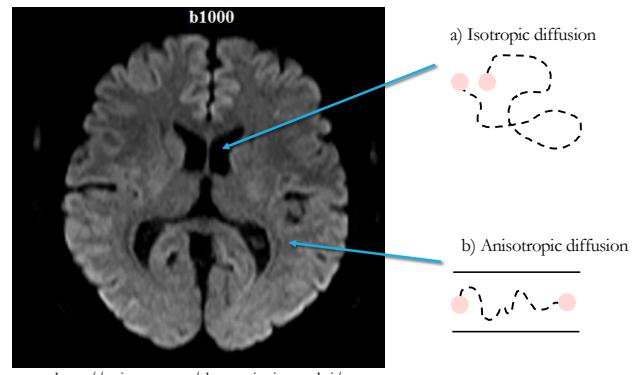
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- Let's start with diffusion MRI
- Diffusion MRI leverages the diffusion of water molecules
- In water, molecules move unrestricted, also called isotropic
- In tissue, molecules move along the cellular structures, also called anisotropic
- The catch: although we measure on the scale of mm, particles move on the scale of micrometers, allowing microstructure imaging

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

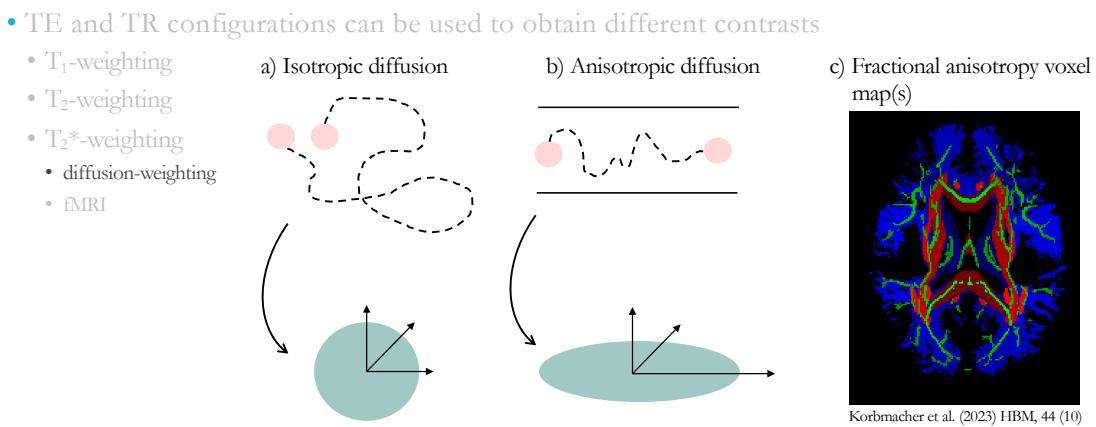


<https://mrимaster.com/characterise-image-dwi/>

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- To image diffusion, we attenuate the T_2^* signal
- The more easily water can diffuse the less initial T_2^* signal will remain.
- For example, water within the CSF can diffuse very easily, so very little signal remains, and the ventricles appear black.
- For diffusion MRI, we take images from several directions over time to make sure to capture the water molecule movement
- This makes diffusion MRI particularly useful to map white matter

Imaging: diffusion-weighted (T_2^*)



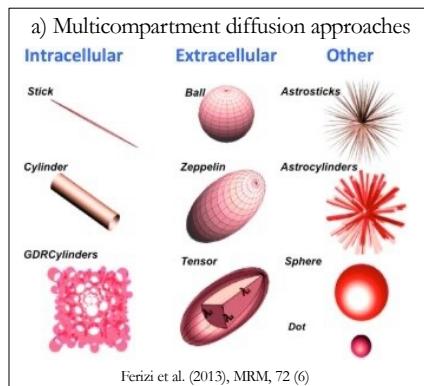
- From the diffusion images, one can **estimate parameters applying different diffusion approaches**
 - For example one can make **assumptions** about the **geometry** of the underlying tissue
- By showing diffusion processes, these maps can **give indications about the organisation of tissue**
- In **figure (c)** we see for example diffusion indicated by a **tensor fitted to each voxel**, which we can describe by a metric called fractional anisotropy or FA
- A **tensor has a dominant direction when** diffusion is restricted/**anisotropic** (b) or more circular when isotropic (a)
- For statistics, ...
 - We can for example restrict WM probabilistically to only encompass areas, where we can be more certain that there is white matter across people
 - This would be the thinner regions, in the image, whereas thicker means less restricted
 - We can again average or do voxel-based analyses, which allows to **compare different groups or run associations**

- **For example**, we know that **white matter deterots during ageing, and potentially even more so when cardiometabolic disorders are present**

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



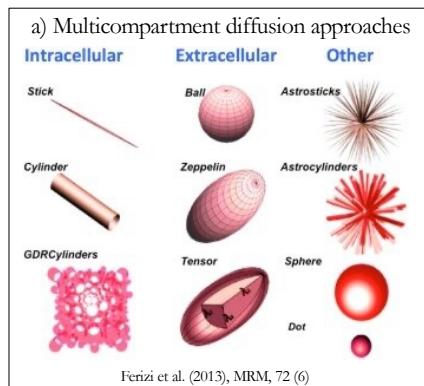
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- With the appropriate data, we can extend the idea of tensor fitting & model different tissue compartments
- For example we can assume that diffusivity differs within compared to outside the neurons' axons (a)
- We use the different shapes presented here to describe the tissue
- For example, diffusion within an axon can be modelled by
 - a stick or cylinder,
 - and outside spherical or
 - with astro-shapes or a dot for nuclei

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



White matter is not a collection of cylinders

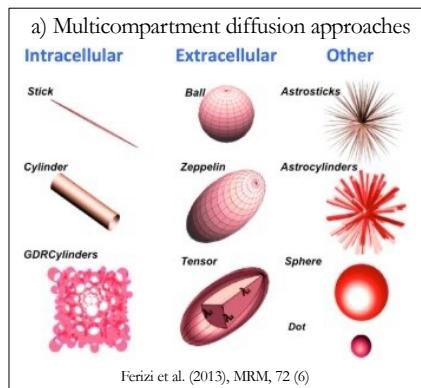


- The reason for this is that tissue is not homogenously consisting of white matter with a simple diffusion direction

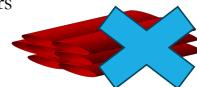
Imaging: diffusion-weighted (T_2^*)

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

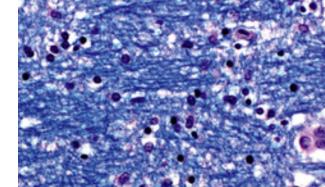
- T_1 -weighting
- T_2 -weighting
- T_2^* -weighting
 - diffusion-weighting
 - fMRI



White matter is not a collection of cylinders



White matter histology



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

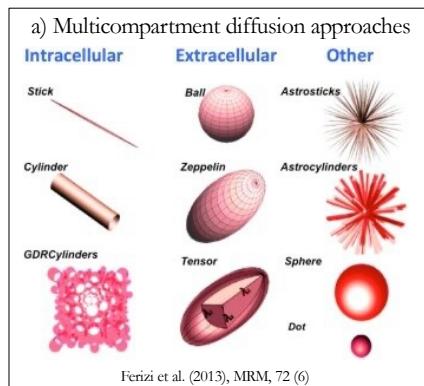
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- Instead, there are **multiple cell bodies and tissue types included in one voxel**
- For example, when using **staining in histology of white matter**, we can here see **the nuclei in dark blue**
- So, there are **cell bodies right in the white matter**

Imaging: diffusion-weighted (T_2^*)

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

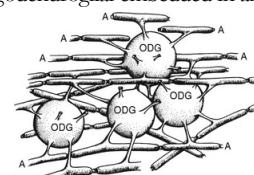
- T_1 -weighting
- T_2 -weighting
- T_2^* -weighting
 - diffusion-weighting
 - fMRI



White matter is not a collection of cylinders



Oligodendroglial embedded in axons



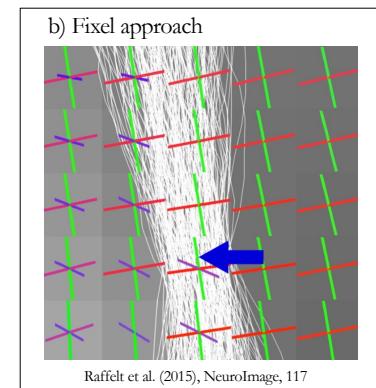
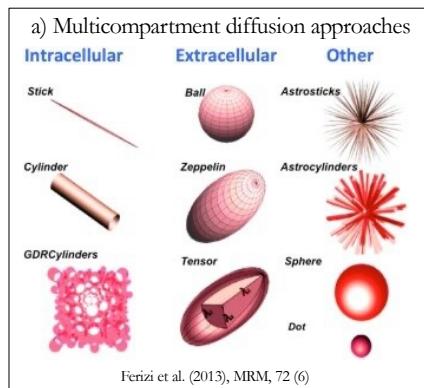
<https://radiologykey.com/white-matter/>

- We have to conclude that a very **simple diffusion model ignoring these different tissue types might not be sufficient**
- The reality looks probably more like in the illustration,
 - we have different cell types in a single imaging voxel
 - complex tissue
 - and still this image is a simplification
- Hence the different shapes on the left to fit diffusion in different compartments might be useful to closer describe the true shape of tissue microstructure

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



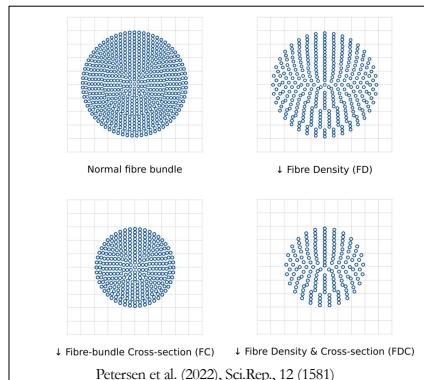
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- We can also model fibre populations within a single voxel, which we call fixels
- Estimated based on probable fibre orientations and are useful when describing fibre characteristics

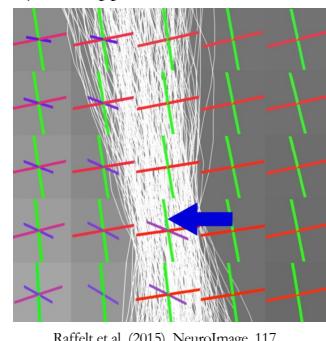
Imaging: diffusion-weighted (T_2^*)

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

- T_1 -weighting
- T_2 -weighting
- T_2^* -weighting
 - diffusion-weighting
 - fMRI



b) Pixel approach



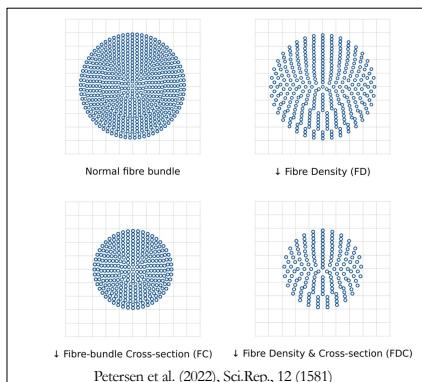
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- In particular, the **fibre density and cross section** can be **uniquely described by pixels** using 3 metrics, FD, FC, and FDC
- In the Fig on the left, we see on the top left a normal fibre bundle
 - That can decrease in density as on the right or in cross-section as below.
 - Or both as in the bottom right

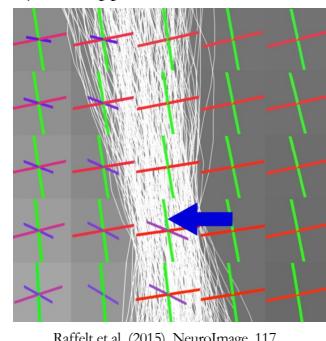
Imaging: diffusion-weighted (T_2^*)

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

- T_1 -weighting
- T_2 -weighting
- T_2^* -weighting
 - diffusion-weighting
 - fMRI



b) Fixel approach



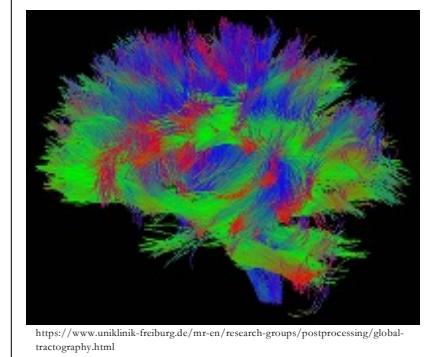
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- This distinction is important as phenomena like axonal swelling might misrepresent the structural integrity of a fibre tract
 - As an example, reduced blood flow can lead to axonal swelling
 - So, after a stroke, white matter fibres might appear thicker and indicated by some metrics "better intact" than before the stroke
 - These issues are attempted to be tackled by fixel-based analyses

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

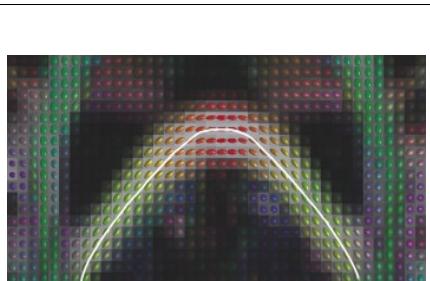


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- We can also use tractography to reconstruct individuals' fibres probabilistically or deterministically
- The figures are two different tractograms based on different assumptions about tract shapes where the colour indicates the direction of the fibres

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



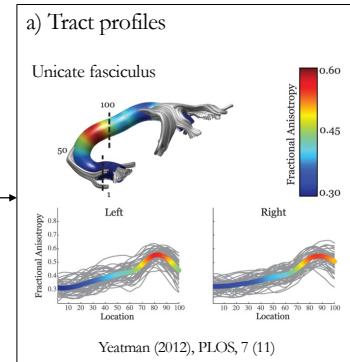
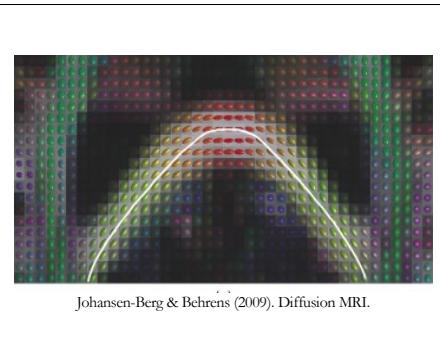
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- **How are these tracts constructed?**
- Simplified, there is a **seed point** from which the white line in the image **follows the plausible path**
- While these tract constructions produce beautiful qualitative images (as you have seen), there are many ways of analysing them quantitatively

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

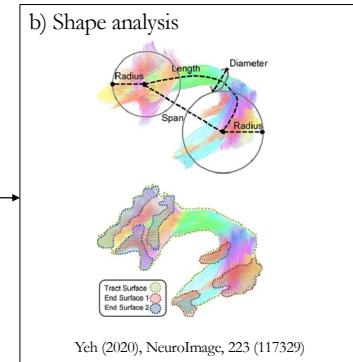
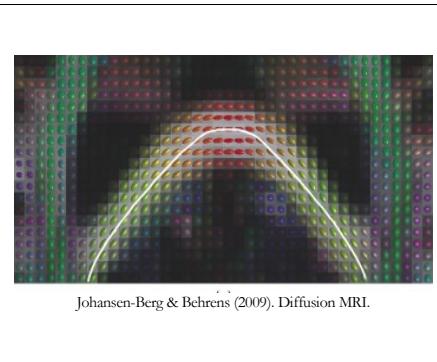


- One approach: Along-tract analyses, establishing tract profiles

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

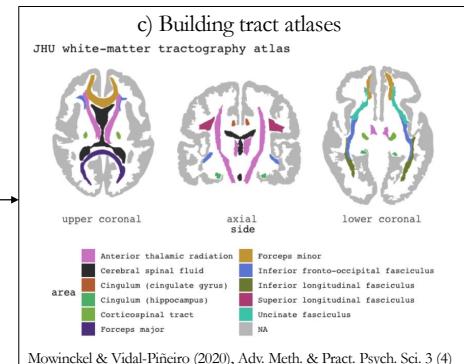
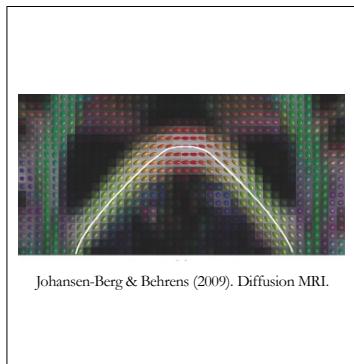


- Shape based analyses, e.g. Radius, length, diameter, span, and surface characteristics

Imaging: diffusion-weighted

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

- T₁-weighting
- T₂-weighting
- T_{2*}-weighting
 - diffusion-weighting
 - fMRI



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- A third approach is to use the tracts to build atlases or regions of interestst
- Here, we see the John Hopkins University white matter tract atlas, which is commonly used
 - Atlas can include finer regions as well and depends on what one is interested in
 - These atlases are usually aided by additional histology or other forms of multimodal data
- The point of the atlases is to run comparable studies, observe similar phenomena across subjects
- Within the atlas, one can average metrics and do statistics on these averages

Imaging: functional MRI (T_2^*)

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

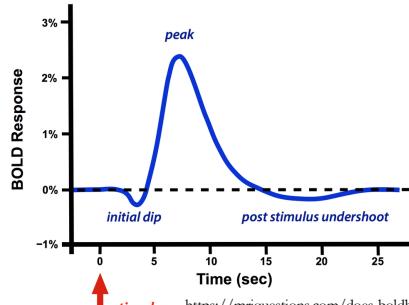
- T_1 -weighting
- T_2 -weighting
- T_2^* -weighting
 - diffusion-weighting
 - fMRI

a) Functional MRI slice



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

b) Hemodynamic response function



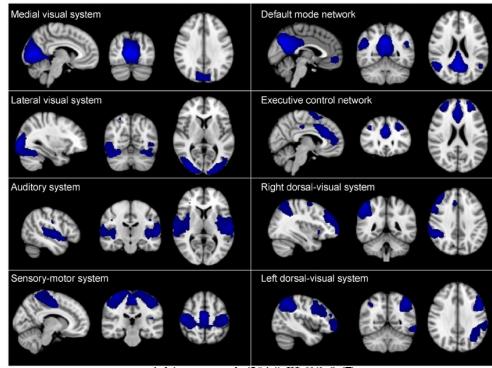
<https://mriquestions.com/does-boldbrain-activity.html>

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- functional MRI
- Most commonly, one uses a fast acquisition, to get multiple images over a time course (for a single slice see a)
- Often, a sequence is selected which is sensitive to blood oxygen level changes
- Incoming blood contains hemoglobin which binds oxygen
- This oxyhemoglobin is diamagnetic in contrast to deoxyhemoglobin which is paramagnetic
- What this particularly means is that neural firing is followed by blood flow
 - Potentially due to necessary oxygen and glucose supply
 - Potentially for metabolic waste cleaning
- Hence, after neural activity, there is bloodflow, and hence signal
- The signal change during this process is expressed by the hemodynamic response function (b)
- We assume HRF occurs after a stimulus, for example showing images
 - should increase bloodflow to visual areas in the occipital lobe

Imaging: functional MRI (T_2^*)

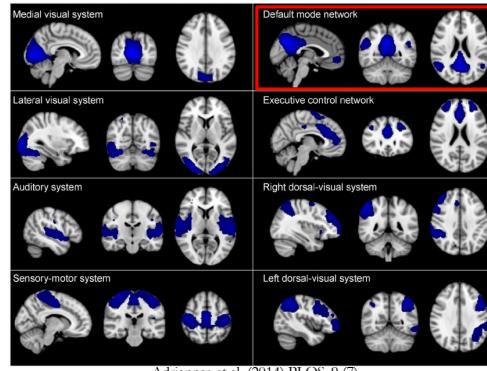
- TE and TR configurations can be used to obtain different contrasts
 - T_1 -weighting
 - T_2 -weighting
 - T_2^* -weighting
 - diffusion-weighting
 - fMRI



- The resulting spatial distribution of signal change appear as blobs
- We can covary the signal change, often called connectivity
- Separate the covariance into principal or independent components, then we have networks, which comprise regions as shown in the figure

Imaging: functional MRI (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

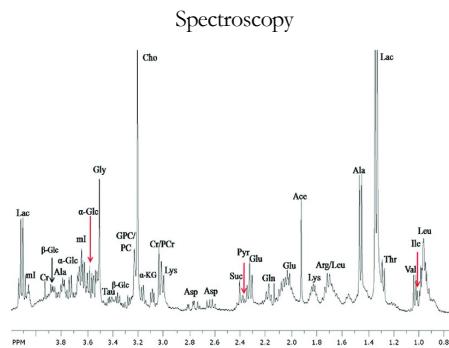


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- These network «blobs» appear both during tasks and rest
- Recent trends focus on further investigating resting state networks in the context of psychiatric disorders using multimodal MRI
 - That way, there is a spatial restriction of the analyses which might be behaviourally, perhaps biologically informative
- The same principals can also be used in susceptibility weighted MRI to image small amounts of haemorrhage/blood products or calcium, both of which may be inapparent on other MRI sequences.

Imaging: spectroscopy

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy

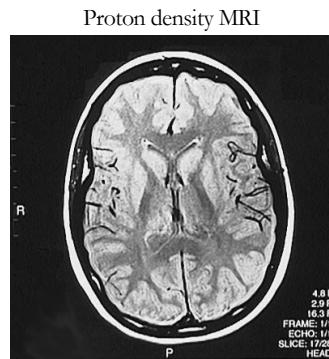


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- And there are many more imaging techniques, which require different sequences, etc.
- Just to mention a few:
 - Spectroscopy (metabolites)

Imaging: proton density

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy
 - proton density



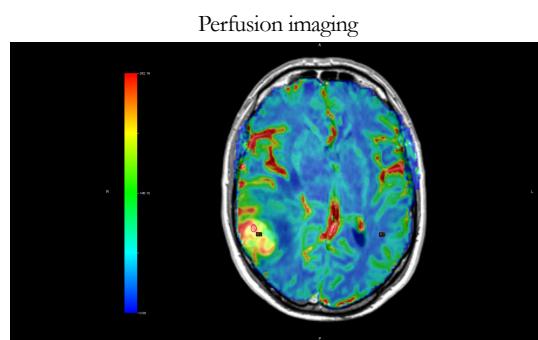
<https://webpath.med.utah.edu/HISTHTML/NEURANAT/MRIPRA21.html>

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- Proton density imaging (as the name says proton density, structural detail)
- Represent apparent concentration of water protons (mobile hydrogen atoms) in each voxel

Imaging: perfusion

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy
 - proton density
 - perfusion

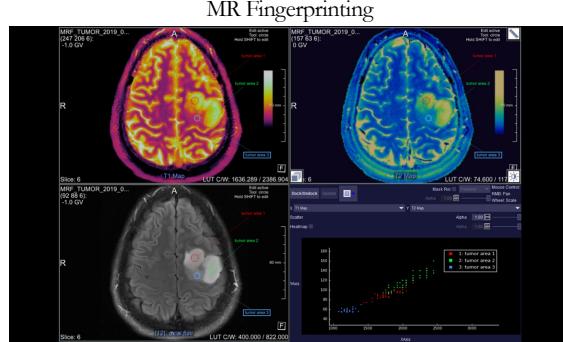


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- Perfusion imaging (BV (blood volume), BF (blood flow), MTT (mean transit time) and TTP (time to peak) to assess tissue function and necrosis)

Imaging: fingerprinting

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy
 - proton density
 - perfusion
 - fingerprinting



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

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- Instead of T1w and T2w we have looked at before, where we have long acquisition times to measure the properties of a single tissue
- MR fingerprinting allows **simultaneous efficient measurements of multiple tissue properties with one acquisition**
- The hope is to generate maps which generalise across sequences, scanners and so on (which has yet been a problem)
- Image shows different tissue maps characterising a tumor

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)

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- A multimodal study linking brain anatomy and function to Parkinson's disease outcomes
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 - 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



- Image: <https://www.pickpik.com/directory-signposts-trail-direction-arrow-target-130014>

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

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- In MRI, we record signal which helps to establish proxies of how the tissue really looks or functions
- 1. This includes that the interpretation is not always so clear
 - For example, as outlined, WM microstructure characteristics can be described in different ways
 - But to draw inference, about underlying biological processes producing different parameters in our diffusion models we need sometimes more information than can be provided from routine clinical examinations
 - Could be in form of different sequences, stronger gradients, etc.
 - (This is also true for other modalities)
- 2. Instead of using a microscope on dead tissue, we come up with good representations of biological phenomena
- Multimodal MRI, as described in the sample study might answer some questions about the complex biological phenomena
- Only recently this research picks up speed
- 3. we have to deal with noise, artifacts and many different technical challenges
- Always new frontiers in terms of hardware and software

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



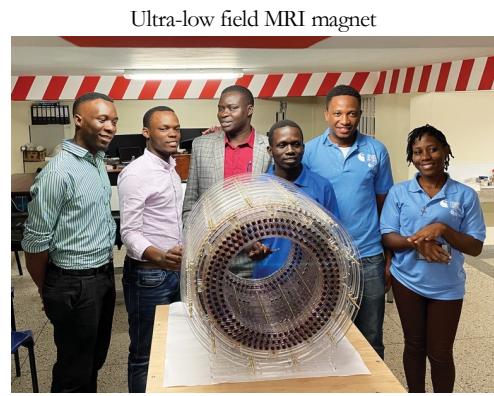
Image generated with NightCafe

64

- Reliability, replicability and even reproducibility issues (particularly fMRI)
 - The many decision points during the research process
 - “the garden of forking paths” (term coined by Andrew Gelman)
 - Individual differences, variability
- A few solutions
 - Open Science
 - Large samples
 - Streamlined analyses
 - Multiverse analyses

Future directions

- Portable, affordable low field scanners



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

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- Here a few future directions in the order in which I think they might happen
- Portable, affordable low field scanners >> developing countries or remote areas
- **Gradients** that work at **ultrahigh fields**
 - >> technical issues which need to be resolved
 - >> can we measure more accurately?
 - >> can we increase spatial and temporal resolution?

Future directions

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



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

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- **Gradients** that work at **ultrahigh fields**
 - >> technical issues which need to be resolved
 - >> can we measure more accurately?
 - >> can we increase spatial and temporal resolution?

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://awarchub.com.au/resources-2/transcranial-magnetic-stimulation/>

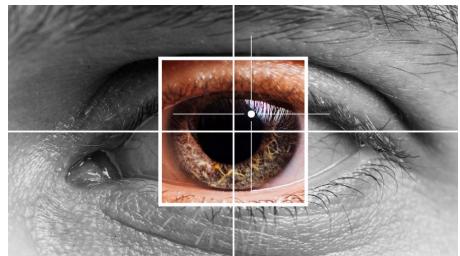
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- Treatment & diagnostic aid
 - MRI guided transcranial or direct current stimulation
 - Better surgical mapping
 - Automated diagnostic flagging [when getting an routine hospital scan also other disorders are being checked automatically]

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/>

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- **DIFFICULT TO SAY WHEN THIS HAPPENS**
- Surrogate markers of MRI

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
- Understanding basic phenomena such as ageing

Yet not fully understood
phenomenon: ageing



Night Cafe

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- Understanding basic phenomena such as ageing

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
- 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

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- Biologically founded understanding of psychiatric (or generally) disease

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

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- 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 can be quantitatively examined in multiple ways, and have been studied in the context of multiple fields

Thank you for your attention!

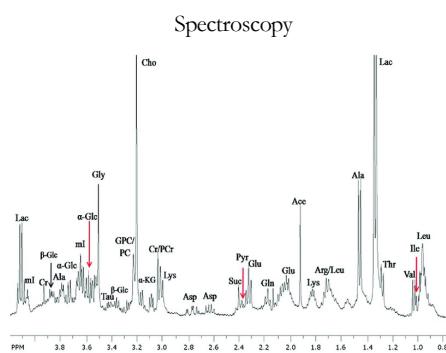


Data available from <https://bigbrain.loris.ca>

Supplement

Imaging: spectroscopy

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy



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The basic principle that enables MR spectroscopy (MRS) is that the distribution of electrons within an atom cause nuclei in different molecules to experience a slightly different magnetic field. This results in slightly different resonant frequencies, which in turn return a slightly different signal

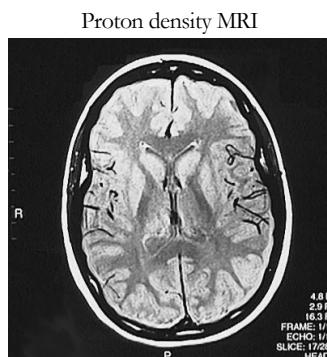
If raw signal was processed then the spectra would be dominated by water, which would make all other spectra invisible. Water suppression is therefore part of any MRS sequence, either via inversion recovery or chemical shift selective (CHESS) techniques. If water suppression is not successful then a general slope to the baseline can be demonstrated, changing the relative heights of peaks.

Magnetic resonance spectroscopy (MRS) is performed with a variety of pulse sequences. The simplest sequence consists of a 90 degree radiofrequency (RF) pulse, without any gradients, with reception of the signal by the RF coil immediately after the single RF pulse. Many sequences used for imaging can be used for spectroscopy also (such as the spin echo sequence). The important difference between an imaging

sequence and a spectroscopy sequence is that for spectroscopy, a read-out gradient is not used during the time the RF coil is receiving the signal from the person or object being examined. Instead of using the frequency information (provided by the read-out or frequency gradient) to provide spatial or positional information, the frequency information is used to identify different chemical compounds. This is possible because the electron cloud surrounding different chemical compounds shields the resonant atoms of spectroscopic interest to varying degrees depending on the specific compound and the specific position in the compound. This electron shielding causes the observed resonance frequency of the atoms to slightly differ and therefore identifiable with MRS.

Imaging: proton density

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy
 - proton density

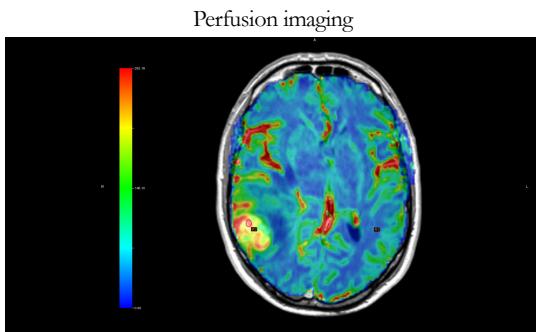


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Proton density (PD) weighted images are related to the number of nuclei in the area being imaged (number of hydrogen protons), as opposed to the magnetic characteristics of the hydrogen nuclei. They are produced from the first echo. Proton density weighted images result when the contribution of both T1 and T2 contrast is minimised. They have a long TR (2000+ms) to minimise T1 differences because all tissues exhibit full longitudinal relaxation before the next 90 degrees RF pulse. They have a short TE (TE1, 20ms) to minimise T2 differences. Higher proton density tissues appear brighter (CSF > fat > gray matter > white matter). In musculoskeletal imaging, TR is more than 1000 msec and TE is less than 30 msec. It provides good anatomic detail but little overall tissue contrast. In the cervical spine, cerebrospinal fluid (CSF) has slightly higher intensity than intervertebral discs in proton density images ².

Imaging: perfusion

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy
 - proton density
 - perfusion



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Perfusion weighted imaging is a term used to denote a variety of MRI techniques able to give insights into the perfusion of tissues by blood. There are three techniques in wide use to derive one or more perfusion values:

• techniques

- [dynamic susceptibility contrast \(DSC\) MR perfusion](#)
- [dynamic contrast enhanced \(DCE\) MR perfusion](#)
- [arterial spin labelling \(ASL\) MR perfusion](#)

• derived values

- [time to peak \(TTP\)](#)
- [mean transit time \(MTT\)](#)
- [cerebral blood volume \(CBV\)](#)
- [cerebral blood flow \(CBF\)](#)
- [negative enhancement integral \(NEI\)](#)
- [k-trans](#)

The main role of perfusion imaging is in evaluation of ischaemic conditions (e.g. [acute cerebral infarction](#) to determine [ischaemic penumbra](#), [moya-moya disease](#) to identify vascular reserve), neoplasms (e.g. identify highest grade component of diffuse astrocytomas, help

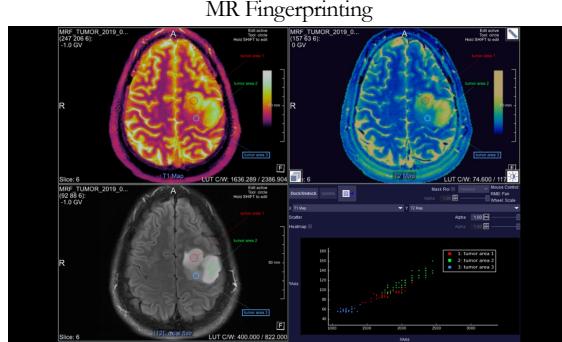
distinguish [glioblastomas](#) from [cerebral metastases](#)) and neurodegenerative diseases.

Dynamic susceptibility contrast (DSC) MR perfusion is one of the most frequently used techniques for [MRI perfusion](#), and relies on the susceptibility induced signal loss on T2*-weighted sequences which results from a bolus of gadolinium-based contrast passing through a capillary bed. The most commonly calculated parameters are [rCBV](#), [rCBF](#), and [MTT](#). This technique is sometimes referred to, perhaps more accurately, as **dynamic susceptibility contrast-enhanced MR perfusion**, still abbreviated to DSC. This should not be confused with [dynamic contrast-enhanced \(DCE\) MR perfusion](#), which relies on T1 shortening due to gadolinium-based contrast.

Dynamic contrast-enhanced (DCE) MR perfusion, sometimes also referred to as **permeability MRI**, is one of the main [MRI perfusion](#) techniques which calculates perfusion parameters by evaluating T1 shortening induced by a gadolinium-based contrast bolus passing through tissue. The most commonly calculated parameter is [k-trans](#). This technique should not be confused with [dynamic susceptibility contrast \(DSC\) MR perfusion](#) which is sometimes referred to as dynamic susceptibility contrast-enhanced MR perfusion.

Imaging: fingerprinting

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T₂*-weighting
 - diffusion-weighting
 - fMRI
 - spectroscopy
 - proton density
 - perfusion
 - fingerprinting

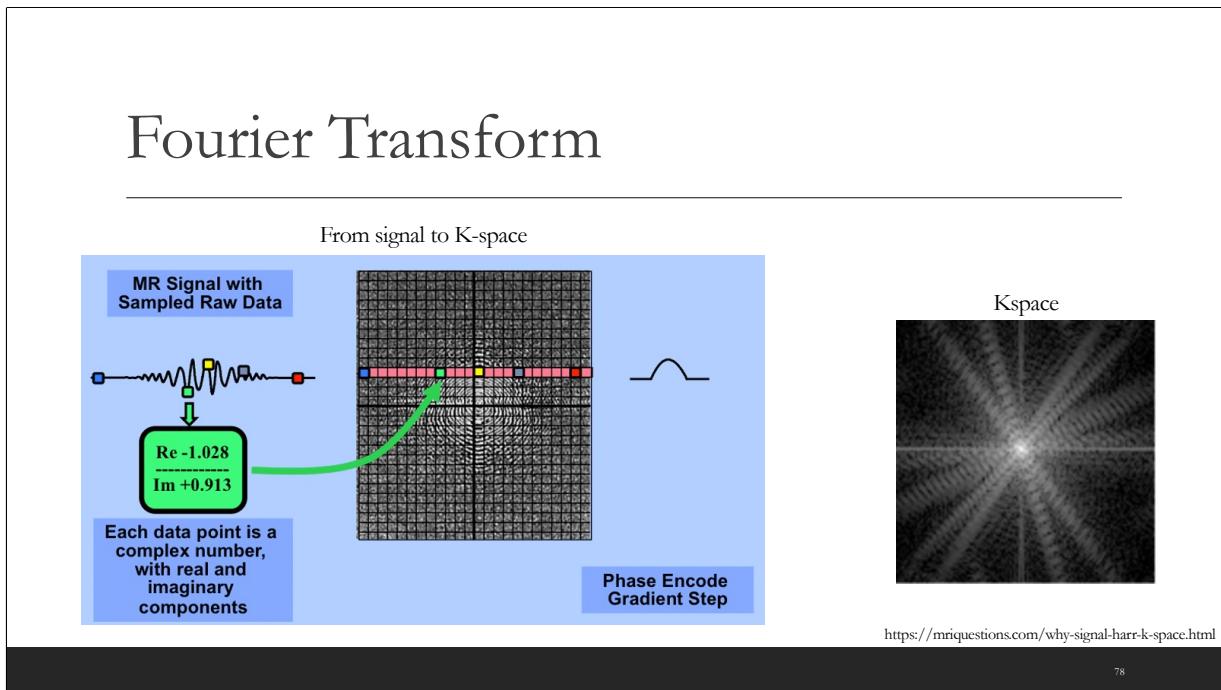


<https://www.siemens-healthineers.com/magnetic-resonance-imaging/options-and-upgrades/clinical-applications/mr-fingerprinting>

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- Instead of T1w and T2w we have look at before, where we have long acquisition times to measure the properties of a single tissue
- MR fingerprinting allows **simultaneous efficient measurements of multiple tissue properties with one acquisition**
- Image shows different tissue maps characterising a tumor

Fourier Transform



- What I did not mention in the presentation, due to time restrictions, is **how we get from complicated time-dependent signal to our image.**
- Signal is time and space dependent, or in other words of the gradients
- Use of Fourier transform to encode signal into k-space or q-space (different directions) by decomposing different wave forms from signal
- Simply said, we can then subtract the gradient-dependent signal and see where frequencies are left, representing the tissue

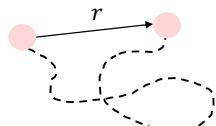
Diffusion: background

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

Mean square displacement

Number of particles

Time dependent



Isotropic diffusion

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

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- We can estimate mean displacement from the direct path travelled within a given time, assuming isotropic diffusion

Diffusion: background

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

$$MSD(t) = 6Dt$$

Constant depending on the dimensions, here 3
 $D_{iso} = 3\mu m^2/ms$

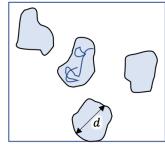
Example: Diffusion length: $L(t) = \sqrt{6Dt}$
For $t = 20\text{ms}$: $L = \sqrt{6*3*20} = 19\mu m$

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

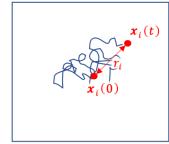
Diffusion: background

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

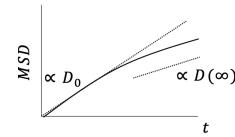
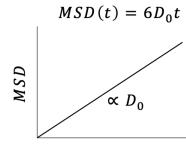
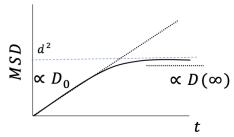
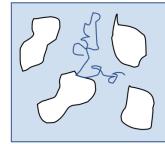
Diffusion in isolated pores



Free diffusion



Diffusion in interconnected pores



Callaghan (2011) Diffusion MRI

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- What that translates to are differing diffusion times or displacement in different tissue types
- logarithm

Diffusion signal

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

- T₁-weighting

- T₂-weighting

- T_{2*}-weighting

- diffusion-weighting

- fMRI

Estimating diffusion signal

Signal

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

b-value

Signal at baseline

Diffusion coefficient
(area/time)

Equivalent to

Diffusion coefficient

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

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

Gyromagnetic ratio

Amplitude

Duration between gradients

Gradient application time

Stcjskal & Tanner (1965). J Chem Phys

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- **Diffusion signal** depends on b-value and diffusion coefficient, as well as signal at baseline
- Baseline signal is established using b=0, reflecting no diffusion weighting
 - captures the inherent signal intensity of tissues without directional sensitivity to water diffusion
- **Diffusion coefficient**
 - Can also be estimated from the standard
- **B-value**
 - indicates the diffusion weighting
 - Consists of amplitude (G), time of applied gradients (δ) and duration between the paired gradients (Δ)
 - If wanting to detect slow moving molecules, higher b-values are necessary

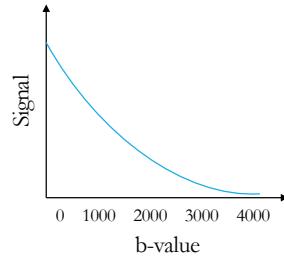
Diffusion signal

- TE and TR configurations can be used to obtain different contrasts
 - T₁-weighting
 - T₂-weighting
 - T_{2*}-weighting
 - diffusion-weighting
 - fMRI

Estimating diffusion signal

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

Signal Signal at baseline Diffusion coefficient (area/time)
b-value Stcjskal & Tanner (1965). J Chem Phys



- Dependence of the diffusion signal on the b-value
- B-values > 1000 introduce parameters sensitivities when using DTI. We want insensitive parameters >> avoid b > 1000 for DTI

Diffusion signal

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

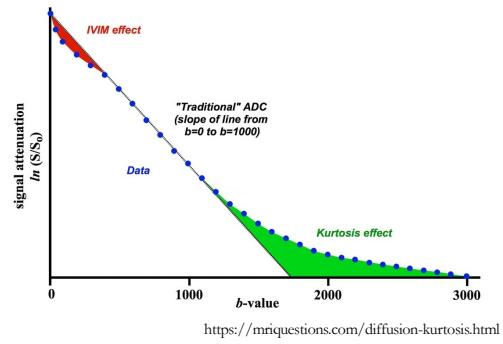
- T₁-weighting
- T₂-weighting
- T_{2*}-weighting
 - diffusion-weighting
 - fMRI

Estimating diffusion signal

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

Signal Signal at baseline b-value Diffusion coefficient (area/time)

Stcjskal & Tanner (1965). J Chem Phys



- Deviation of the expected MR signal in DWI from a mono-exponential model.
- At low b -values IVIM effects due to microscopic perfusion must be considered (red), while at high b -values kurtosis effects must be considered (green).

b-value parametrisation

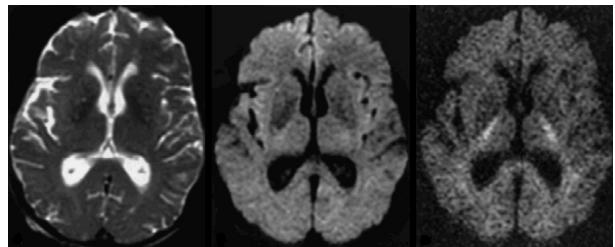
- TE and TR configurations can be used to obtain different contrasts

- T₁-weighting
- T₂-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>

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- The b value indicates the diffusion weighting in time by area (inverse of the signal)
- Consists of amplitude (G), time of applied gradients (δ) and duration between the paired gradients (Δ)
- If wanting to detect slow moving molecules, higher b-values are necessary
- B = 0 serves as a reference value

b-value parametrisation: *more practical*

- Imaging techniques

- T₁-weighting
- T₂-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

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

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- this particular implementation is seldom used in modern clinical or experimental systems. Rather than pure rectangular pulses, either sinusoidal or trapezoidal pulses are more frequently employed. (1-2)
- Diffusion schemes other than the pulsed gradient method have also been studied, with the calculation of the b-value depending on the details of the gradient scheme used. (3-4)

b-value parametrisation: *more practical*

- Imaging techniques
 - T₁-weighting
 - T₂-weighting
 - T_{2*}-weighting
 - diffusion-weighting
 - fMRI

Introducing kurtosis into the diffusion equation

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

Future direction for dMRI

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