Al-Mustaqbal University College
Biomedical Engineering Department

Subject: Biomedical Instrumentation Design.

Class (code): 5th (MU515)

Lecture: *2*

BME 515

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MRI Design: Atomic structure

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The atom consists of the following particles:

- Protons: in the nucleus, are positively charged and spinning on their own axes.
- Neutrons: in the nucleus, have no charge
- Electrons: orbit the nucleus, are negatively charged spinning on their own axis, and orbiting the nucleus.

The **Mass number:** sum of the neutrons and protons in the nucleus.

- *In MRI we are concerned with the motion of particles within the nucleus and the nucleus itself.*

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MRI Design: MR active nuclei

› When a nucleus has an *even mass number*, the spins cancel each other out so the nucleus has *no net spin.*

› When a nucleus has an *odd mass number,* the spins do not cancel each other out and the *nucleus spins.*

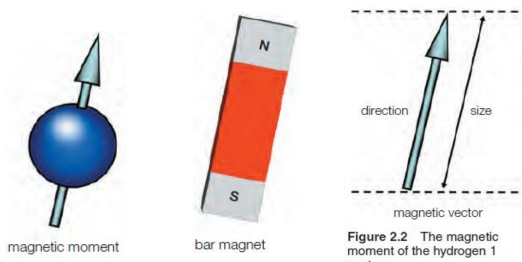

Figure 2.2 The magnetic moment of the hydrogen 1 nucleus.

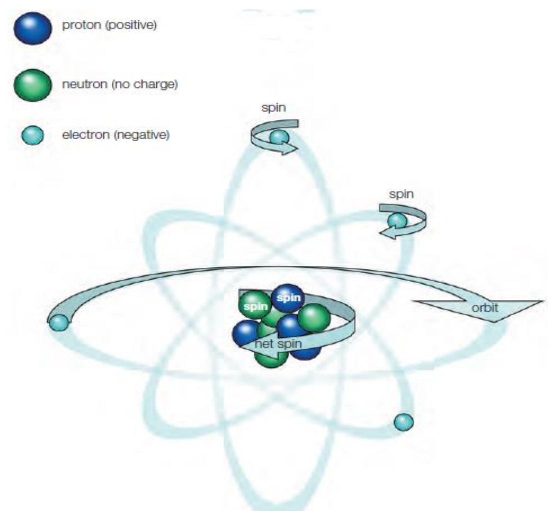

Figure 2.1 The atom.

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MRI Design: MR active nuclei

› *The isotope of hydrogen called* ***protium (or spins)*** *is the MR active nucleus used in MRI,*

➢ It has a mass and atomic number of 1.

➢ The nucleus consists of a single proton and has no neutrons.

It is used for MR imaging because:

› it is abundant in the human body (e.g. in fat and water);

› the solitary proton gives it a relatively large magnetic moment because there are no neutrons present in this type of nucleus.

Table 2.1 Constants of selected MR active nuclei.

Element	Protons	Neutrons	Nuclear spin	% Natural abundance
^{1}H (protium)	1	0	1/2	99.985
^{13}C (carbon)	6	7	1/2	1.10
^{15}N (nitrogen)	7	8	1/2	0.366
^{17}O (oxygen)	8	9	5/2	0.038

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MRI Design: Alignment

- In a normal environment the magnetic moments of MR active nuclei (spins) point in a random direction, and produce *no overall magnetic effect.*
- When spins are placed in an external magnetic field, their magnetic moments line up with the magnetic field flux lines.
- At room temperature there are always more spins with their magnetic moments aligned parallel than anti-parallel.
- The net magnetism of the patient (termed the **net magnetization vector**; **NMV**) is therefore aligned parallel to the main field.

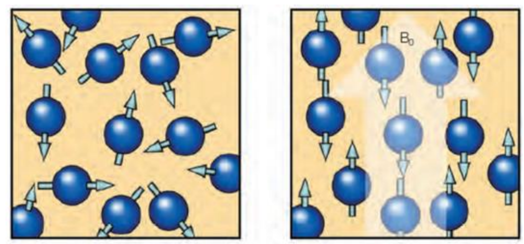

Figure 3.1 Alignment: classical theory.

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MRI Design: Alignment

- Hydrogen only has two energy states: high or low. Therefore, the magnetic moments of hydrogen spins only align in the parallel or anti-parallel directions.
- In thermal equilibrium, at any moment there are a greater proportion of spins with their magnetic moments aligned with the field than against it. This excess aligned with B_0 produces a net magnetic effect called the NMV that aligns with the main magnetic field.
- B_0 increases, NMV increases.

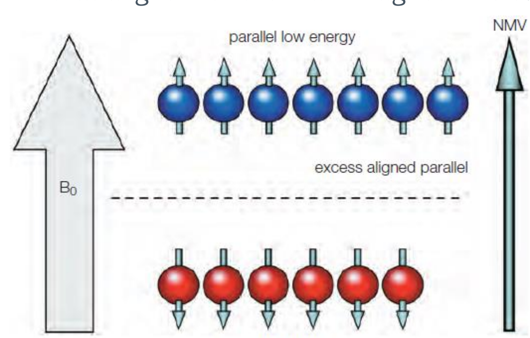

Figure 3.3 The net magnetization vector (NMV).

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MRI Design: Precession

- Precession: is the slow movement of the axis of a spinning body around another axis due to a torque acting to change the direction of the first axis.
- Every MR active nucleus is spinning on its own axis. The magnetic field exerts a torque on the magnetic moments of all MR active nuclei, causing a secondary spin called **precession** and causing the magnetic moments of all MR active nuclei to describe a circular path around B_0.
- **Precessional frequency :** is the speed at which the magnetic moments spin about the external magnetic field.

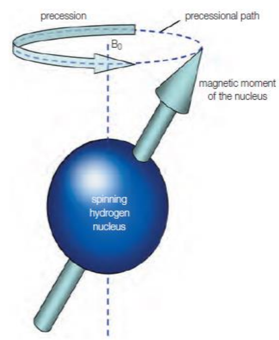

Figure 4.1 Precession.

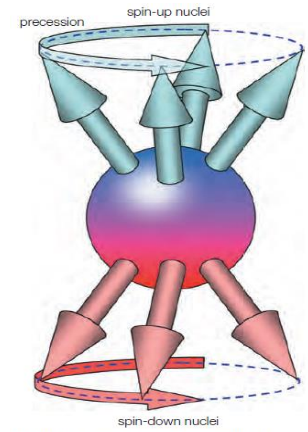

Figure 4.2 Precession of the spin-up and spin-down populations.

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MRI Design: Precession

- The Larmor equation is used to calculate the frequency or speed of precession for the magnetic moments of a specific nucleus in a specific magnetic field strength.

$$\omega_0 = \gamma B_0$$

- ω_0 : the precessional frequency (MHz).
- B_0: the strength of the external field (T).
- **γ**: the **gyromagnetic ratio**,is the precessional frequency of the magnetic moments of a specific nucleus at 1T (MHz/T).
- The precessional (Larmor) frequency is proportional to the strength of the external field and can be calculated for any type of MR active nucleus and field strength.

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MRI Design: Precession

- The precessional frequencies of the magnetic moments of hydrogen spins (gyromagnetic ratio (γ) 42.57 MHz/T) commonly found in clinical MRI are:
- 21.285 MHz at 0.5 T   42.57 MHz at 1 T   63.86 MHz at 1.5 T
- The precessional frequency corresponds to the range of frequencies in the electromagnetic spectrum of **radiowaves**.
- Therefore, the magnetic moments of hydrogen spins precess at a relatively low radio frequency (RF).
- This is why from the perspective of the energies used, MRI is thought to be safe. RF energy is not sufficiently energetic to ionization.

Non-ionizing					Ionizing
100 kHz	1000 kHz	10MHz	100MHz	1000MHz	
Frequency					
	AM Radio	CB Radio	Cordless Phones FM Radio **MRI Scanners**	Cell Phones	

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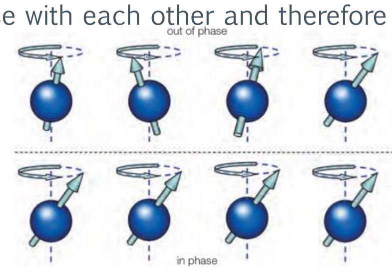
MRI Design: Precession

- **The Precessional phase (rad)** refers to the position of the magnetic moments of spins on their precessional path at any moment in time.
- In MRI, the relative phase position of all the magnetic moments of hydrogen spins *in the tissue we are imaging* is of particular interest.
- · **Out of phase** or **incoherent** means that the magnetic moments of hydrogen spins are at different places on the precessional path at a moment in time.
- · **In phase** or **coherent** means that the magnetic moments of hydrogen spins are at the same place on the precessional path at a moment in time.

when the patient is simply placed inside the magnetic field and exposed to B_0, the magnetic moments of the hydrogen spins are out of phase with each other and therefore the NMV does not precess.



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MRI Design: Precession

› Precession

› 1: Precession 1.mkv

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MRI Design: Resonance and signal generation

Resonance is an energy transition that occurs when an object is subjected to a frequency the same as its own. Resonance is induced by applying a **radiofrequency (RF) pulse**:

- at the same frequency as the precessing magnetic moments hydrogen spins;
- at 90˚ to B_0.

› This causes the hydrogen spins to resonate (receive energy from the RF pulse), whereas other types of MR active nuclei do not resonate, as their gyromagnetic ratios are different.

› Two things happen to the hydrogen spins at resonance: *energy absorption and phase coherence.*

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MRI Design: Resonance and signal generation

Energy absorption: the energy and frequency of electromagnetic radiation (including RF) are related to each other.

$$\Delta E = h\omega_0 = h\gamma B_0$$

- The frequency required to cause resonance is related to the difference in energy between the high- and low-energy populations and thus the strength of B_0
- The spin-up, low-energy hydrogen spins absorb energy from the RF pulse (excitation pulse) and move into the high energy population.
- At the same time, the spin-down, high-energy spins give energy away and return to the low-energy state.

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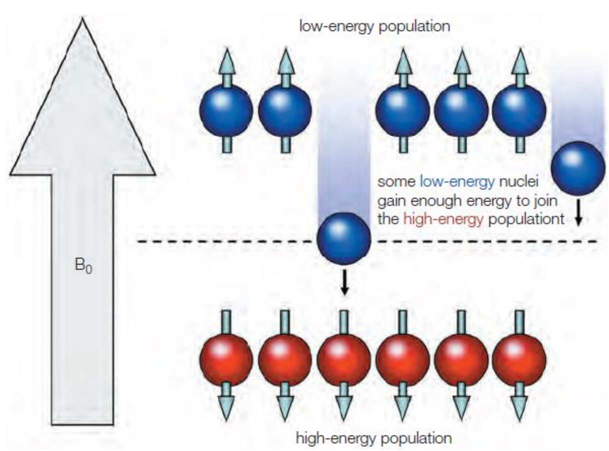
MRI Design: Resonance and signal generation

- As there are more low-energy spins, the net effect is of energy absorption.
- This absorption of applied RF energy at 90° to B_0 causes a ***net increase*** in the number of high-energy, spin-down nuclei compared to the pre-resonant state.



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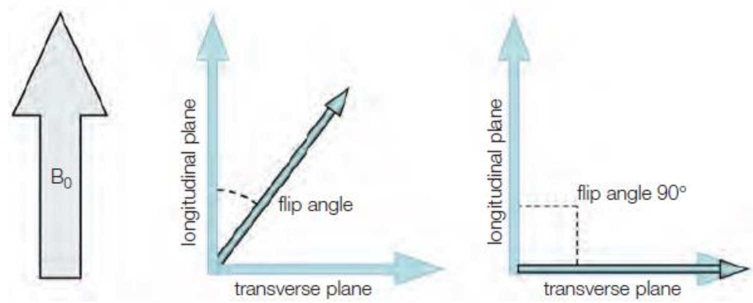
MRI Design: Resonance and signal generation

- When applying appropriate energy where the number of nuclei in the spin-up position equals the number in the spin-down position, the NMV (which represents the balance between spin-up and spin-down nuclei) lies in a plane at 90° to the external field (the **transverse plane**) as the net magnetization lies between the two energy states.
- As the NMV has been moved through 90° from B_0, it has a **flip or tip angle** of 90°.



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MRI Design: Resonance and signal generation

Phase coherence: the magnetic moments of the spins move into phase with each other.

Since the magnetic moments of the spins are in phase in both the spin-up and spin-down positions and the spin-up nuclei are in phase with the spin-down nuclei, the net effect is one of precession, so the NMV precesses in the transverse plane at the Larmor frequency.

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MRI Design: Resonance and signal generation

MR Signal: the receiver coil is situated in the transverse plane.

- As the NMV rotates around the transverse plane as a result of resonance, it passes across the receiver coil, inducing a voltage in it. This voltage is the **MR signal**
- When the RF pule is removed, the signal induced in the receiver coil begins to decrease.
- That is because the in-phase component of the NMV in the transverse plane begins to decrease as an increasingly higher proportion of spins become out of phase with each other.
- The amplitude of the voltage induced in the receiver coil therefore decreases. This is called **free induction decay** or **FID.**

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MRI Design: Resonance and signal generation

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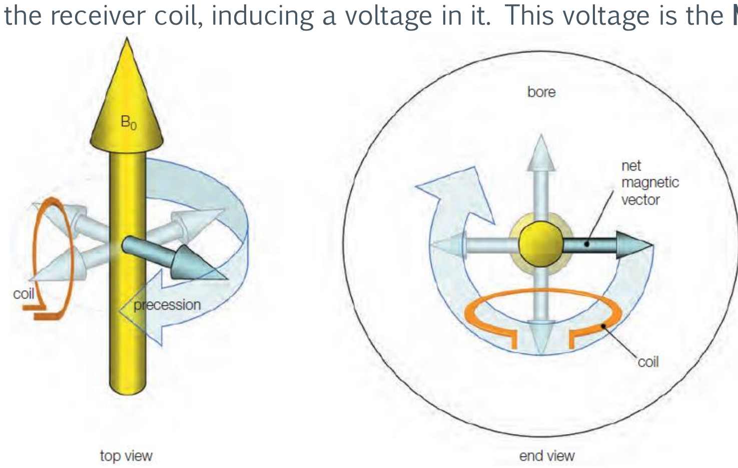

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MRI Design: Resonance and signal generation

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- "free" because of the absence of the RF pulse;
- "induction decay" because of the decay of the induced signal in the receiver coil.

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MRI Design: Contrast mechanism

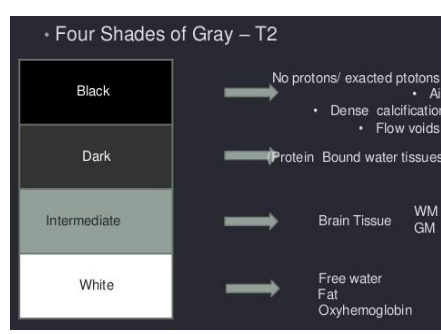
Contrast: An image has contrast if there are:

- areas of high signal (white on the image),
- areas of low signal (dark on the image).
- Some areas have an intermediate signal (shades of grey, between white and black).
- The NMV can be separated into the individual vectors

of the tissues present in the patient,

such as fat, cerebrospinal fluid (CSF),

grey matter and white matter.



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MRI Design: Contrast mechanism

Since the amplitude of the voltage induced in the receiver coil depends on the amplitude of the transverse magnetic field, the signal intensity in MRI is determined by the magnitude of precessing coherent transverse magnetization that cuts through the windings of the receiver coil when the signal is measured.

- A tissue has a *high signal (white, hyper-intense)* if it has a *large transverse component of magnetization*. As there is there is a large component of transverse magnetization, and the signal induced in the receiver coil is large.
- A tissue has a *low signal (black, hypo-intense)* if it has a *small transverse component of magnetization*. As there is a small component of transverse magnetization, and the signal induced in the receiver coil is also small.

› A tissue has an intermediate signal (grey, iso-intense) if it has a medium transverse component of magnetization when the signal is measured.

› *Image contrast is determined by the difference in signal intensity between tissues.*

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MRI Design: Contrast mechanism

Extrinsic contrast parameters:

These parameters are controlled by the operator

- **Repetition time (TR)**: This is the time from the application of one RF pulse to the application of the next for a particular slice. It is measured in milliseconds (ms). The TR affects the length of a relaxation period in a particular slice after the application of one RF excitation pulse to the beginning of the next.
- **Time to echo (TE)**: This is the time between an RF excitation pulse and the collection of the signal. The TE affects the length of the relaxation period after the removal of an RF excitation pulse and the peak of the signal received in the receiver coil. It is also measured in ms.
- **Flip angle**: This is the angle through which the NMV is moved as a result of an RF excitation pulse.

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MRI Design: Contrast mechanism

Extrinsic contrast parameters

- **Turbo-factor (TF)** or **echo train length (ETL)**: the number of echoes acquired after each excitation.
- **Time from inversion (TI)**: the time between the 180° inverting pulse and the 90°-pulse
- **'b' value**: parameter that defines gradient strength and duration, hence determines the degree of diffusion weighting.

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MRI Design: Contrast mechanism

Extrinsic contrast parameters

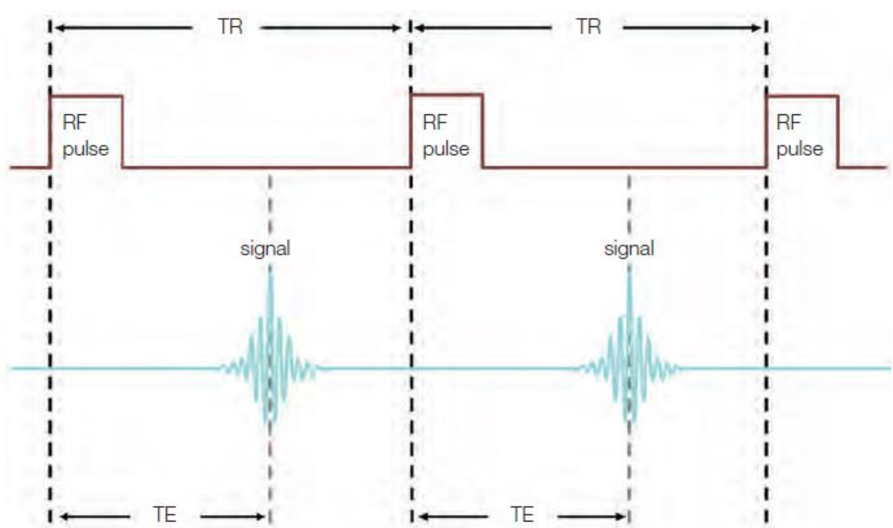

Figure 6.2 A basic pulse sequence showing TR and TE intervals.

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MRI Design: Contrast mechanism

Intrinsic contrast parameters

These parameters are inherent to the tissue and are not controlled by the operator. They are:

- T1 recovery time.
- T2 decay time.
- proton density.
- flow: the quantity of blood (cm^3/sec) passes a point at certain time.
- apparent diffusion coefficient (ADC): is a measure of the magnitude of diffusion (of water molecules) within tissue, and is commonly clinically calculated using MRI with diffusion-weighted imaging (DWI).