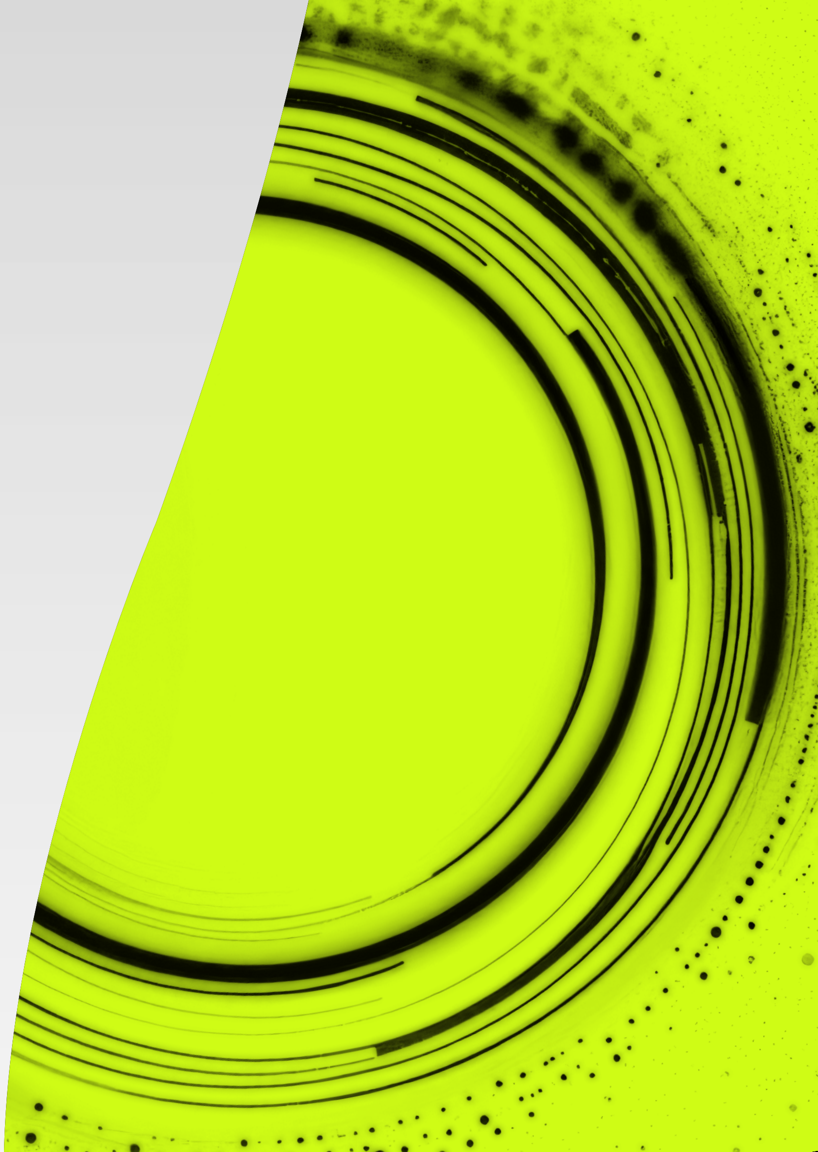
MODERN RADIOLOGY
eBook

Magnetic Resonance Imaging



EUROPEAN SOCIETY OF RADIOLOGY

Preface

Modern Radiology is a free educational resource for radiology published online by the European Society of Radiology (ESR). The title of this second, rebranded version reflects the novel didactic concept of the ***ESR eBook*** with its unique blend of text, images, and schematics in the form of succinct pages, supplemented by clinical imaging cases, Q&A sections and hyperlinks allowing to switch quickly between the different sections of organ-based and more technical chapters, summaries and references.

Its chapters are based on the contributions of over 100 recognised European experts, referring to both general technical and organ-based clinical imaging topics. The new graphical look showing Asklepios with fashionable glasses, symbolises the combination of classical medical teaching with contemporary style education.

Although the initial version of the ***ESR eBook*** was created to provide basic knowledge for medical students and teachers of undergraduate courses, it has gradually expanded its scope to include more advanced knowledge for readers who wish to 'dig deeper'. As a result, ***Modern Radiology*** covers also topics of the postgraduate levels of the ***European Training Curriculum for Radiology***, thus addressing postgraduate educational needs of residents. In addition, it reflects feedback from medical professionals worldwide who wish to update their knowledge in specific areas of medical imaging and who have already appreciated the depth and clarity of the ***ESR eBook*** across the basic and more advanced educational levels.

I would like to express my heartfelt thanks to all authors who contributed their time and expertise to this voluntary, non-profit endeavour as well as Carlo Catalano, Andrea Laghi and András Palkó, who had the initial idea to create an ***ESR eBook***, and - finally - to the ESR Office for their technical and administrative support.

Modern Radiology embodies a collaborative spirit and unwavering commitment to this fascinating medical discipline which is indispensable for modern patient care. I hope that this ***educational*** tool may encourage curiosity and critical thinking, contributing to the appreciation of the art and science of radiology across Europe and beyond.

Minerva Becker, Editor
Professor of Radiology, University of Geneva, Switzerland

MR Imaging

CHAPTER OUTLINE:

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Signage

<■> **CORE KNOWLEDGE**

>■< **FURTHER KNOWLEDGE**

<!> **ATTENTION**

>|< **COMPARE**

<?> **QUESTIONS**

<↑> **HYPERLINKS**

<∞> **REFERENCES**

CHAPTER OUTLINE:

MODERN RADIOLOGY eBook

Based on the ESR Curriculum for Radiological Education

Magnetic Resonance Imaging

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/ MR Imaging

CHAPTER OUTLINE:

Chapter Outline

/ MRI System

CHAPTER OUTLINE:

/ The Basics

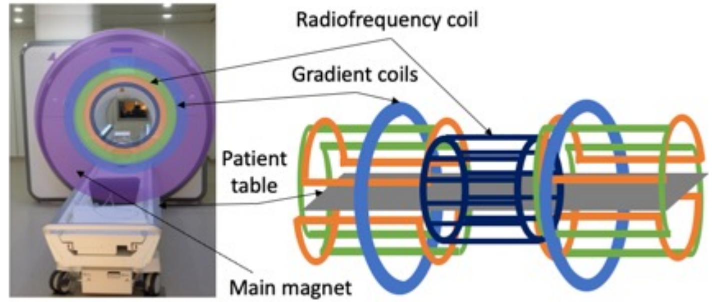
MRI is a non-invasive sophisticated technique that uses powerful magnetic fields to image the human body.

An MRI scanner is composed of 3 main parts:

- / **Main magnet**: to produce the main static magnetic field (B_0).
- / **Gradient coils**: to produce deliberate variations in B_0.
- / **Radiofrequency (RF) coils**: which act like the antennas of the MRI system: they transmit the RF field, and they receive the resulting signal.

Main magnet

The superconductive magnet (superconductive = no resistance to electricity) produces a high intensity magnetic field called "B_0". The magnet is cooled with liquid Helium (and liquid Nitrogen). It is used to generate a net magnetisation of tissue inside the bore. The bore size is 60-70 cm in diameter.



Order of magnitude for magnetic field strengths:

- / Earth magnetic field at latitude 0°: 31 µT
- / Fridge magnet : 5 mT
- / Junkyard/scrap magnet : 1T
- / Medical MRI : most often 1.5T and 3.0T, rarely 7.0T

>■< FURTHER KNOWLEDGE

Constant electric current in a wire generates a static magnetic field (Biot-Savart law). The magnetic field strengths is proportional to the electric current.

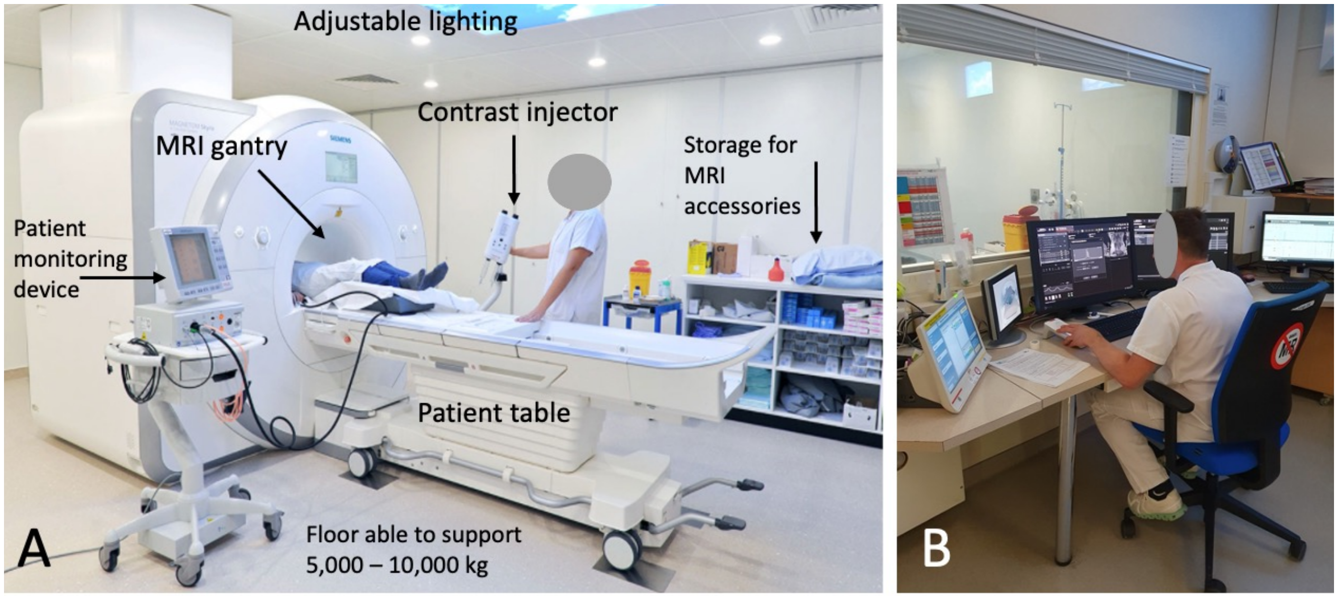
<!> ATTENTION

Contraindications or restrictions for MRI :

- / Claustrophobia
- / Ferromagnetic metal in the body
- / Some pacemakers, electronic implants, ...

/ MR Imaging

CHAPTER OUTLINE:



The walls of the MRI magnet room (A) have layers which perform different functions: magnetic shielding to confine the stationary magnetic field, RF shielding to hinder electromagnetic noise to enter or exit the magnet room and acoustic shielding to restrict noise transmission beyond the magnet room. The control room (B) is located immediately outside the magnet room. It contains the operator console, computer equipment, communication devices, monitors (ECG and O_2).

/ Safety and Access Restriction

/ The magnet is always ON!

/ The main magnetic field B_0 is always active. Never approach the field with a **ferromagnetic*** object.

/ The attraction force associated with the torque will pull the object through the main magnet with **uncontrollable** force: projectile effect or missile effect.

/ **Past incidents unfortunately killed people!**

/ This explains why safety rules around MRI are very strict!

/ Patients undergoing MRI examinations must remove all metallic objects. Some radiology departments use ferromagnetic detection devices.

MRI accident on a 1.5T MR system. A floor polishing machine was attracted by the magnetic field. It could only be removed by ramping down the magnetic field. Shown is the back side (head end) of the MRI. Reproduced from:

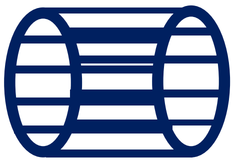
https://commons.wikimedia.org/wiki/File:MRI_accident_on_a_1.5_Tesla_MR_system.jpg

* Ferromagnetic objects contain :

/ Iron, Cobalt, Nickel
/ Alloys of these components

CHAPTER OUTLINE:

/ Components

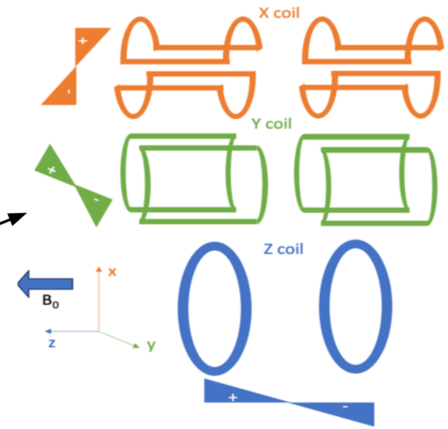


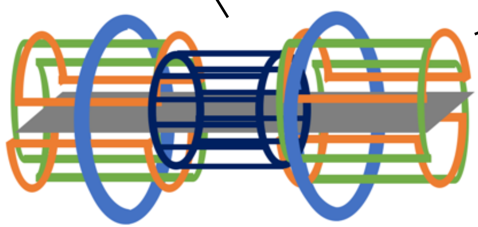
Radiofrequency coil

Produces a varying magnetic field that is used to tip the net magnetisation perpendicularly to the main magnetic field B_0.

Gradient coils

Produce varying magnetic fields in 3 spatial directions (x, y, z). Used to spatially encode the MRI signal.





We'll see on the next pages how each of these parts contributes to the production of images →

/ MR Imaging

/ MRI Principle

CHAPTER OUTLINE:

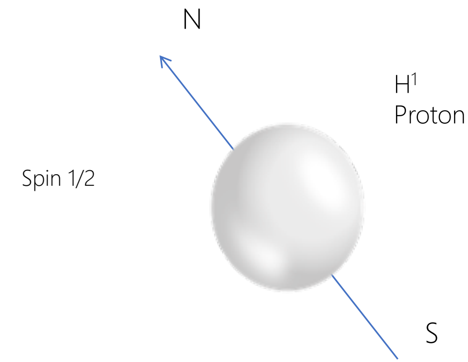
MRI Principle

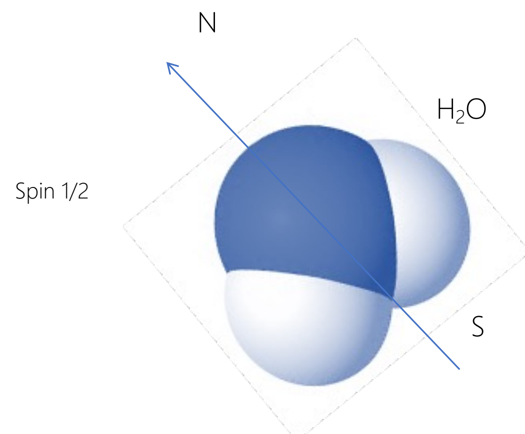
The nucleus of an atom is composed of protons (positive charge) and neutrons (no charge) which all rotate around their own axis. The electrons (negative charge) revolve around the nucleus, and they also rotate around their own axis.

The rotation of all these particles produces an angular moment of rotation, which is called **spin**. A spin is a fundamental property of atoms like mass or electrical charge. Spin comes in multiples of ½.

As the proton has a positive charge and as it rotates continuously, it creates a small magnetic field, called **magnetic moment** (i.e., it behaves like a tiny magnet with a north and south pole).

- There is a natural abundance of H2O in biological tissues and, therefore, an abundance of H^1.
- H^1 **mainly occurs** in water in the human body.
- Human body composition → ~ 60% - 70% water (2 H^1).
- H^1 has a **large** magnetic moment.
- The magnetic property of H^1 is used to mainly image the water distribution of tissues in the body with MRI.





MR Imaging

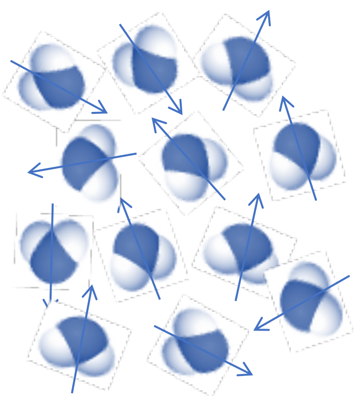
CHAPTER OUTLINE:

/ MRI Principle

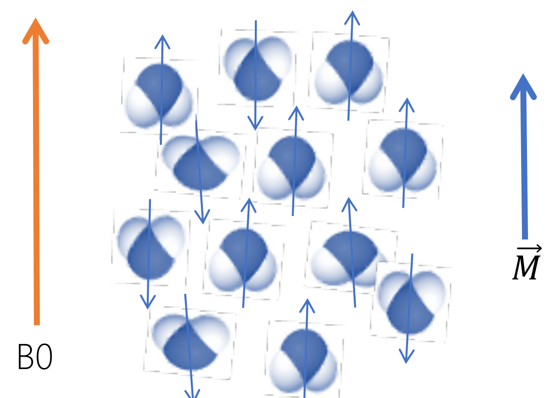
When biological tissue is placed in a strong magnetic field, a **net magnetisation vector** is created. To effectively explain this phenomenon, quantum mechanics is required, which is beyond the scope of this chapter.

This effect applies to atoms with **specific magnetic moment properties,** i.e., nucleus with spin quantum number = ½ : H^1 / C^{13} / N^{15} / O^{17} / Na^{23} / ...

Alignment **parallel ↑ or anti-parallel ↓ to the magnetic field**, corresponds to two different energy states. Most protons align parallel to B_0 as this requires less energy than the antiparallel alignment. The net magnetisation $\vec{M}$ is created by the fraction of spin in excess in one of the energy states:



Outside the magnetic field



Inside the magnetic field

EXAMPLE :
fraction in excess
@ 3T ~10 on 10^6 !

/ MR Imaging

CHAPTER OUTLINE:

/ Signal Production

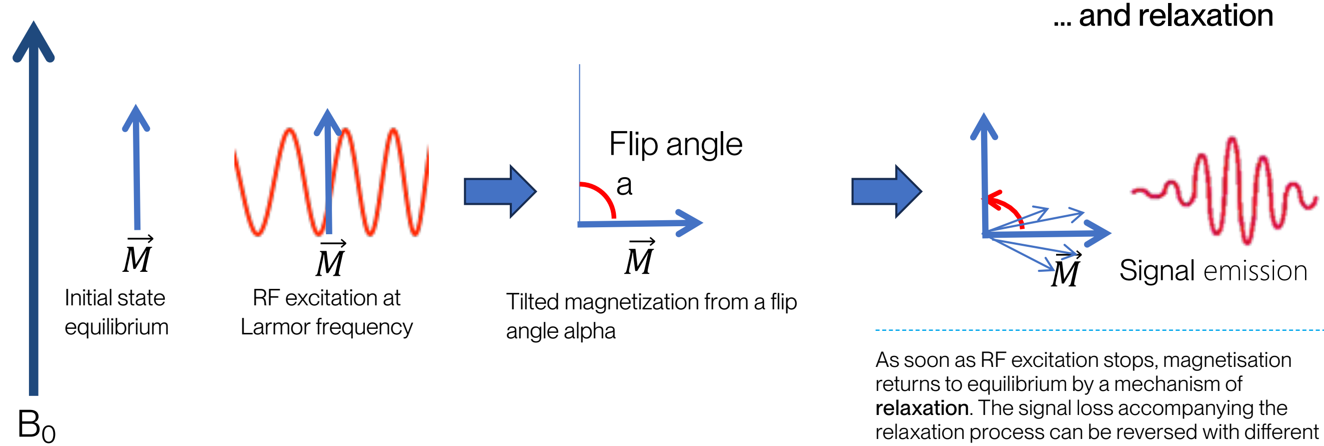
Excitation ...

/ To create a signal from the tissue, a radiofrequency (RF) wave is used. It is tuned to the resonance frequency of the spins called « Larmor frequency » f, defined by:
$f = \gamma B_0$

/ Where γ is the gyromagnetic ratio (γ = 42.58 MHz/T) and B_0 the magnetic field strength.

- / At 1.5T, f = 64 MHz
- / At 3T, f = 128 MHz

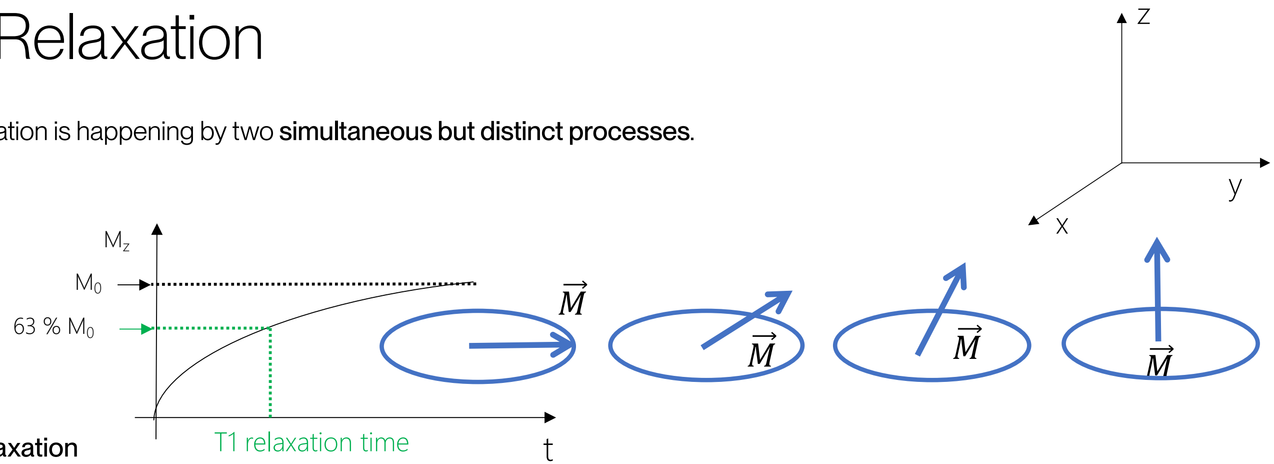
... and relaxation



As soon as RF excitation stops, magnetisation returns to equilibrium by a mechanism of **relaxation**. The signal loss accompanying the relaxation process can be reversed with different techniques and the reversed signal can be recorded!

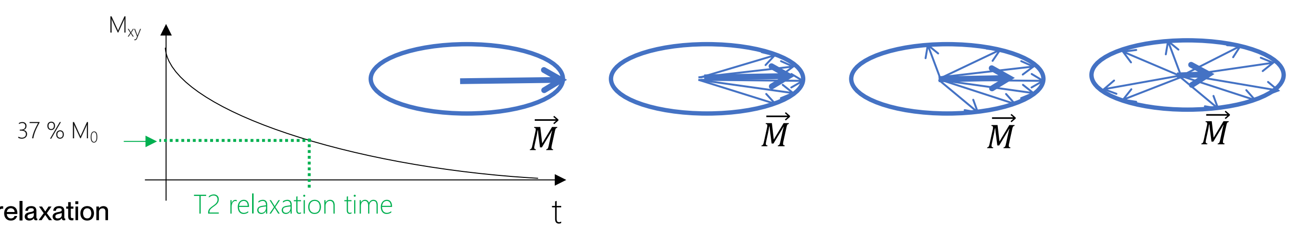
/ Relaxation

Relaxation is happening by two **simultaneous but distinct processes.**



T1 relaxation

Spin energy is dispersed into its environment (mainly nucleus and other atoms), the magnetisation is recovering its initial state along B_0 (longitudinal magnetisation). The mechanism by which $\mathbf{M_z}$ exponentially relaxes from a higher energy state to thermodynamic equilibrium is also called **spin-lattice relaxation**.



T2 relaxation

Magnetisation flipped in the transverse plane is reduced due to spin dephasing. Phase coherence is lost, reducing net magnetisation in the x-y plane (while net magnetisation is re-growing in the z direction through T1 relaxation!). The mechanism by which $\mathbf{M_{xy}}$ exponentially decays towards its equilibrium value is also called **spin-spin relaxation**.

<:!> ATTENTION

T1 is the the time constant for regrowth of M_z (longitudinal magnetisation).

T2 is the time constant for decay/dephasing of $M_{x,y}$ (transverse magnetization).

T1 and T2 relaxation times depend on the environment, they are characteristic for different tissues!

Below some examples of T1 and T2 relaxation values at 1.5T

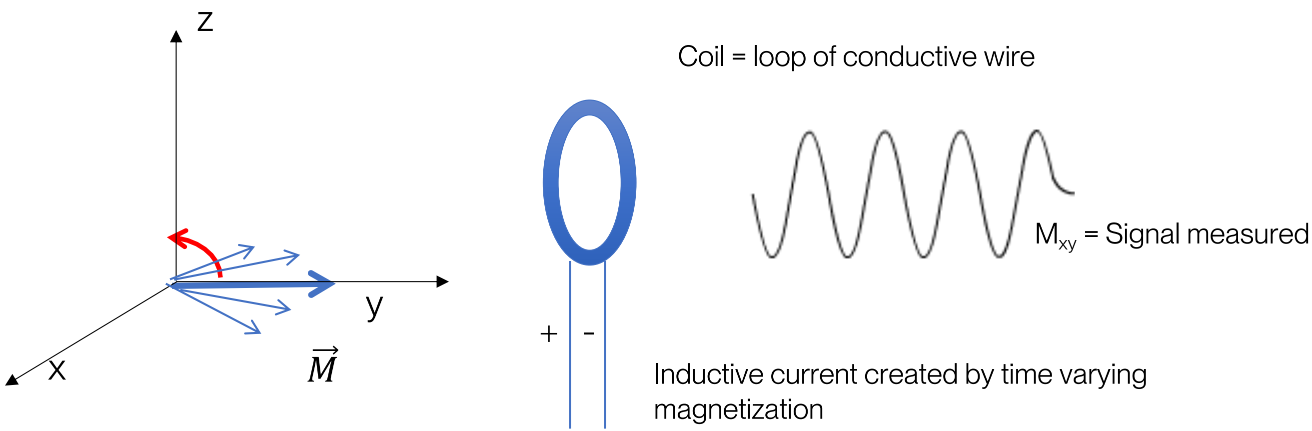
TISSUE TYPE	APPROXIMATE T1 VALUE IN MS	APPROXIMATE T2 VALUE IN MS
Adipose tissues	240-250	60-80
Whole blood (deoxygenated)	1350	50
Whole blood (oxygenated)	1350	200
Cerebrospinal fluid (similar to pure water)	4200 - 4500	2100-2300
Gray matter of cerebrum	920	100
White matter of cerebrum	780	90
Liver	490	40
Kidneys	650	60-75
Muscles	860-900	50

From: https://en.wikipedia.org/wiki/Relaxation_(NMR)

CHAPTER OUTLINE:

Signal Reception

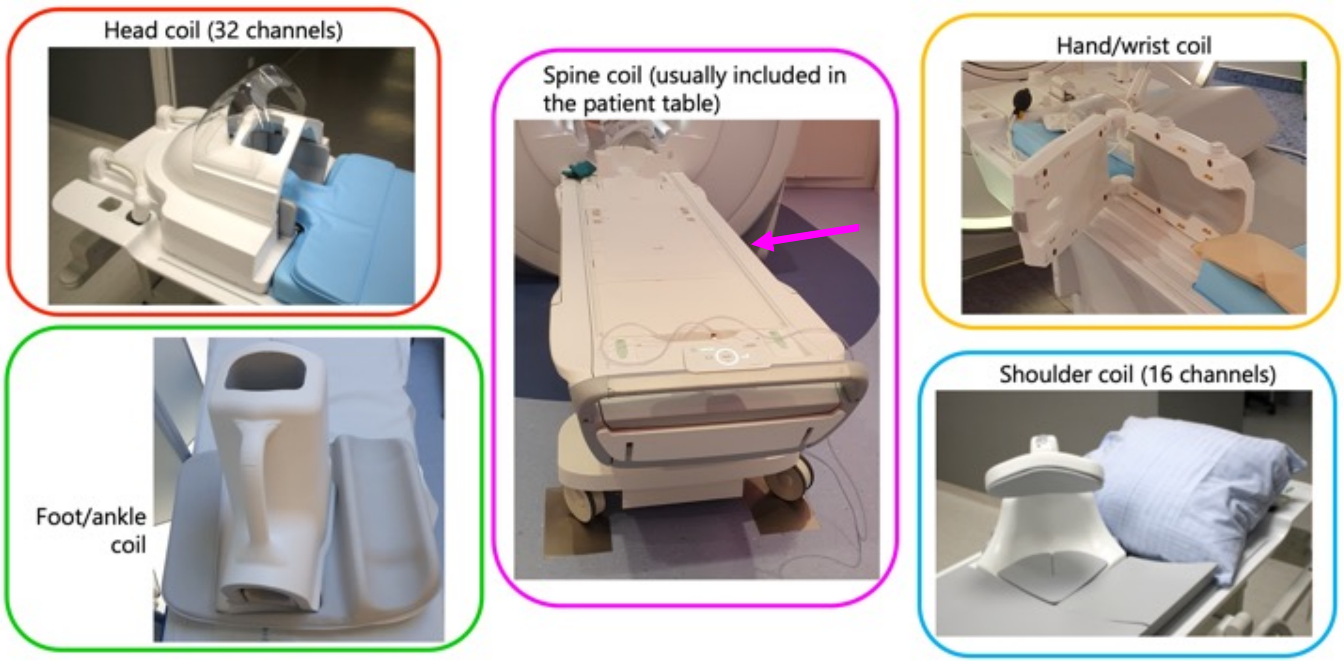
The periodic signal accompanying the relaxation of the excited net magnetisation can be recorded by a coil.



CHAPTER OUTLINE:

Dedicated coils are used for each application:

Modern receiving coils contain several small coils (also called channels), each one receiving the emitted signal. Such configurations help to achieve high signal to noise ratio, as well as a large coverage of the anatomy to investigate.



CHAPTER OUTLINE:

/ Spatial Encoding – Z Direction

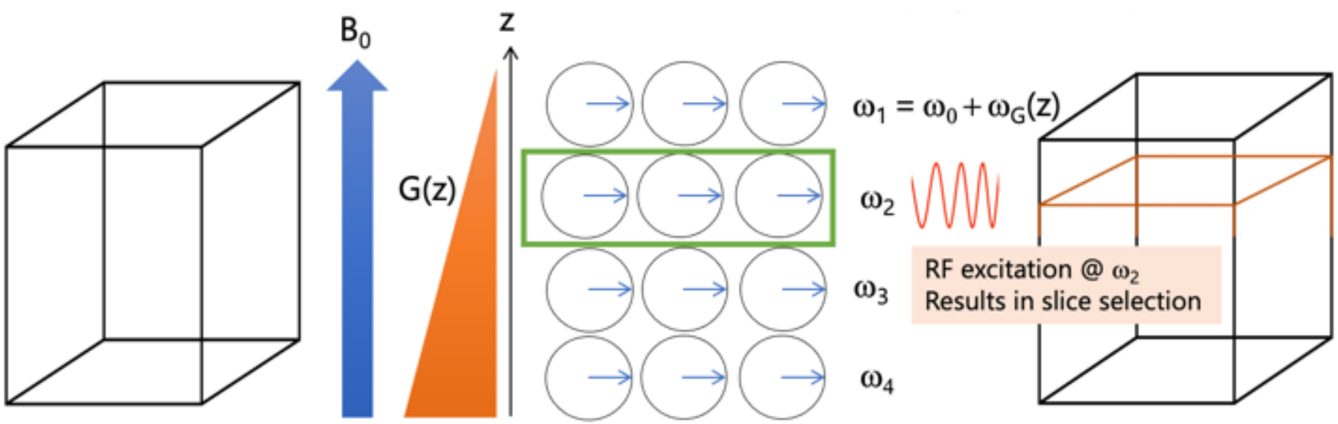
- At this stage, signal is provided by the whole volume of tissue excited by the RF coil.
- Remember: the system is composed of 3 gradient coils, one for each geometrical dimension (x, y, z).
- The gradient coils are used to add some spatial encoding to the signal!
- How does it work?

Example with slice encoding

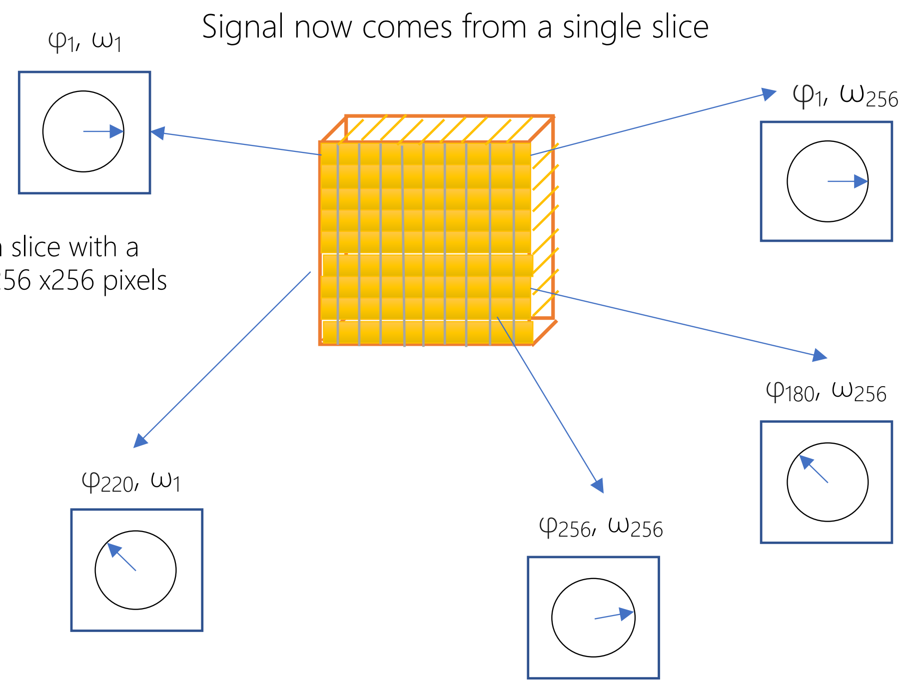
Volume excited by the RF tuned at ω_0 (without any gradient).

Addition of magnetic field varying in z direction with the z-gradient.

To spatially select signal coming from one slice, we tune the RF to the corresponding modified frequency, here ω_2 for example.



To add spatial information on the two other dimensions, x- and y-gradients are also used at specific timing before and during signal reception. They are used to add **spatially varying dephasing** (in the so-called **phase encoding direction**) and spatially varying frequency (in the so-called **frequency direction**).



Each voxel will contain spins with spatial information encoded within:

- phase φ
- frequency ω

At this step, the signal received is not yet an image but a complex combination of varying phase and frequency signals.

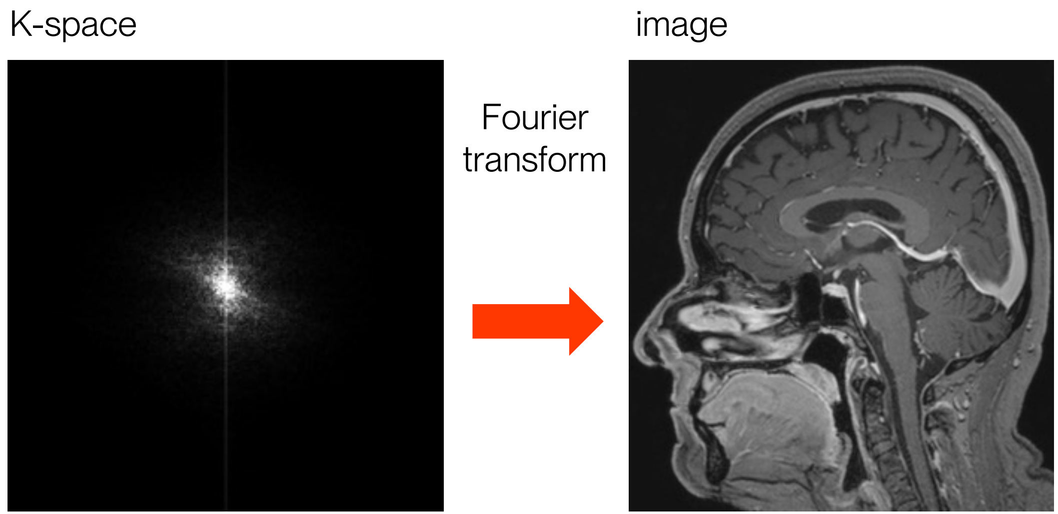
/ Relationship between Signal and Image

The measured signal is in the frequency space, the so called “k-space”. The “k” stands for a number that keeps the gradient spatial encoding information. This “k-space” can be translated into the final image using the **Fourier transform**.

<!> ATTENTION

REMEMBER:

Until now we have measured magnetisation of spins with varying additional gradients, to create information contained in the frequency space (k-space). The image will be created by the Fourier transform of this k-space.



CHAPTER OUTLINE:

Gradients and MRI Noise

Gradient coils used to add spatial information to the signal produce varying magnetic fields during image acquisition. These variations make the gradient coils vibrate. This is the origin of the loud noise heard during MR image acquisition.

Illustration from: https://pixabay.com/de/photos/mann-arbeiter-presslufthammer-785548/

ATTENTION

The patient must wear hearing protection during the exam!

140 dB	= Airplane taking off
130 dB	**= MRI**
110 dB	= Concert or nightclub
95 dB	= school cafeteria
85 dB	= lawn mower
80 dB	= car
60 dB	= conversation

CHAPTER OUTLINE:

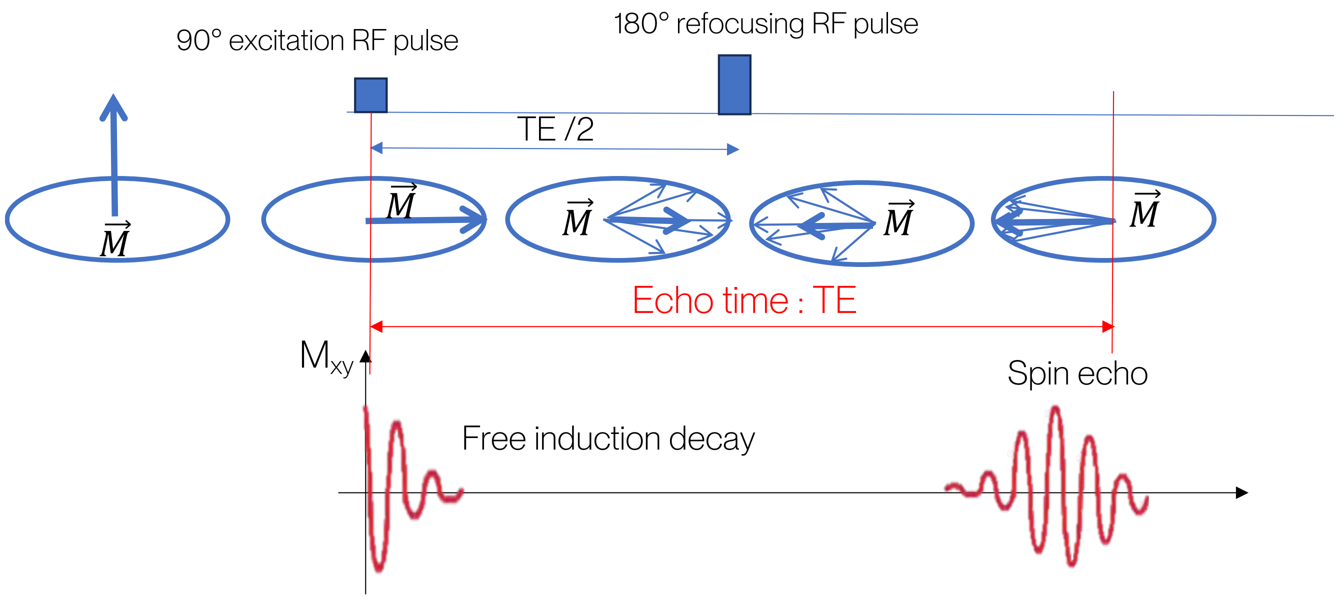
The Spin Echo Sequence

CHAPTER OUTLINE:

What is an Echo?

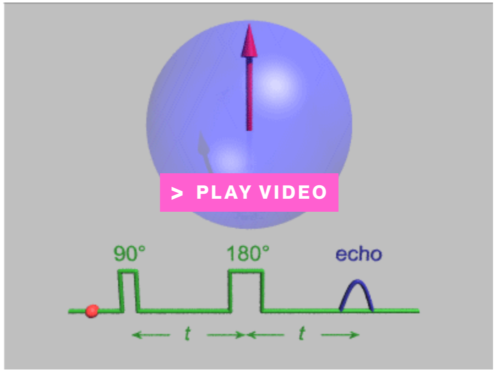
When the magnetisation is coming back to equilibrium after the application of an RF pulse, the signal produced is called a "**free induction decay**".

When a second RF pulse is used, in particular a 180° pulse, or **refocusing pulse**, then an echo is created! The time between the first RF pulse and the echo is called the **echo time**.

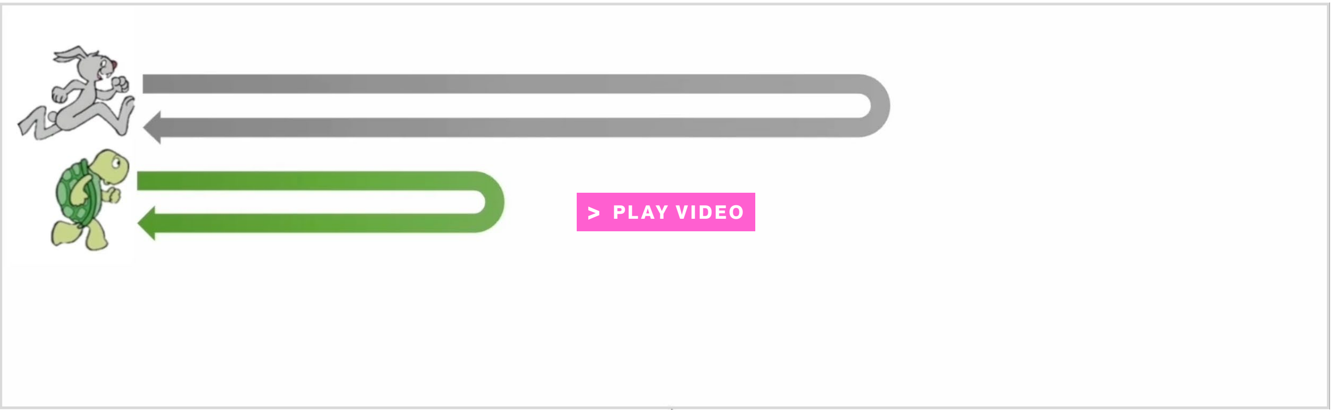


Between the 90° and the 180° pulses spins are dephasing. Fast spinning components dephase more than slow spinning components. The 180° pulse rephases the spins by "reversing" the dephasing, so the fast-spinning components are then regaining phase to join the slow-spinning components.

Illustration from: https://en.wikipedia.org/wiki/Spin_echo
Click to Play Video in Browser



Analogy > The Hare and the Tortoise
The Hare : fast spinning component
The Tortoise : slow spinning component



Click to Play Video in Browser

As explained previously, the signal coming from the echo is emitted by the whole excited volume!

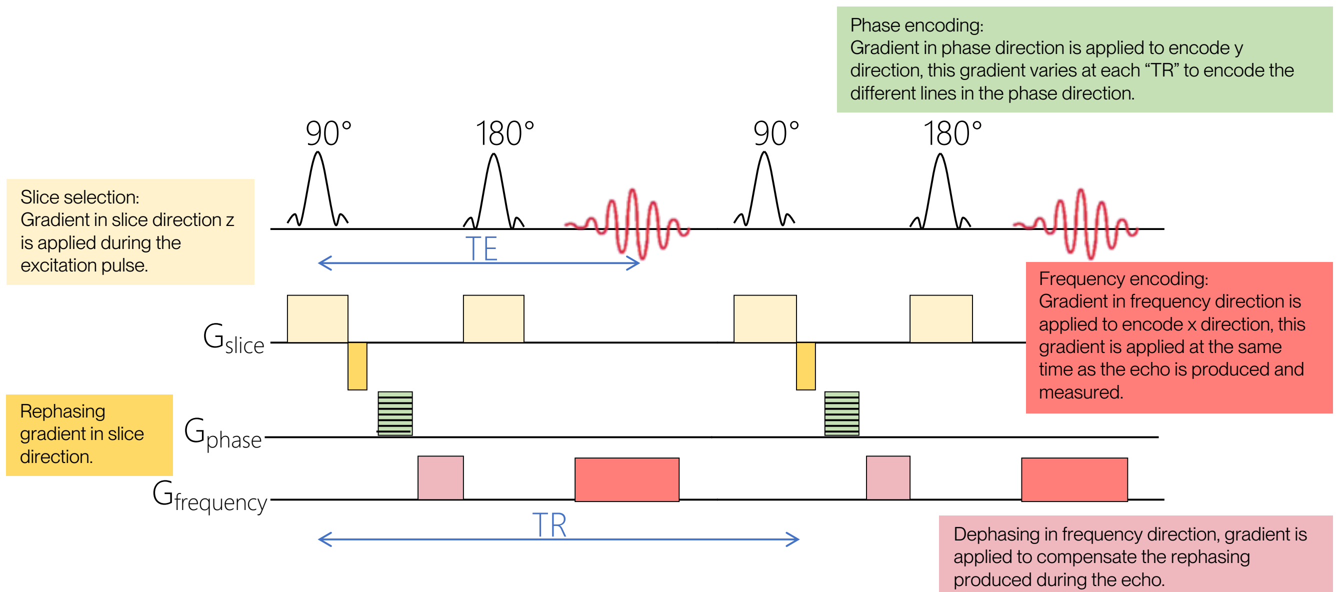
Gradients are added to encode the spatial origin of the signal. The timing diagram of when and where these gradients are applied regarding the excitation RF pulses and the echo reading represents the “MR sequence”.

There are 2 important timing parameters in the sequence :

/ Time between the excitation pulse and the echo: Echo time, TE.

/ Time between two successive excitation pulses: Repetition time, TR.

/ TE and TR are chosen by the operator!



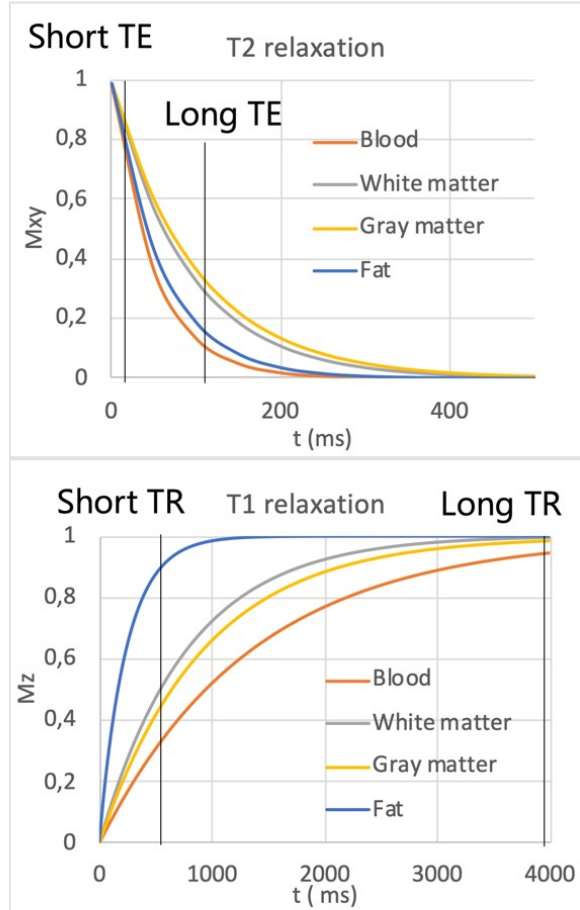
/ Importance of TE and TR for Contrast

Long TE contributes to T2 contrast.

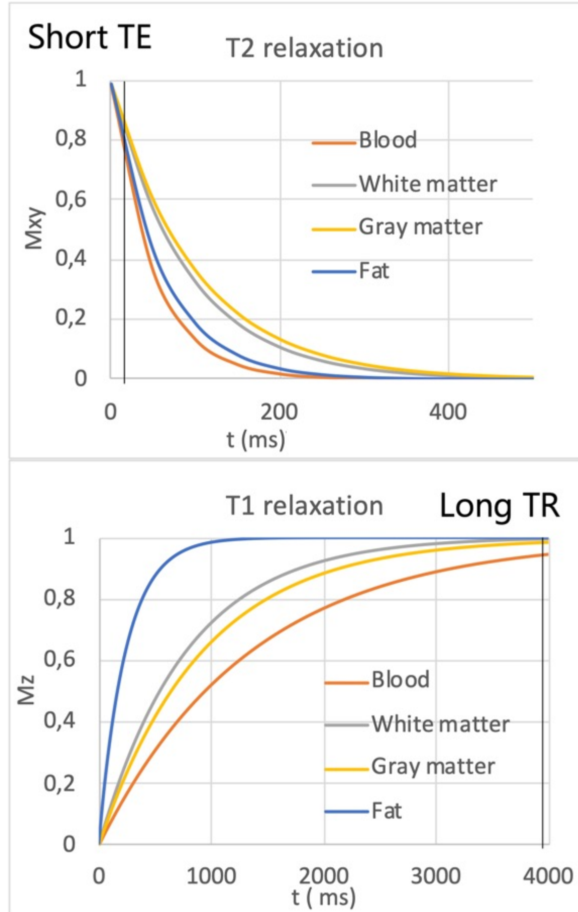
- Signal is less prominent for fast dephasing spins (low T2) than for slow dephasing spins (high T2).
- Short TE does not allow spins to dephase, no contribution of T2 contrast in the signal.

Short TR contributes to T1 contrast.

- Magnetisation regrowing is not complete, slowly growing magnetisation will give less signal (high T1) than fast growing magnetisation (low T1).
- Long TR lets the longitudinal magnetisation regrowth to its original state, no contribution to T1 contrast.



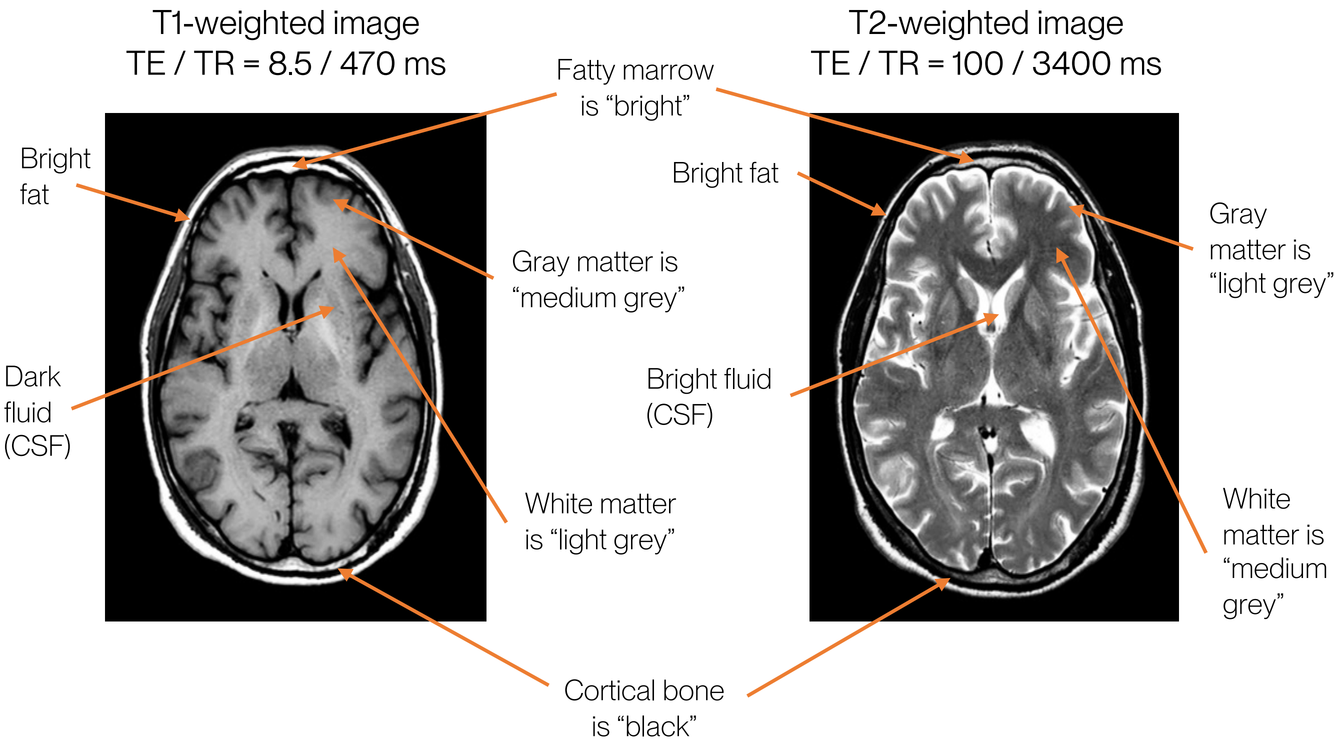
To obtain an image without T1 nor T2 contrast but only sensitive to proton density, a short TE and a long TR should be used.



<>> CORE KNOWLEDGE

Summary:

- Short TE, short TR : T1-weighted image
- Long TE, long TR : T2-weighted image
- Short TE, Long TR : Proton density weighted image
- (Long TE, short TR is not used in practice)



MR Imaging

CHAPTER OUTLINE:

/ MRI Sequences: Why are They so Long?

The **acquisition time** of an MRI sequence depends mainly on TR, on the number of phase encoding lines (matrix) and on the number of slices:

Acquisition time = TR · NPy · Nslices

- TR = Repetition time
- NPy = Number of phase encoding lines
- Nslices = Number of slices

Example for a T1 sequence:
TR = 500 ms, 128 matrix size, 10 slices;
Acquisition time = 0.5 sec * 128 * 10 = 10 min 40 sec!

MRI is a slow acquisition technique!

In practice, several techniques have been developed to accelerate sequence acquisition:

- Typical acquisition time for a 2D sequence covering the whole brain is 2 to 4 minutes.
- Acquisition for 3D sequences is longer, typically around 4 to 6 minutes

The Gradient Echo Sequence

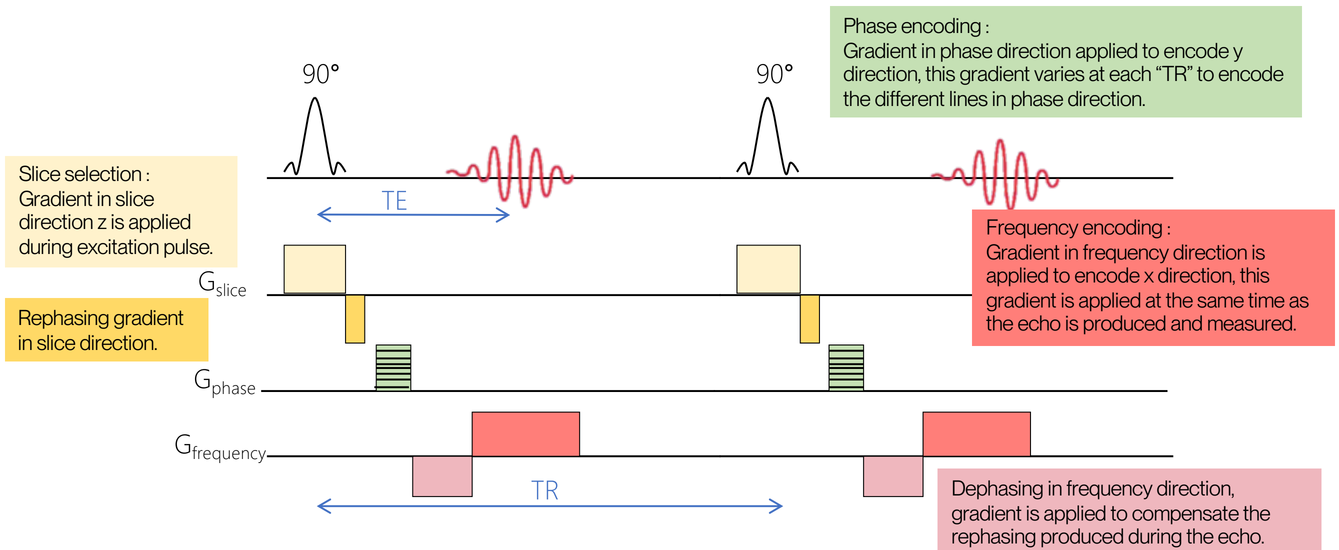
CHAPTER OUTLINE:

/ The Gradient Echo (GRE) Sequence

/ **MR** Imaging

The GRadient Echo (GRE) sequence doesn't use a 180° RF pulse to refocus the dephasing spins but uses instead a gradient to dephase and then rephase the spins, thus creating an echo.

This can shorten a lot the TE and TR and make faster images!
But... it adds dephasing errors, so it is more prone to artifacts.

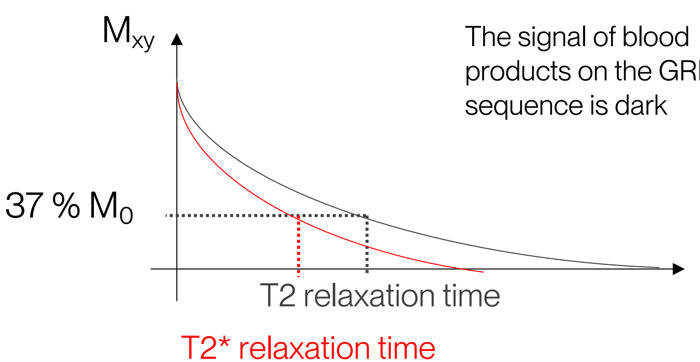


CHAPTER OUTLINE:

Since there is no more refocusing RF pulse, spin dephasing is now due to local magnetic field inhomogeneities in addition to the T2 effect. Therefore, the signal decreases with the T2* constant. The difference between T2 and T2* is that T2 is the ideal spin-spin relaxation caused by atomic/molecular interactions whereas T2* is the observed T2 (i.e., T2 affected by local field inhomogeneities).

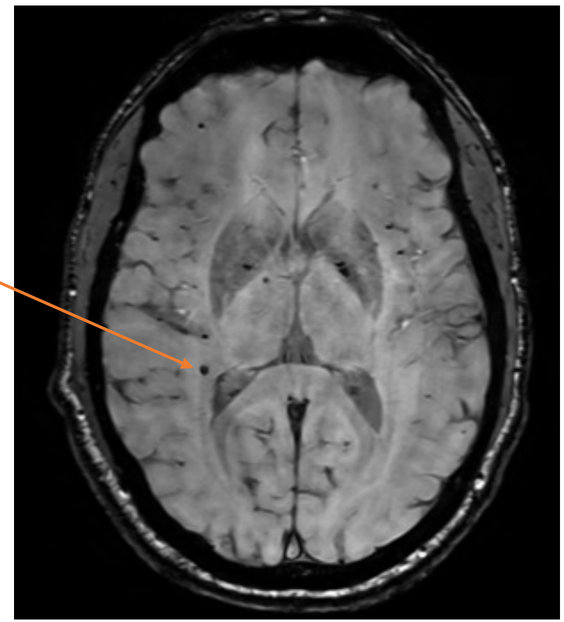
<!> ATTENTION

This effect allows a **high sensitivity to local magnetic inhomogeneities** typically around blood degradation products and calcifications that are locally disturbing the magnetic field.



T2* is always ≤ T2 !

The signal of blood products on the GRE sequence is dark



Other Sequences: The MRI Jungle

CHAPTER OUTLINE:

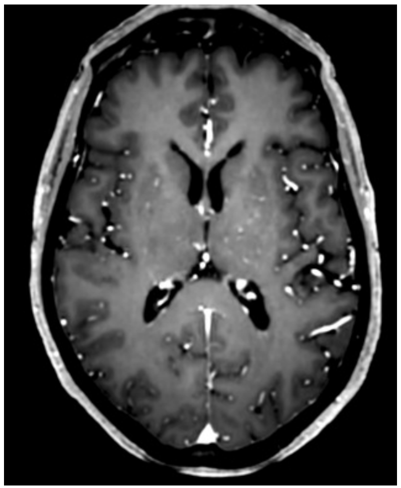
Other Sequences : The MRI Jungle

Many different types of sequences are used for MR imaging named differently by each vendor. Nearly all are derived from SE or GRE sequences.

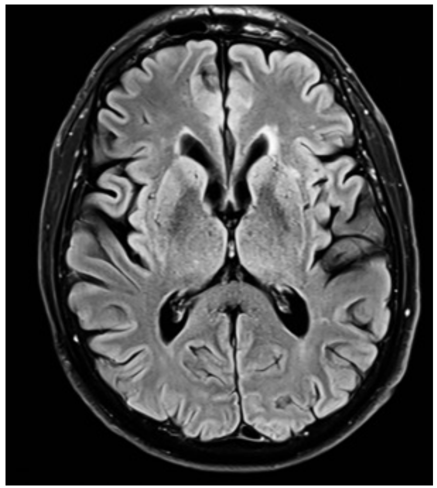
CHAPTER OUTLINE:

/ Inversion Recovery (IR)

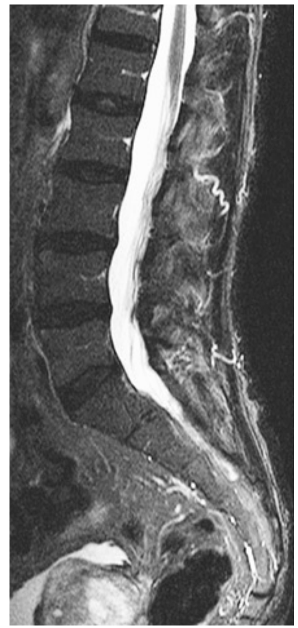
Adding a preparation pulse **before** the acquisition of the signal can increase tissue contrast or remove signal from a specific tissue. The IR-sequence uses an inversion pulse (180°) before the sequence to invert the entire magnetisation. IR techniques are widely used in neuroradiology, head and neck and cardiac Imaging applications.



IR-prepared 3D T1-weighted GRE sequence: Inversion pulse increases white matter/grey matter contrast (this image is acquired after contrast agent injection).



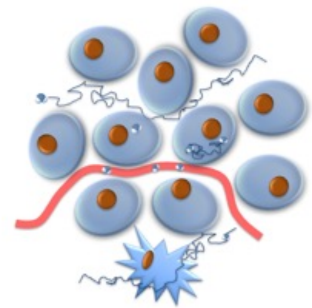
Fluid Attenuated IR (FLAIR): Inversion pulse is used to remove signal from cerebrospinal fluid. Hyperintense signal in white matter lesions is more visible.



STIR : Inversion pulse removes signal from fat. Hyperintense signal due to fluids or oedema is more visible.

/ Diffusion Weighted Imaging (DWI)

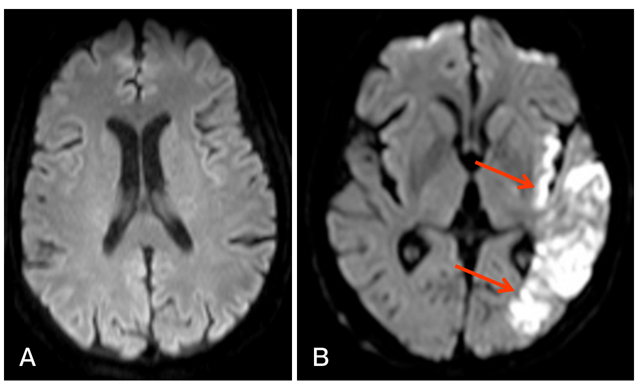
Diffusion is defined as the transport of matter resulting from the migration of **atoms due to the random movements** caused by differences in temperature or concentration.



<!> ATTENTION

One of the successes of MRI is the ability to detect cellular oedema in the very early stages of a stroke, before any other type of imaging modality can show the stroke.

MRI can be sensitive to water molecule diffusion, which depends on the environment (intracellular, extracellular, intravascular water). The MRI signal can, therefore, reflect cellular membrane integrity or cellular density.



Diffusion-weighted Images (b1000) in a normal brain (A) and in a patient with **stroke in the middle cerebral artery** territory (B).

In stroke, due to hypoperfusion, there is failure of the sodium/potassium pumps of cell membranes in the affected areas. This creates an influx of intracellular water, thus decreasing diffusion movement ("restricted diffusion"). On MRI, there is an increased signal on the DWI image.

<!> ATTENTION

Hypercellular tumours also show restricted diffusion because the free movement of water molecules is hindered by the densely packed cells.

/ MR Imaging

CHAPTER OUTLINE:

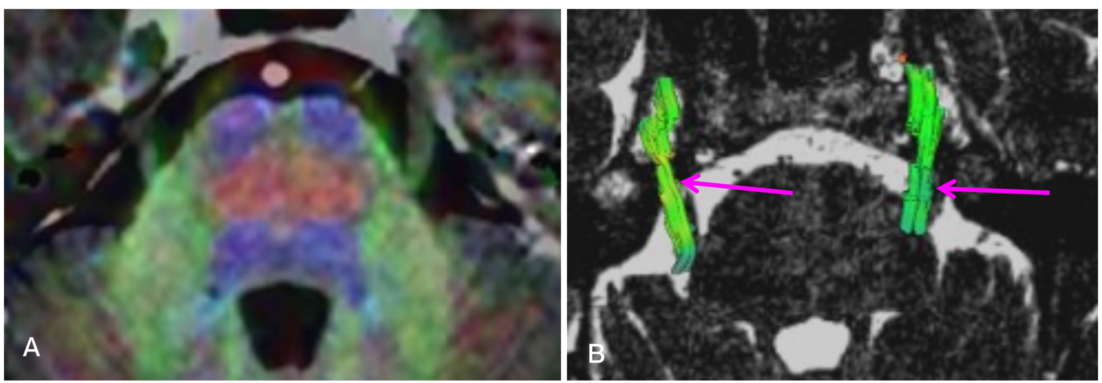
/ Diffusion Tensor Imaging (DTI)

Biological tissues are highly **anisotropic** > i.e., the diffusion rate is NOT the same in all directions.

Water diffusion in the brain is **constrained by fibres**, The MRI signal is sensitive to the **preferential direction of motion** of water molecules. This can be used to "track" fibres and depict white matter tracts. The anatomical orientation of axons and fibres is coded with colours on DTI images, each colour corresponding to a specific direction of the fibres:

- **Red** > transverse orientation
- **Green** > anterior-posterior or posterior-anterior
- **Blue** > craniocaudal orientation

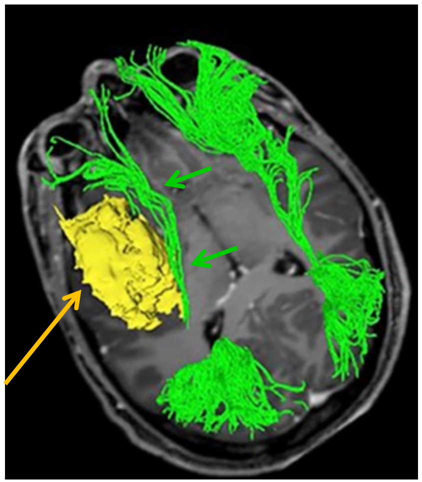
Fibre tracts are then reconstructed depending on the clinical question using a dedicated software. Quantitative measures can be obtained, e.g., measuring the **fractional anisotropy (FA)** which is thought to reflect fibre density, myelination and axonal diameter.



Example of a DTI examination in trigeminal neuralgia. DTI images with overlaid colour-by-orientation fibres at the mid-pontine level (A). Reconstructed tracts of the trigeminal nerves onto colour-by-code orientation (B).

<!> ATTENTION

In addition to showing the 3D representation of fibre tracts, DTI can detect micro-structural changes in the absence of morphologic changes. It can reveal altered white matter connectivity and allows quantitative evaluation of the integrity of different brain circuits in a variety of conditions including tumours, demyelinating diseases, trauma, Parkinson disease, pain syndromes, depression and anxiety disorders and many more.



Example of a left temporo-insular low-grade glioma (LGG) and fibre tract involvement. 3D reconstruction of the tumour (yellow), which involves the fronto-occipital longitudinal fasciculus (green).

Reproduced from: Ius T et al. Risk Assessment by Pre-surgical Tractography in Left Hemisphere Low-Grade Gliomas. Front Neurol. 2021 Feb 15;12:648432. doi: 10.3389/fneur.2021.648432.

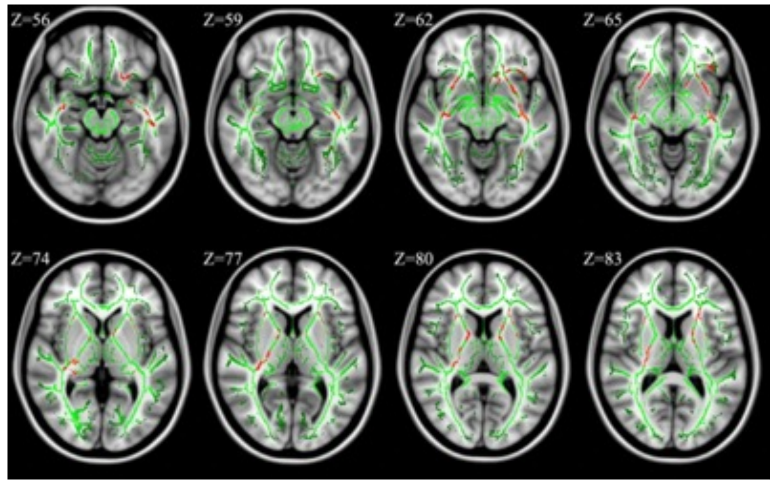


Image illustrating white matter abnormalities in adolescents with generalised anxiety disorder (GAD). Voxels are overlaid on the white matter skeleton (green). The regions of significant FA reduction in comparison to adolescents without GAD are shown in red.

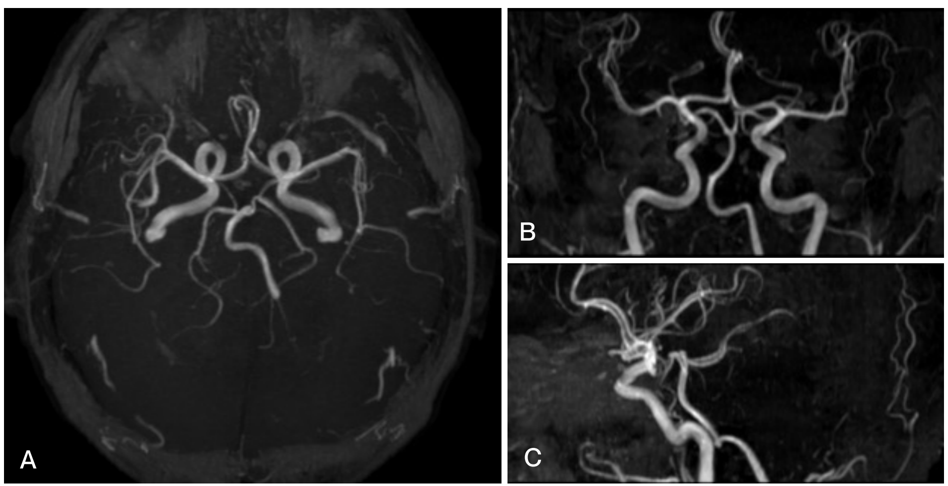
Reproduced from: Liao, M. et al. White matter abnormalities in adolescents with generalized anxiety disorder: a diffusion tensor imaging study. BMC Psychiatry 14, 41 (2014). https://doi.org/10.1186/1471-244X-14-41

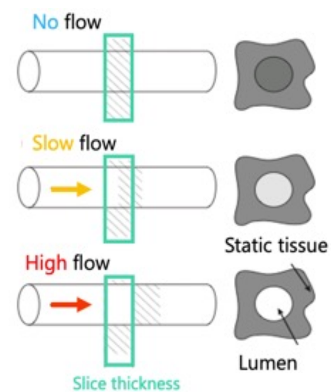
/ Time of Flight (TOF) MR Angiography (MRA)

The Time of Flight (TOF) MRA sequence allows visualisation of flowing blood in vessels thus providing angiographic images **without** the need of injecting contrast agents. The TOF sequence is based on the principle of **flow related enhancement** (i.e., fresh blood has a high initial magnetisation as opposed to stationary tissues, which are magnetically saturated by multiple repetitive RF pulses). On the TOF sequence, the signal of inflowing blood appears very bright (see below). The maximal flow enhancement occurs when the vessel is perpendicular to the imaging plane.

<!> ATTENTION

TOF is one of the most useful techniques for **non-contrast neurovascular and peripheral MRA**
> See eBook chapter on Vascular Imaging





TOF image : Maximum Intensity Projection (MIP) of the polygon of Willis: axial (A), coronal (B) and sagittal (C) views.

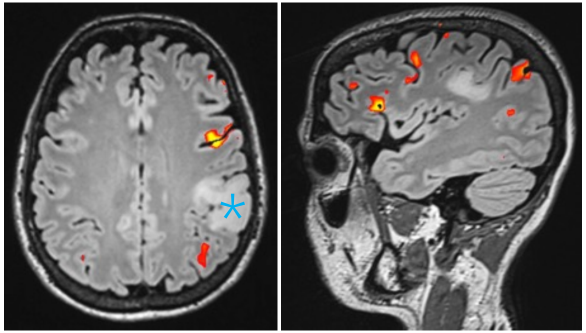
/ Functional MRI (fMRI)

Blood Oxygenation Dependent (BOLD) imaging, is the standard **functional** MRI modality, which provides information about cerebral areas that are activated while performing certain tasks. For example, it is possible to identify the areas of language in the brain. This is very useful to determine if an area is impacted by surgery or if a lesion is located in immediate vicinity of an area that needs to be resected.

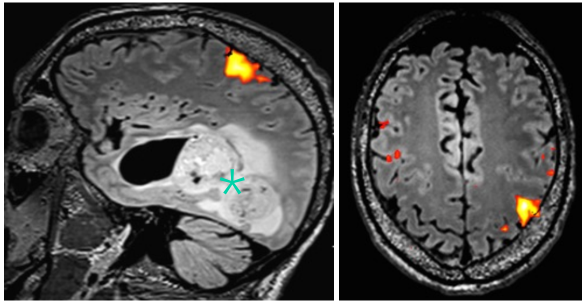
BOLD imaging is based on the principle that if a task leads to an increase in the activity of a specific brain region, there is an **initial drop in oxygenated haemoglobin and an increase in CO_2 and deoxygenated haemoglobin**. After a delay of a few seconds, the increased cerebral blood flow (CBF) delivers a **surplus** of oxygenated haemoglobin, which "washes away" deoxyhaemoglobin.

Oxygenated and deoxygenated haemoglobin differ significantly with respect to their **paramagnetic** properties.

T2* sequences are used to detect these differences, which are in the range of 1-5%.



Example of BOLD fMRI maps obtained in a patient with a high-grade glioma (blue) and silent word generation task producing activation of the left prefrontal cortex and Broca's area. Figure courtesy José Manuel Baiao Boto, Division of Neuroradiology, Geneva University Hospitals.

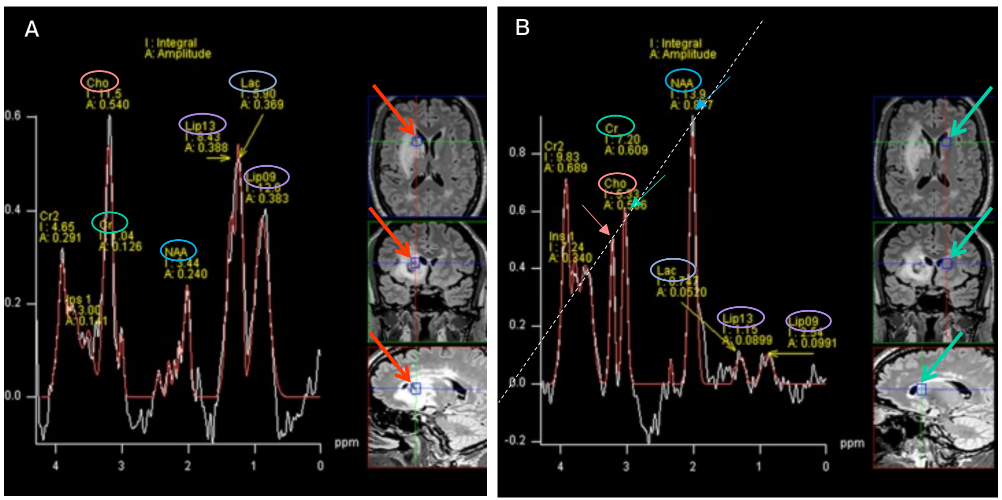


Example of BOLD fMRI maps obtained in a patient with a high-grade glioma (asterisk) and right-sided finger tapping. The contralateral (left) sensorimotor cortex is most strongly activated. Figure courtesy José Manuel Baiao Boto, Division of Neuroradiology, Geneva University Hospitals.

/ MR Spectroscopy (MRS)

MR Spectroscopy (MRS) is a method to measure the chemical composition of tissue. It allows measurement of metabolites **in vivo in specific brain regions** such as N-acetyl aspartate (NAA), Choline (Cho), Creatine (Cr), and others. MRS uses the fact that the proton resonant frequency is **slightly different** for each metabolite compared to water.

MRS is **mostly used in the brain**, but it is not restricted to this area. Advances were made to increase the spatial resolution and even create metabolite maps of the brain. Most common indications for MRS include imaging of gliomas, post-radiation changes, ischemia, white matter and mitochondrial diseases. MRS increases specificity and correlates with the histologic grade of a tumour.



MRS obtained in a patient with a high-grade glioma in the right basal ganglia (red arrows) (A) showing metabolite changes. As the tumour grade increases, NAA and Cho decrease whereas lipids (Lip) and lactate (Lac) increase. Normal MRS metabolites in the left basal ganglia (green arrow), (B). Measurements on the left are used as control. Note that the normal Cho, Cr and NAA peaks are on a line which has a 45-degree angle with the x- axis (Hunter's angle). Figure courtesy José Manuel Baiao Boto, Division of Neuroradiology, Geneva University Hospitals.

/ MR Imaging

CHAPTER OUTLINE:

Contrast Agents in MRI

CHAPTER OUTLINE:

MRI Contrast Agents

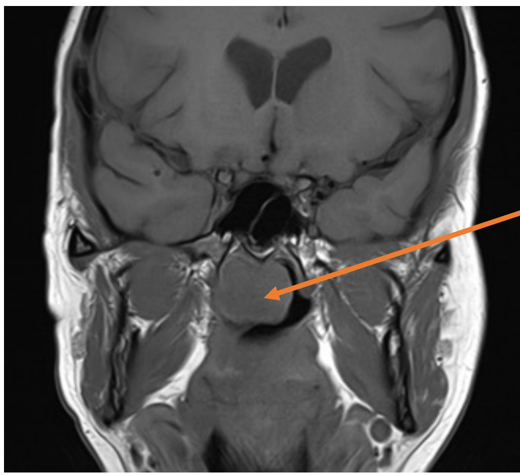
Contrast agents (CA)s used in MRI are mostly based on gadolinium chelates. Gadolinium is paramagnetic and has the property of reducing T1 relaxation of surrounding tissues, thus rendering them hyperintense on T1 contrast. At high concentrations, gadolinium-based CA also shortens T2 relaxation time. It normally stays extracellular in the circulation and microcirculation system and it is excreted by the kidneys.

ATTENTION

Safety: Nephrogenic Systemic Fibrosis (NSF)

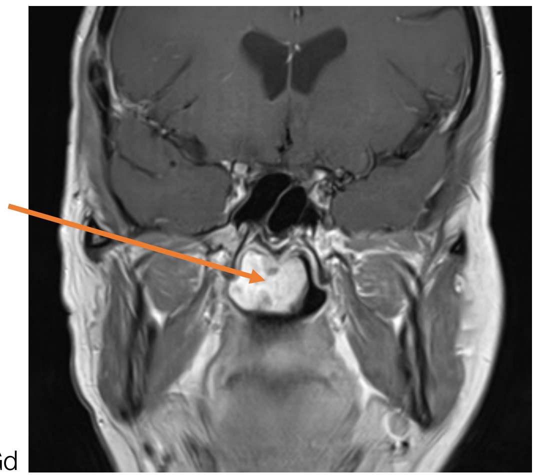
In 2006 gadolinium-based contrast agents were recognised to be the potential triggers of a late inflammatory and fibrotic disease of soft tissues in patients with severe renal function impairment: nephrogenic systemic fibrosis (NSF). Even though NSF is rare it remains mandatory to **screen patients for renal dysfunction prior to Gd-chelate administration, and to assess risk and benefits** prior to contrast agent injection.

> See eBook chapter on Contrast Agents.



T1 SE

Enhancing signal in the lesion after contrast injection



T1 SE with Gd

MR Imaging

Gadolinium (Gd) accumulation in the central nervous system

Accumulation of Gd in central nervous system (CNS), basically in the basal ganglia, was reported in patients with multiple administrations of Gd-chelates (2014).

The trans-metalation reaction is a possible mechanism by which the Gd ion is extracted from the chelate by another cation. It has been shown that Gd-chelates with a linear configuration are more at risk to accumulate in the CNS than macrocyclic chelates **> see eBook chapter Contrast Agents**.

This is the reason why the European Medicines Agency recommended to suspend or limit the use of commercially available **linear Gd-based contrast agents**.

Even though Gd accumulation is now well described, there is **no evidence of clinical short- or long-term effects. Precaution principle has to be applied** by reducing amount and frequency of Gd injection when possible.

<∞> REFERENCE

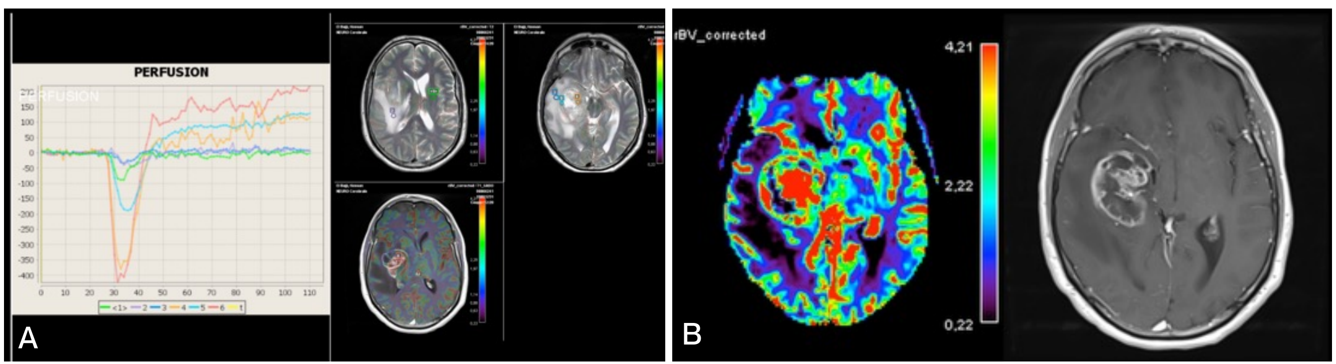
Kanda T, Ishii K, Kawaguchi H, et al. High signal intensity in the dentate nucleus and globus pallidus on unenhanced T1-weighted MR images: relationship with increasing cumulative dose of a gadolinium-based contrast material. Radiology 2014; 270:834-841. (Landmark first report of Gd accumulation in the brain).

/ MRI Perfusion Weighted Imaging (PWI)

MRI PWI encompasses different MRI techniques used to assess **the perfusion of tissues by blood**. To assess perfusion, contrast-enhanced techniques and non-contrast enhanced techniques (e.g., arterial spin labelling, ASL) can be applied.

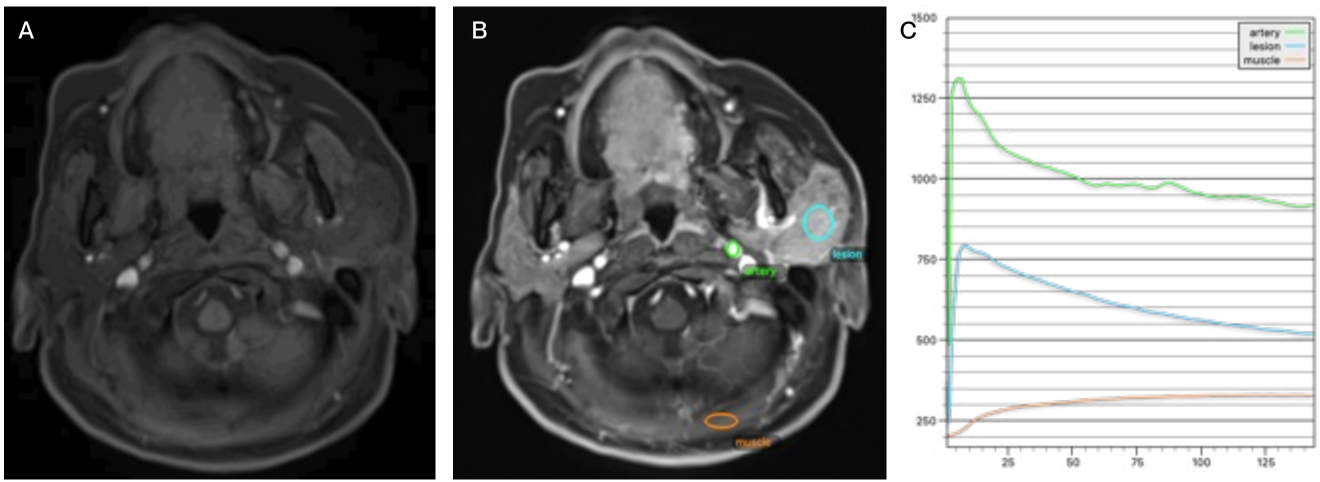
Dynamic Susceptibility Contrast (DSC) MRI PWI relies on the signal loss induced by a bolus of Gd-based contrast agent **on T2*-weighted sequences**. The calculated parameters include a **Time signal Intensity Curve (TIC)** from which **cerebral blood volume (CBV** = volume of blood in a given brain tissue amount in ml blood/100g brain tissue), **cerebral blood flow (CBF** = CBV per unit of time, in ml blood/100g brain tissue/minute) and other parameters are calculated. These parameters are then used to create colour maps of the brain. Due to the difficulty to precisely calculate CBV and CBF, most often CBV / CBF relative to an internal control, e.g., contralateral normal white matter are calculated (rCBV and rCBF). rCBV and rCBF have no units as they correspond to ratios.

T2*-weighted DSC MRI perfusion in a patient with a glioblastoma. A. TICs obtained in different regions of interest (ROIs). B. rCBV colour map and the corresponding axial contrast enhanced T1 weighted image showing increased tumour perfusion. Figure courtesy José Manuel Baiao Boto, Division of Neuroradiology, Geneva University Hospitals.



Dynamic Contrast Enhanced (DCE) MRI PWI is one of the most important MRI PWI techniques. Perfusion parameters are calculated on the basis of **T1 shortening effects** due to the bolus of Gd-based contrast agent passing through tissue. The following parameters are calculated: TICs, k-trans (= volume transfer constant from blood plasma to extravascular extracellular space), fractional volume of extravascular-extracellular space, and others. TICs are very useful for the characterisation of certain tumours. For example, certain TIC types can be found only in malignant tumours whereas other TIC types only in benign lesions.

DCE MRI PWI is mainly used for oncologic imaging.



T1-weighted Dynamic Contrast Enhanced (DCE) PWI in a patient with a diffusely infiltrating left parotid tumour. A. Time resolved dynamic sequence. B. ROIs placed for measurements (carotid artery - green, parotid tumour - blue, muscle - orange). C. Time-intensity curves (TIC)s in the different regions of interest shown in B. TIC colours correspond to the ROIs indicated in B.

CHAPTER OUTLINE:

Artefacts in MRI

MR Imaging

CHAPTER OUTLINE:

Artefacts in MRI

The image acquisition process can be responsible for different artifacts in the image, some can easily be addressed while other not. MRI sequence optimisation requires understanding of numerous parameters, this ability is essential to obtain images with the best mitigation of artefacts.

Recognition of these artefacts in the images is an important part of the radiologist experience!

Origin of artefacts can be separated in three categories:

- Technique :
  - Type of sequence
  - Parameters

CAN BE CORRECTED

- Patient :
  - Motion (uncontrollable)
  - Breathing, blood flow
  - Implants, tattoo, piercing, ...

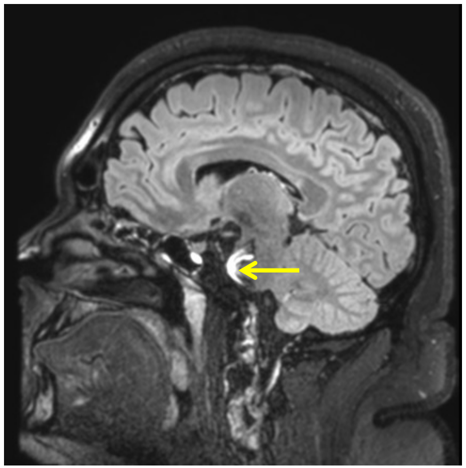
CAN BE MITIGATED WITH SPECIFIC TECHNIQUES

- Hardware :
  - Receiver coil, RF coil, gradient coils
  - Faraday cage

HAS TO BE REPAIRED

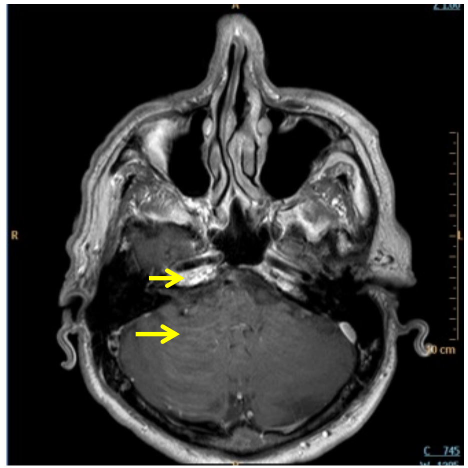
/ Artefacts: Examples

Artefact due the technique: wrong parameters of the sequence.



Fold over artefact: nose (outside of the field of view) is projected in the centre of the image!

Artefact due to the patient: blood flow in arteries.



Flow artefact: signal from blood flowing in arteries is propagated in the phase encoding direction.

Artefact due to the patient: presence of braces

Susceptibility artefact: signal loss due to presence of metal in the mouth (braces), magnetic field perturbation extends largely outside the mouth.

MRI Advantages and Dis-advantages

CHAPTER OUTLINE:

/ MRI Advantages and Disadvantages

>|< COMPARE

ADVANTAGES:

+ Non-ionising modality suitable for follow-up examinations.
+ Excellent soft tissue contrast (ligaments, tendons, muscles, brain grey and white matter, ...).
+ Different type of contrast images available (sensitive to fluid, with fat suppression, ...).
+ Good image resolution, 2D images in any orientation and 3D images possible.
+ Anatomical but also functional imaging possible (diffusion, perfusion, fMRI, MRS, ...).

DISADVANTAGES:

– Not all implants are allowed in the magnetic field.
– Not suitable for claustrophobic patients (larger bore available nowadays).
– Noisy and generally long examinations.
– More expensive than CT or X-ray.
– Requires good knowledge of the technique (sequence optimisation and artefact mitigation).

/ Take-Home Messages

- MRI is a non-ionising, non-invasive imaging modality.
- It provides excellent soft tissue contrast and offers unique anatomical and functional information.
- Some restrictions or contraindications exist for patients with implanted material or devices.
- The main magnet is used to magnetise the tissues.
- Radiofrequency is applied to tip magnetisation out of equilibrium states.
- Gradients are added to encode the spatial origin of the signal.
- Finally, the acquired signal requires a Fourier transform to obtain the final image.
- Images can be sensitive to T1 and T2 relaxation of the tissues by appropriately tuning TE and TR of the sequence.
- Two main type of sequences are the spin echo and the gradient echo sequences.
- Contrast agents can be used to enhance pathology visualisation; they are mainly gadolinium-based.

CHAPTER OUTLINE:

/ References

Excellent websites to understand the MRI technique and all its related questions :

- https://www.imaios.com/en/e-mri
- https://mriquestions.com/index.html

MRI safety :

- A Practical Guide to MR Imaging Safety: What Radiologists Need to Know
  Leo L. Tsai, Aaron K. Grant, Koenraad J. Mortele, Justin W. Kung, and Martin P. Smith
  RadioGraphics 2015 35:6, 1722-1737

MRI physics :

- Plewes, D.B. and Kucharczyk, W. (2012), Physics of MRI: A primer. J. Magn. Reson. Imaging, 35: 1038-1054. https://doi.org/10.1002/jmri.23642

Sequences:

- Jung, B.A. and Weigel, M. (2013), Spin echo magnetic resonance imaging. J. Magn. Reson. Imaging, 37: 805-817. https://doi.org/10.1002/jmri.24068

- MR Pulse Sequences: What Every Radiologist Wants to Know but Is Afraid to Ask
  Richard Bitar, General Leung, Richard Perng, Sameh Tadros, Alan R. Moody, Josee Sarrazin, Caitlin McGregor, Monique Christakis, Sean Symons, Andrew Nelson, and Timothy P. Roberts
  RadioGraphics 2006 26:2, 513-537

CHAPTER OUTLINE:

Test Your Knowledge

/ Test Your Knowledge

<?> QUESTION

1

Some objects will be attracted by an uncontrollable force into the MRI scanner bore due to the main magnetic field; these are:

- ☐ Ferromagnetic objects (Iron, nickel, cobalt and their alloys)
- ☐ Metallic objects (all that are electrically conductive)
- ☐ All medical implants without exception

/ Test Your Knowledge

<?> ANSWER

1

Some objects will be attracted by an uncontrollable force into the MRI scanner bore due to the main magnetic field; these are:

- ■ Ferromagnetic objects (Iron, nickel, cobalt and their alloys)
- ☐ Metallic objects (all that are electrically conductive)
- ☐ All medical implants without exception

/ Test Your Knowledge

<?> QUESTION

2 Which element of the MRI system allows encoding spatial origin of the signal emitted:

- ☐ Main magnet
- ☐ Radiofrequency
- ☐ Gradients x,y,z

/ Test Your Knowledge

<?> ANSWER

2

Which element of the MRI system allows encoding spatial origin of the signal emitted:

- ☐ Main magnet
- ☐ Radiofrequency
- ■ Gradients x,y,z

/ Test Your Knowledge

<?> QUESTION

3 The magnetisation of the tissues occurs when:

- ☐ The MRI sequence is starting
- ☐ The subject receives radiofrequency wave
- ☐ The subject is lying on the table inside the scanner bore

/ Test Your Knowledge

<?> ANSWER

3 The magnetisation of the tissues occurs when:

- [ ] The MRI sequence is starting
- [ ] The subject receives radiofrequency wave
- [x] The subject is lying on the table inside the scanner bore

/ Test Your Knowledge

<?> QUESTION

4 The echo time TE is the time between:

- ☐ The RF excitation pulse and the RF refocusing pulse in the spin echo sequence
- ☐ The RF excitation pulse and the echo emission in the gradient echo sequence
- ☐ Two consecutive RF excitation pulses

CHAPTER OUTLINE:

/ Test Your Knowledge

<?> ANSWER

4 The echo time TE is the time between:

- ☐ The RF excitation pulse and the RF refocusing pulse in the spin echo sequence
- ■ The RF excitation pulse and the echo emission in the gradient echo sequence
- ☐ Two consecutive RF excitation pulses

/ Test Your Knowledge

<?> QUESTION

5 The repetition time TR is the time between:

- ☐ The RF excitation pulse and the RF refocusing pulse in the spin echo sequence
- ☐ The RF excitation pulse and the echo emission in the gradient echo sequence
- ☐ Two consecutive RF excitation pulses

/ Test Your Knowledge

<?> ANSWER

5 The repetition time TR is the time between:

- ☐ The RF excitation pulse and the RF refocusing pulse in the spin echo sequence
- ☐ The RF excitation pulse and the echo emission in the gradient echo sequence
- ■ Two consecutive RF excitation pulses

/ Test Your Knowledge

<?> QUESTION

6 T1-weighted contrast is obtained with:

- ☐ A short TE and a short TR
- ☐ A long TE and a short TR
- ☐ A long TE and a long TR

/ Test Your Knowledge

<?> ANSWER

6 T1-weighted contrast is obtained with:

- ■ A short TE and a short TR
- ☐ A long TE and a short TR
- ☐ A long TE and a long TR

/ Test Your Knowledge

<?> QUESTION

7

For a T2-weighted image, a long TR is used so that the magnetisation is regrowing to its initial state at equilibrium between each successive RF pulse. How should the TE be?

- ☐ Short TE
- ☐ Long TE
- ☐ TE should equal TR/2

/ Test Your Knowledge

<?> ANSWER

7 For a T2-weighted image, a long TR is used so that the magnetisation is regrowing to its initial state at equilibrium between each successive RF pulse. How should the TE be?

- ☐ Short TE
- ■ Long TE
- ☐ TE should equal TR/2

/ Test Your Knowledge

<?> QUESTION

8 Which sentence is correct:

- ☐ An MRI exam is cheap and fast
- ☐ An MRI exam is long and more expensive than CT
- ☐ An MRI exam is very quiet

CHAPTER OUTLINE:

Test Your Knowledge

<?> ANSWER

8 Which sentence is correct:

- ☐ An MRI exam is cheap and fast
- ■ An MRI exam is long and more expensive than CT
- ☐ An MRI exam is very quiet

/ Test Your Knowledge

<?> QUESTION

9 With an MRI I can get:

- ☐ Excellent soft tissue contrast but no other information
- ☐ Anatomical images, information about water diffusion, parameters related to brain activation for motor task
- ☐ Excellent bone contrast and poor discrimination of soft tissues

/ Test Your Knowledge

<?> ANSWER

9 With an MRI I can get:

- ☐ Excellent soft tissue contrast but no other information
- ■ Anatomical images, information about water diffusion, parameters related to brain activation for motor task
- ☐ Excellent bone contrast and poor discrimination of soft tissues

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