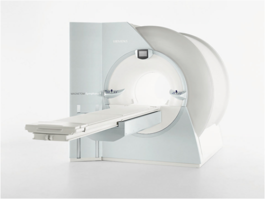
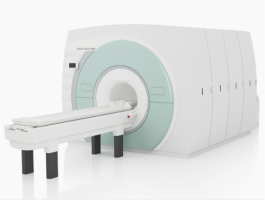
Magnetic Resonance Imaging

Magnetic Resonance Imaging

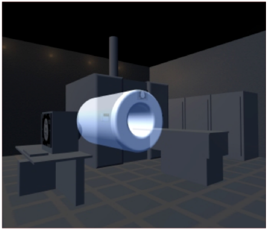
Introduction



Mangetom Symphony 1.5T



Mangetom Symphony 7T

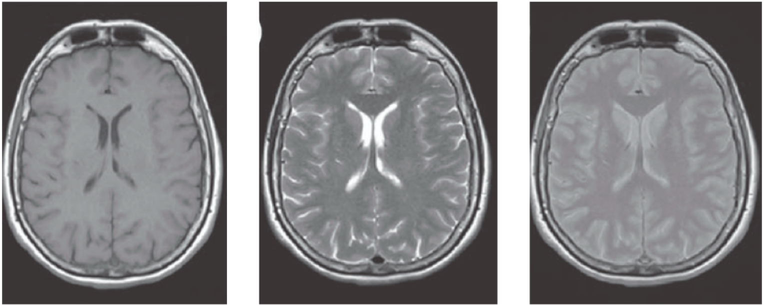


- T ... Tesla (unit for magnetic field density)
- For comparison: Earth's magnetic field: 5×10^{-5}T

Image courtesy of Siemens Healthcare.

Magnetic Resonance Imaging

Examples



From *left to right*: T_1-weighted, T_2-weighted, Proton density

At the end of the lecture, we should be able to explain the different appearances of the tissue types.

Magnetic Resonance Imaging

With MR Imaging ...

- ... we get high-resolution information of anatomic structures
- ... we get high-contrast for soft-tissue types
- ... we have *no* exposure to radiation!

However,

- ... we have more complicated instrumentation
- ... scan acquisition takes longer (problem with patient motion)
- ... precautions must be taken to keep metal objects away
- ... imaging is expensive (acquisition, maintenance, operation)

To understand MR imaging, we need to understand Nuclear Magnetic Resonance (NMR) first.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

- Spin is a fundamental property of nature (like electric charge)
- Spin comes in multiples of $1/2$ and can be positive or negative
- Protons/electrons/neutrons possess spin of $+1/2$ or $-1/2$
- Particles of opposite spin eliminate observable spin

Unpaired spins

In nuclear magnetic resonance, *unpaired* nuclear spins are of importance.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

A nucleus consists of protons and neutrons (aka "nucleons").

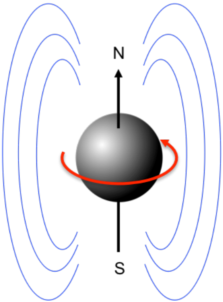
When the total number of protons and neutrons is *odd*, or the number of protons is odd, the spin gives the nucleus

1. (spin) angular momentum, and
2. magnetic moment.

Formulated very simplistically, the spin causes the nucleus to behave like a *tiny magnet*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)



Spin angular momentum is quantized, i.e.,

$$|\mathbf{s}| = \sqrt{q(q+1)}\hbar$$

with $q = {}^{n}/_{2}$, $n \in \mathbb{N}_+$ and $\hbar$ being the *reduced Planck constant.*

The magnetic moment of the nucleus is

$$\boldsymbol{\mu} = \gamma \boldsymbol{s}, \text{ with } \gamma = \frac{g\mu_m}{\hbar}$$

being the gyromagnetic ratio.

For ^{1}H (hydrogen), $n = 1 \Rightarrow q = 1/2$ and $\gamma/2\pi$ is 42.58Mhz/T.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Note

Spin angular momentum only says something about the *speed* of rotation, *not* about the orientation direction.

Nuclei with spin can be imaged by MRI! Below is a table[1] with isotopes relevant to MRI:

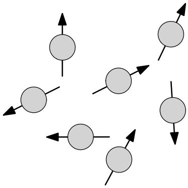
Nucleus	Spin	$\gamma/2\pi$ Mhz/T	Concentration
Hydrogen ^{1}H	$1/2$	42.58	88M
Sodium ^{23}Na	$3/2$	11.27	80mM
Oxygen ^{17}O	$5/2$	-5.77	16mM

[1] M…Molar, mM…milliMolar

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

In the absence of external magnetic field, the spin orientations of the nuclei are *random* and cancel each other.



Without external magnetic field
(the distribution of magnetic moments is isotropic)

Particles with $q = 1/2$ have $(2q + 1)$ energy sublevels with slightly different energy; these are *degenerate* without an external field.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

When placed in an (external) magnetic field $\mathbf{B}_0$, the energy of a nucleus is

$$E = -\langle \boldsymbol{\mu}, \mathbf{B}_0 \rangle$$

In general, for the z-component of $\boldsymbol{\mu}$ we have

$$\mu_z = \gamma m \hbar$$

with m as the *magnetic quantum number* $m = -q, -q+1, \ldots, +q$.

By convention, we consider an external magnetic field $\mathbf{B}_0$, aligned with the z-direction. We get (for the energy)

$$E_m = -\mu_z B_0 = -\gamma m B_0 \hbar$$

Example for ^{1}H, i.e., $m = \pm{}^1\!/_2$:

$$E_{+1/2} = -\gamma {}^1\!/_2 B_0 \hbar$$
$$E_{-1/2} = +\gamma {}^1\!/_2 B_0 \hbar$$

Consequently, $\Delta E = \gamma \hbar B_0$, or

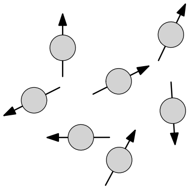
$$\Delta E = \gamma \hbar B_0 = \gamma \frac{h}{2\pi} B_0 = h \underbrace{\frac{\gamma}{2\pi} B_0}_{\nu_L} = h\nu_L,$$

where ν_L is referred to as the Lamor frequency.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

At the same time, in the presence of an external magnetic field spins tend to align with the magnetic field lines.



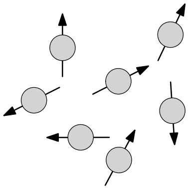
Without external magnetic field

(the distribution of magnetic moments is isotropic)

Magnetic Resonance Imaging

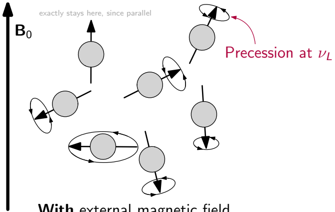
Physics primer – Nuclear Magnetic Resonance (NMR)

At the same time, in the presence of an external magnetic field spins tend to align with the magnetic field lines.



Without external magnetic field

(the distribution of magnetic moments is isotropic)



With external magnetic field

(the distribution of magnetic moments is slightly **skewed** now)

We do observe a torque of

$$\mathbf{t} = \boldsymbol{\mu} \times \mathbf{B}_0$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

We know that torque is also defined as the time-derivative of the angular momentum (in our case: spin angular momentum), i.e.,

$$\mathbf{t} = \frac{d}{dt}\mathbf{s} = \frac{1}{\gamma}\frac{d}{dt}\boldsymbol{\mu}$$

With $\mathbf{t} = \boldsymbol{\mu} \times \mathbf{B}_0$ from above, we have

$$\frac{d\boldsymbol{\mu}}{dt} = \gamma\boldsymbol{\mu} \times \mathbf{B}_0$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

For the net magnetization $\mathbf{M}$ (and omitting indices in $\mathbf{B}_0$), we have the motion equation

$$
\begin{aligned}
\frac{d}{dt}\mathbf{M} &= \frac{d}{dt}\sum_i \boldsymbol{\mu}_i \\
&= \sum_i \frac{\boldsymbol{\mu}_i}{dt} \\
&= \sum_i \gamma(\boldsymbol{\mu}_i \times \mathbf{B}) \\
&= \gamma(\mathbf{M} \times \mathbf{B})
\end{aligned}
$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

In other words, **M** precesses around the axis of the external field (in our case around the *z*-axis, see previous slides).

Net magnetization

In a static magnetic field $\mathbf{B}_0$, we refer to $\mathbf{M}_0$ as the *net magnetization*

We will next consider this in a more formal setting.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Splitting $\gamma(\mathbf{M} \times \mathbf{B})$ up (by components), we get

$$\frac{d}{dt}M_x = \gamma(M_y B_z - M_z B_y)$$
$$\frac{d}{dt}M_y = \gamma(M_z B_x - M_x B_z)$$
$$\frac{d}{dt}M_z = \gamma(M_x B_y - M_y B_x)$$

This is, however, only true if the spins would be *independent* of each other.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

The Bloch equations describe the motion equations for magnetization in an external magnetic field.

$$
\begin{aligned}
\frac{d}{dt}M_x &= \gamma(M_y B_z - M_z B_y) - \frac{1}{T_2}M_x \\
\frac{d}{dt}M_y &= \gamma(M_z B_x - M_x B_z) - \frac{1}{T_2}M_y \\
\frac{d}{dt}M_z &= \gamma(M_x B_y - M_y B_x) - \frac{1}{T_1}(M_z - M_0)
\end{aligned}
$$

These equations take into account interdependencies between spins, i.e., *spin-spin relaxation* and *spin-lattice relaxation*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Lets consider one concrete example (without relaxation) of $\mathbf{B}_0$ parallel to the z-axis.

$$\text{We have } \mathbf{B}_0 = \begin{pmatrix} 0 \\ 0 \\ B_0 \end{pmatrix} \Rightarrow \frac{d}{dt}\mathbf{M} = \begin{pmatrix} +\gamma B_0 M_y \\ -\gamma B_0 M_x \\ 0 \end{pmatrix}$$

The solution to this motion equation (without derivation) is

$$\begin{pmatrix} M_x(t) \\ M_y(t) \\ M_z(t) \end{pmatrix} = \begin{pmatrix} m_0 \cos(w_0 t) \\ m_0 \sin(w_0 t) \\ C \end{pmatrix}$$

with $w_0 = \nu_L$ being the Lamor frequency and $\mathbf{M}(0) = m_0$.

The net magnetization $\mathbf{M}_0$ results from *more* nuclear spins in the energetically lower state (out of $2q + 1 = 2$)

The ratio N_+/N_- of energy levels is governed by

$$\frac{N_+}{N_-} = e^{-\frac{E_+ - E_-}{kT}} = e^{-\frac{\Delta E}{kT}} = e^{-\frac{\gamma \hbar B_0}{kT}}$$

where k is the Bolzmann constant and T is temperature (e.g. $\approx$ 310 Kelvin for a human body).

$\Rightarrow$ Larger $\mathbf{B}_0$ lead to greater net magnetization.

Example for a 3T (Tesla) field $\mathbf{B}_0$:

There are only about 10/million! more protons parallel to the field than anti-parallel.

In practice, we want large magnetic fields (e.g., 7T scanner).

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Spins in energetically lower states can absorb photons and *switch* to the energetically higher state and vice versa.

If we emit radiation, this *switch* happens if the emitted energy E equals ΔE and, since, $E = hf$ for photons, we have

$$f = \nu_L,$$

i.e., the Lamor frequency.

Example: In a 1.5T B_0 field, ν_L for hydrogen and carbon 13 (the atoms most relevant in medical imaging) are 63.9 and 16.1 MHz.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Next, we consider the relaxation mechanisms by introducing a rotating coordinate system (x', y', z) which rotates at the Lamor frequency around the z-axis.

The following parts of the Bloch equations remain

$$\frac{dM_{x'}}{dt} = -\frac{1}{T_2} M_{x'}$$
$$\frac{dM_{y'}}{dt} = -\frac{1}{T_2} M_{y'}$$
$$\frac{dM_z}{dt} = -\frac{1}{T_1} (M_z - M_0)$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

The solution(s) are (without derivation):

$$
\begin{aligned}
M_{x'}(t) &= M_{x',0}e^{-t/T_2} \\
M_{y'}(t) &= M_{y',0}e^{-t/T_2} \\
M_z(t) &= (M_{z,0} - M_0)e^{-t/T_1} + M_0
\end{aligned}
$$

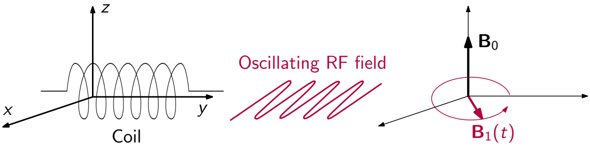
Lets try initial values at the equilibrium state, i.e., $M_{x',0} = M_{y',0} = 0$ and $M_{z,0} = M_0$.

$\Rightarrow$ We get the original precession equations back.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

We are now in the position to consider an additional oscillating magnetic field $\mathbf{B}_1$.



The field is generated by a coil and oriented perpendicular to $\mathbf{B}_0$. With $\mathbf{B}_1(t) = B_1(\cos(w_{ext}t), -\sin(w_{ext}t), 0)^\top$ we get

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1(t) = \begin{pmatrix} +B_1\cos(w_{ext}t) \\ -B_1\sin(w_{ext}t) \\ B_0 \end{pmatrix}$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

We need the nuclei to switch their magnetic moment. This is achieved through the oscillating $\mathbf{B}_1(t)$ field whose photons carry the energy

$$\Delta E = h\nu_L.$$

For *resonance*, i.e., to change energy states, $\mathbf{B}_1(t)$ needs to oscillate at the Lamor frequency $w_{ext} = \nu_L$.

In the following, we will use the Bloch equations to describe what happens to the net magnetization.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

To make our life easier, we switch coordinate systems again. The new axes $\mathbf{x}', \mathbf{y}', \mathbf{z}'$ are:

$$\mathbf{x}' = \begin{pmatrix} +\cos(w_{ext}t) \\ -\sin(w_{ext}t) \\ 0 \end{pmatrix}, \ \mathbf{y}' = \begin{pmatrix} +\sin(w_{ext}t) \\ +\cos(w_{ext}t) \\ 0 \end{pmatrix}, \ \mathbf{z}' = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Remark: $\langle \mathbf{x}', \mathbf{y}' \rangle = 0$.

Lets look at the Bloch equations (without relaxation first). In the rotating new coordinate system we get

$$\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} = \left(\frac{d}{dt}\mathbf{M}\right)_{\text{stat}} + M_x\frac{\partial \mathbf{x}'}{\partial t} + M_y\frac{\partial \mathbf{y}'}{\partial t} + M_z\frac{\partial \mathbf{z}'}{\partial t}$$

The partial derivatives are

$$\frac{\partial \mathbf{x}'}{\partial t} = -w_{ext}\mathbf{y}',\ \frac{\partial \mathbf{y}'}{\partial t} = -w_{ext}\mathbf{x}',\ \frac{\partial \mathbf{z}'}{\partial t} = 0$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

$$\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} = \left(\frac{d}{dt}\mathbf{M}\right)_{\text{stat}} + M_x\frac{\partial \mathbf{x}'}{\partial t} + M_y\frac{\partial \mathbf{y}'}{\partial t} + M_z\frac{\partial \mathbf{z}'}{\partial t}$$

We simply use our expression for **B**, i.e.,

$$\begin{aligned}\left(\frac{d}{dt}\mathbf{M}\right)_{\text{stat}} &= \gamma(\mathbf{M} \times (\mathbf{B}_0 + \mathbf{B}_1(t)) \\ &= \gamma(\mathbf{M} \times (B_0\mathbf{z}' + B_1\mathbf{x}')\end{aligned}$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Also, we can write the partial derivatives as

$$-w_{ext}(M_x\mathbf{y}' - M_y\mathbf{x}') = -w_{ext}(\mathbf{M} \times \mathbf{z}')$$

Rearranging and collecting terms lead to

$$\begin{aligned}\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} &= \gamma\left(\mathbf{M} \times \left[\left(B_0 - \frac{w_{ext}}{\gamma}\right)\mathbf{z}' + B_1\mathbf{x}'\right]\right) \\ &= \gamma\left(\mathbf{M} \times \mathbf{B}_{eff}\right)\end{aligned}$$

with

$$\mathbf{B}_{eff} = \left(\left(B_0 - \frac{w_{ext}}{\gamma}\right)\mathbf{z}' + B_1\mathbf{x}'\right)$$

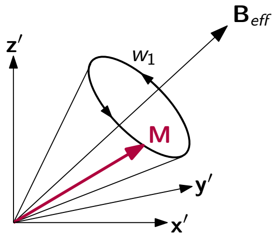
We have resonance if the z-component vanishes, i.e., $\gamma B_0 = w_{ext}$ (Lamor frequency).

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Remember that we are in the rotating coordinate system!

The magnetization vector precesses, with frequency w_1, around the effective magnetic field $\mathbf{B}_{eff}$.



Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

At resonance, i.e., $w_{ext} = \gamma B_0$, we have

$$\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} = \gamma(\mathbf{M} \times B_1\mathbf{x}') = \begin{pmatrix} 0 \\ -\gamma B_1 M_z \\ +\gamma B_1 M_y \end{pmatrix}$$

This system can be solved with

$$\begin{aligned} M_y &= m_1 \cos(\gamma B_1 t + \phi) \\ M_z &= m_1 \sin(\gamma B_1 t + \phi) \end{aligned}$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

We notice that ...

1. ... with

$$\phi = {}^{\pi}/_{2}$$

   the magnetization is in the direction of $\mathbf{B}_0$ at $t = 0$.

2. ... if $\mathbf{B}_1$ is applied for time $t = T$, $\mathbf{M}$ rotates by angle

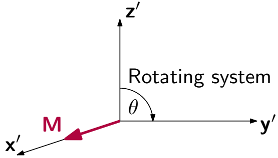
$$\theta = \gamma B_1 T$$

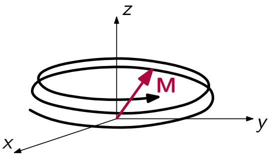
So, choosing the time T and strength B_1 appropriately, allows to tip the magnetization vector into the $\mathbf{x}'\mathbf{y}'$-plane.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

When $\mathbf{B}_1(t)$ is turned off (after time T), we can illustrate what happens to the magnetization as:





In the still coordinate system (right) the precession (at frequency w_1) is mixed with the precession (at frequency w_0) around z.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

With such as 90° pulse, we get maximum magnetization in the xy-plane, referred to as transversal magnetization.

The rotating magnetization induces a current in the RF coil.

Due to relaxation mechanisms, the transversal magnetization decays with time, in particular, exponentially with T_2^*.

This signal is called the *Free Induction Decay*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

T_1 is called longitudinal relaxation time and measures how long it takes for the z-component of $\mathbf{M}$ to "grow back" along z.

This happens, since magnetic moments switch between states (from high to low) and energy is released to the environment ("spin-lattice" relaxation).

T_2 is called transversal relaxation time and measures the decay of transversal magnetization (i.e., perpendicular to $\mathbf{B}_0$).

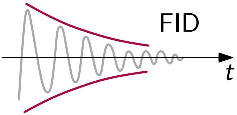
This happens, since spins experience different slightly different magnetic fields and hence precess at different frequencies $\Rightarrow$ "spin-spin" relax.).

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

However, $\mathbf{B}_0$ is not totally homogeneous $\Rightarrow$ different Lamor frequencies $\Rightarrow$ different precession freq. $\Rightarrow$ faster dephasing.

Transversal magnetization decays with $T_2^* < T_2$

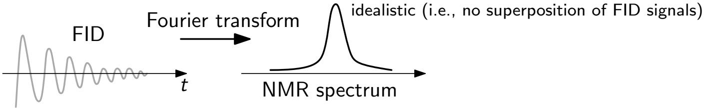


We can only measure T_2^* by observing the FID. To measure T_1 and T_2 we need to work with so called *pulse-sequences*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

A Fourier transform of the FID signal, gives a *Lorentzian* line shape in the frequency domain.



This can be converted to a measure of *proton density* in the patient.

Typically, the relaxation times T_1, T_2 are also taken into account; we then refer to **T_1/T_2-weighted** images.

Magnetic Resonance Imaging

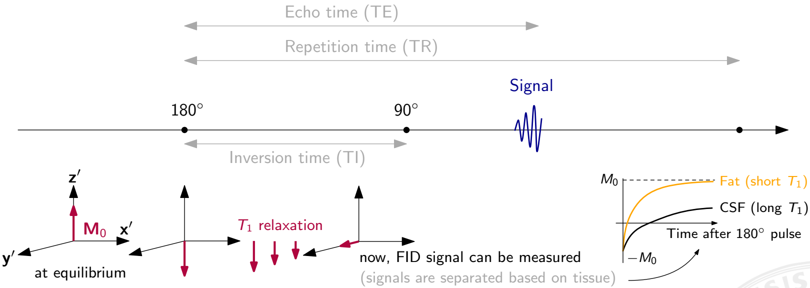
Physics primer – Pulse sequences

Pulse sequences are all about
recovering the relaxation times T_1 and T_2!

Magnetic Resonance Imaging

Physics primer – Pulse sequences

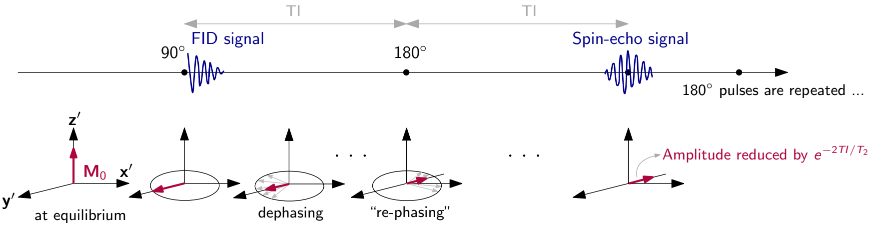
Inversion-Recovery Sequence (to measure T_1)[2]



TR,TI and TE control contrast.

[2]For more info on IR sequences, click here

Spin-Echo Sequence (to measure T_2)

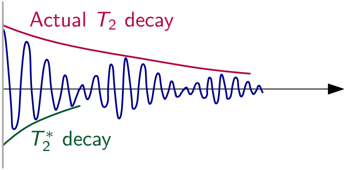


At 2TI, we get a spin-echo signal of a by e^{-2TI/T_2} reduced amplitude.

Magnetic Resonance Imaging

Physics primer – Pulse sequences

Here is a schematic illustration of the whole signal after a couple of 180° re-phasing pulses.

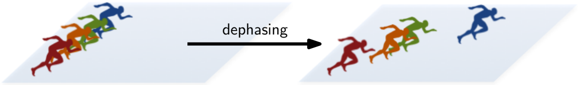


The purpose of multiple re-phasing pulses is to get a better estimate of the T_2 decay.

Magnetic Resonance Imaging

Physics primer – Pulse sequences

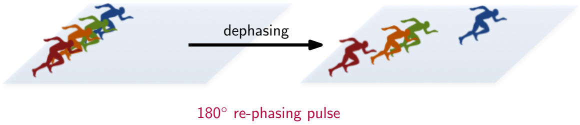
Illustration of re-phasing via a 180° pulse:



Magnetic Resonance Imaging

Physics primer – Pulse sequences

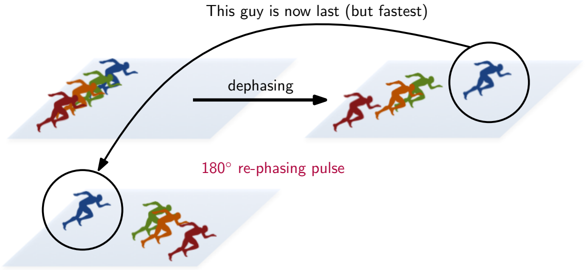
Illustration of re-phasing via a 180° pulse:



Magnetic Resonance Imaging

Physics primer – Pulse sequences

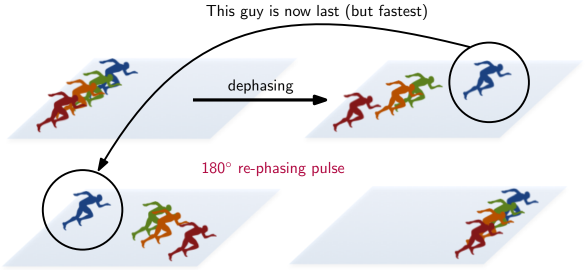
Illustration of re-phasing via a 180° pulse:



Magnetic Resonance Imaging

Physics primer – Pulse sequences

Illustration of re-phasing via a 180° pulse:



Magnetic Resonance Imaging

Physics primer – Pulse sequences

Problem

At this point, we *do not* know the location of the signal, i.e., we do not have spatial resolution and can't assign values to voxel!

The solution to this problem are (linear) *gradient fields*.

Magnetic Resonance Imaging

Physics primer – Pulse sequences

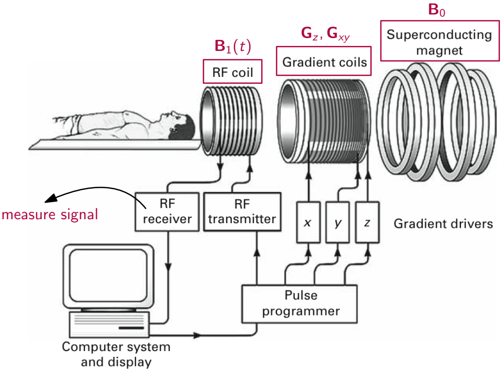
Summary of magnetic fields in MR imaging:

1. Static magnetic field $\mathbf{B}_0$
2. Oscillating RF field $\mathbf{B}_1(t)$
3. Gradient fields $\mathbf{G}_z, \mathbf{G}_{xy}$

Magnetic Resonance Imaging

Physics primer – Pulse sequences

Schematic illustration of the different magnetic fields:



Magnetic Resonance Imaging

Physics primer – Gradient fields (Principle)

We already know almost all the components to understand the principle.

Gradient fields are superimposed on $\mathbf{B}_0$. Remember that Lamor frequencies are proportional to the overall magnetic field.

Through gradients in x, y, z direction, we *could* tessellate the space into cubes.

In practice, this is time-consuming, so this is only done in the z-direction $\Rightarrow$ we get slices of certain thickness!

Magnetic Resonance Imaging

Physics primer – Gradient fields (Principle)

$$\mathbf{B}_{grad} = \mathbf{B}_0 + z\mathbf{G}_z = \begin{pmatrix} 0 \\ 0 \\ B_0 + zG_z \end{pmatrix}$$

Consequently, the Lamor frequency depends on the position of the nuclei on the z-axis, i.e.,

$$w(z) = \gamma(B_0 + zG_z)$$

The 90-degree pulse also has a certain bandwidth Δw. So, we get resonance in only a certain slice of thickness

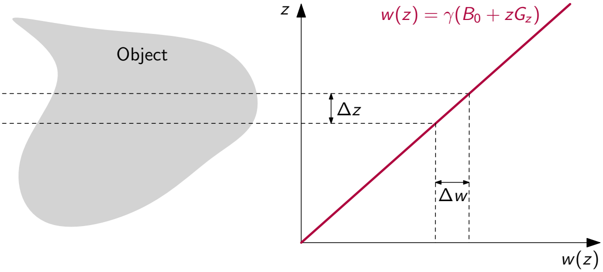
$$\Delta z = \frac{\Delta w - \gamma B_0}{\gamma G_z}$$

This is called slice-selective excitation.

Magnetic Resonance Imaging

Gradient fields (Principle)

Illustration (selective excitation):



The linear gradient constrains the region where resonance occurs to a slice of thickness Δz.

Magnetic Resonance Imaging

Projection-Reconstruction Technique

Next, we turn off the linear z-gradient field and $\mathbf{B}_1$ and turn on a gradient field in xy, i.e.,

$$\mathbf{G}_{xy} = \begin{pmatrix} G_x \\ G_y \\ 0 \end{pmatrix}$$

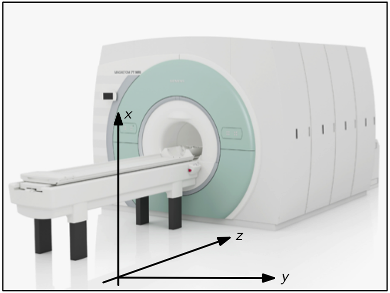
This field remains on during measurement.

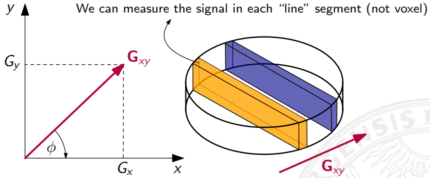
Magnetic Resonance Imaging

Projection-Reconstruction Technique

What happens?

We can set the angle ϕ of the gradient field $\mathbf{G}_{xy}$ by changing G_x and G_y. Say we have the following configuration:





Magnetic Resonance Imaging

Projection-Reconstruction Technique

The spins begin to oscillate at different frequencies once $\mathbf{G}_{xy}$ is turned on (and $\mathbf{B}_1$ and $\mathbf{G}_z$ are off).

Along different "line" segments (perpendicular to $\mathbf{G}_{xy}$), we observe the same frequency (blue and orange on prev. slide).

Obtaining voxel values

Changing ϕ allows us to acquire projections at different angles and then apply *tomographic reconstruction*.

Magnetic Resonance Imaging

MR Imaging in Medicine

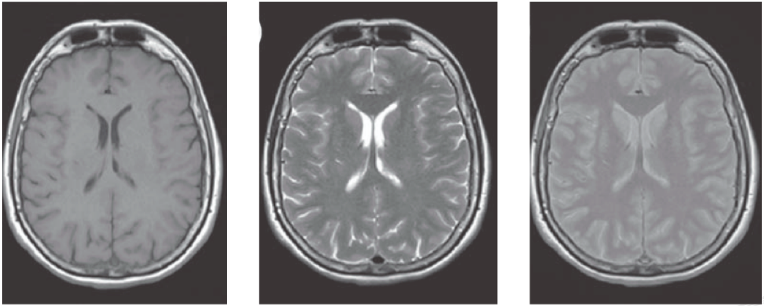
Some relaxation times for 1.5T:

Tissue	T_1 [msec]	T_2 [msec]	Density[3] [%]
Gray matter	950	100	85
White matter	600	80	90
Muscle	900	50	-
Cerebrospinal fluid (CSF)	4500	2200	85
Blood	1400	180-250	85

[3] Proton density

Magnetic Resonance Imaging

Examples



From *left to right*: T_1-weighted, T_2-weighted, Proton density