Advanced biomedical signal and image processing

Master: Plasturgy & Biomedical Engineering

2025-2026

Faculté de Science Meknes

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Section 3 : Processing of Biomedical Images

General Introduction

Chapter 1: X-ray

Chapter 2. Magnetic resonance imaging (MRI)

Chapter 3. Ultrasound imaging

Chapter 4. Nuclear medicine

Chapter 5. Optical imaging

Magnetic resonance imaging (MRI)

- **Introduction**
- **Basic physics**
- **Signal generation in MRI**
- **Image formation in MRI**
- **MRI contrast**
- **Mathematical concepts of MRI**
- **Spatial encoding**
- **Image reconstruction**
- **Advanced concepts**

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Introduction

- MRI is a powerful non-invasive imaging technique.
- Influences nuclear magnetic resonance (NMR) for detailed imaging of organs and tissues.
- No ionizing radiation, making it safer than X-rays and CT scans.

- **How MRI Works**
  - **Magnetic Field:** Aligns hydrogen nuclei (protons) in the body.
  - **Radiofrequency Pulses:** Protons shift out of alignment.
  - **Signal Emission:** Protons emit signals as they return to their original state.
  - **Image Creation:** Sophisticated algorithms convert signals into images.

Introduction

- **Factors Influencing MRI Contrast**
  - **Tissue Composition**
  - **Water Content**
  - **Presence of Specific Metabolites**
- **Applications of MRI**
  - **Neurology:** Imaging brain structures; diagnosing tumors, strokes, neurodegenerative diseases.
  - **Orthopedics:** Assessing joint injuries, cartilage damage, soft tissue abnormalities.
  - **Cardiology:** Evaluating heart structures and function; detecting cardiac diseases.
  - **Oncology:** Identifying and monitoring tumors.

Introduction

- **Role of Biomedical Imaging System Engineers**
  - Understanding MRI intricacies for development and optimization.
  - Evolving hardware and software to enhance MRI capabilities.
  - Improving diagnostic accuracy and patient outcomes.
  - MRI is a crucial tool in medical diagnostics.
  - Continuous advancements enhance its effectiveness and safety.
  - Ongoing innovations promise better imaging techniques and patient care.
  - **Advancements in MRI Technology**
  - **Improved Image Quality**
  - **Faster Scanning Times**
  - **Enhanced Patient Comfort**
- **Techniques:**
  - Functional MRI: Visualizes brain activity via blood flow changes.
  - Diffusion-Weighted Imaging (DWI): Insights into tissue integrity.
- **Please watch carefully and raise questions:** **https://www.youtube.com/watch?v=jLnuPKhKXVM&t=228s**

Basic physics

- **MRI** is a sophisticated medical imaging technique that controls powerful magnets, radio waves, and advanced computing to generate detailed images of internal organs and tissues.
- Unlike X-ray and CT scans, MRI operates without ionizing radiation, making it a safer option for various diagnostic applications.
- The underlying physics of MRI is rooted in the principles of nuclear magnetic resonance (NMR).

Basic physics

- Fundamental concepts
  - Nuclear magnetic resonance (NMR)
  - Alignment in a magnetic field
  - Larmor frequency
- Radiofrequency (RF) pulses
  - Resonance
  - Flip angle

Basic physics

- A magnet

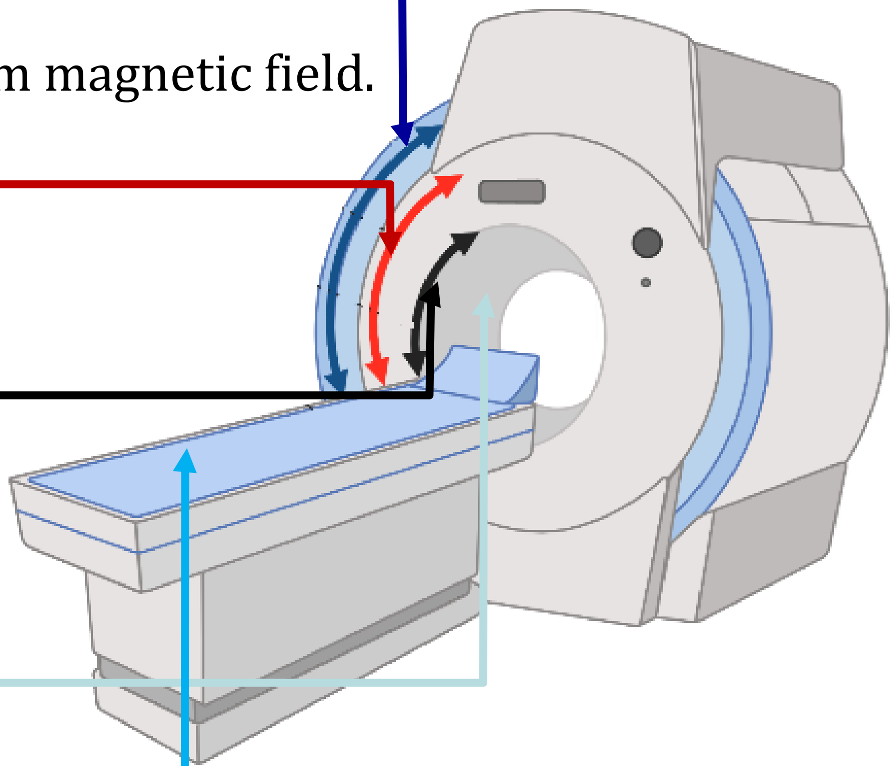
  produces a very powerful uniform magnetic field.
- Gradient Magnets

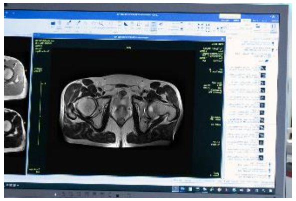
  much lower in strength.
- Radio frequency coil

  Equipment to transmit

  radio frequency (RF)
- Bore
- Patient table
- A powerful computer system

  translates the signals transmitted by the coils





Basic physics

Magnet

- The most important component of the MRI scanner
  - The magnets currently used in scanners are in the 5 tesla to 20 Ktesla range (5,000 gauss to 20,000gauss).

    Higher values are used for research.
  - Earth magnetic field: 0.5gauss
- There are three types of magnets used in MRI systems:
  - Resistive magnets
  - Permanent magnets
  - Super conducting magnets (the most commonly used type in MRI scanners).
- In addition to the main magnet, the MRI machine also contains three gradient magnets. These magnets have a much lower magnetic field and are used to create a variable field.

Basic physics

Type	Magnetic Field Strength	Applications	Advantages	Disadvantages
Permanent Magnets	Up to 0.5 Tesla	Low-field MRI, open MRI	Cost-effective, stable field	Lower resolution, weaker fields
Resistive Magnets	0.2 - 0.3 Tesla	Low- to medium-field	Can be turned on/off, low operational cost	Limited field strength, energy-intensive
Superconducting Magnets	1.5T - 7T+	High-field MRI, research MRI	High resolution, strong stable fields	Expensive, requires liquid helium cooling

- In addition to the main magnet, the MRI machine also contains three gradient magnets. These magnets have a much lower magnetic field and are used to create a variable field.

Basic physics

- Fundamental concepts

- **Spin**:

  - The atoms that compose the human body have a property known as spin (a fundamental property of all atoms in nature like mass or charge).

  - It is a small magnetic field and can be given a + or – sign and a mathematical value of multiples of ½.

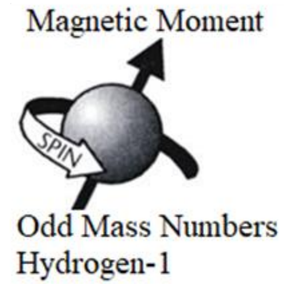
  - Components of an atom such as protons, electrons and neutrons all have spin that are called nuclear spins.

  - An unpaired component has a spin of ½ and two particles with opposite spins cancel one another.

  - In NMR it is the unpaired nuclear spins that produce a signal in a magnetic field.

Basic physics

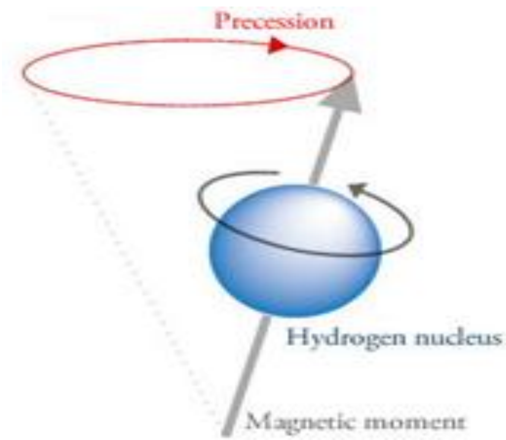
- Fundamental concepts
  - Nuclear magnetic resonance (NMR)
- Human body is mainly composed of fat and water, which makes the human body composed of about 63% hydrogen.
- Protons are Important to MRI
  - positively charged
  - spin about a central axis
  - a moving (spinning) charge creates a magnetic field.
  - the straight arrow (vector) indicates the direction of the magnetic field.



Basic physics

- Fundamental concepts
  - Nuclear magnetic resonance (NMR)

Certain atomic nuclei, such as hydrogen-1 $^{1}_{1}H$, found in water and fat, possess an intrinsic property known as **spin**.

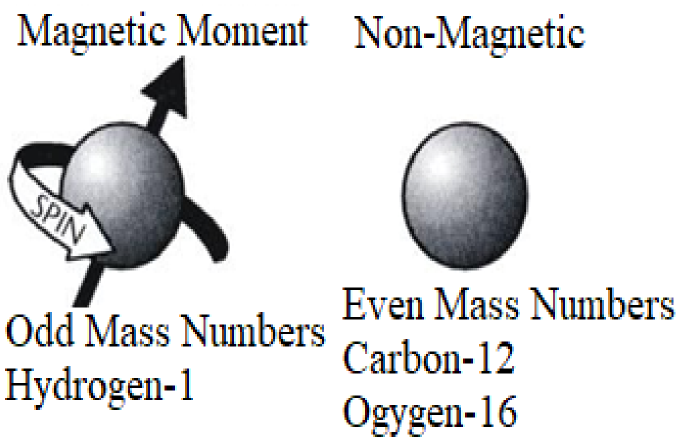


This spin generates a **magnetic moment**, causing these nuclei to behave like tiny magnets

Basic physics

- Fundamental concepts
  - Alignment in a magnetic field

When these nuclei are subjected to a strong external magnetic field (**B_0**), their magnetic moments align either parallel or anti-parallel to the field.

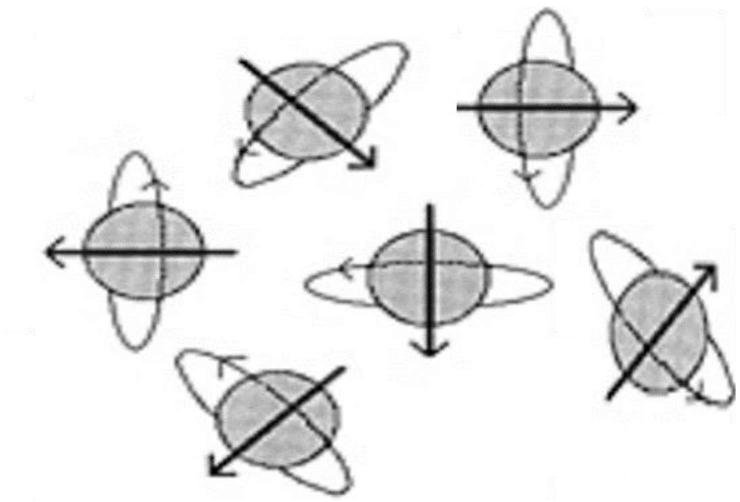


The parallel alignment, which is slightly lower in energy, leads to a majority of nuclei aligning in this manner, resulting in a **net magnetization** along the direction of the magnetic field.

Basic physics

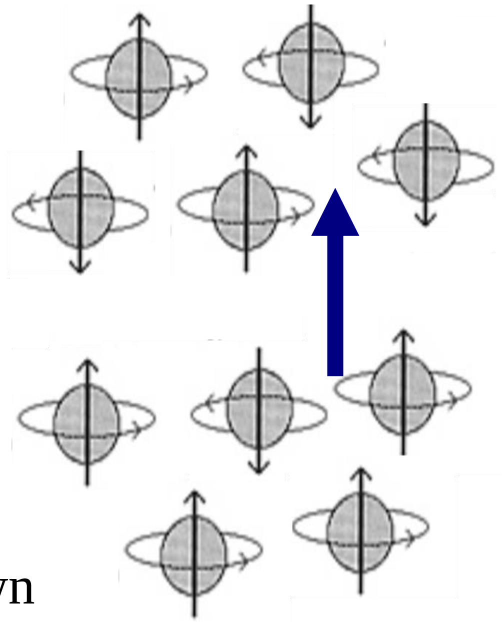
- Fundamental concepts
  - Alignment in a magnetic field

Protons in the Absence of a Strong Field
The protons spinning in nature, without an external strong field, have random directions of spin that cancel each other out. The net magnetization is nearly 0.



Basic physics

- Fundamental concepts
  - Alignment in a magnetic field



Protons in a Strong Magnetic Field

When placed in a large magnetic field, such as inside the bore of an MRI scanner, hydrogen atoms have a strong tendency to align themselves either:

Against the magnetic field (high energy state)

Along the magnetic field (low energy state)

There is a slight abundance of spins aligned in the low energy state.

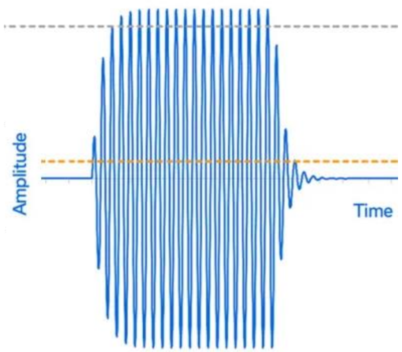
Inside the bore of the scanner, the magnetic field runs down the center of the tube in which the patient is placed, so the hydrogen protons will line up in either the direction of the feet or the head.

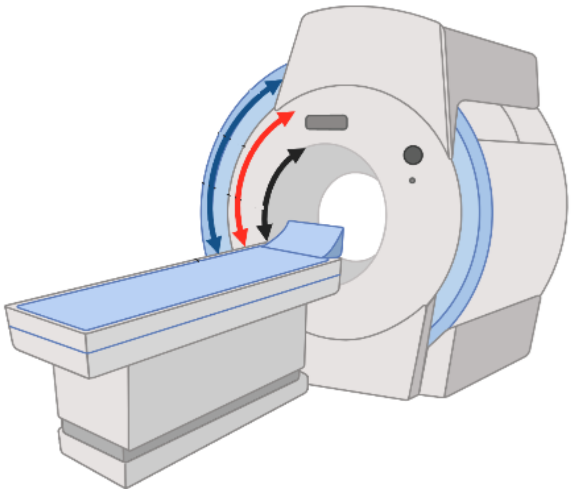
The majority of the protons will cancel each other out, but the net number of protons aligned in the low energy state is sufficient to produce an MRI image.

Basic physics

- Fundamental concepts
  - Larmor frequency

- **Energy Absorption:**
  - The MRI machine applies radio frequency (RF) pulse that is specific to hydrogen.

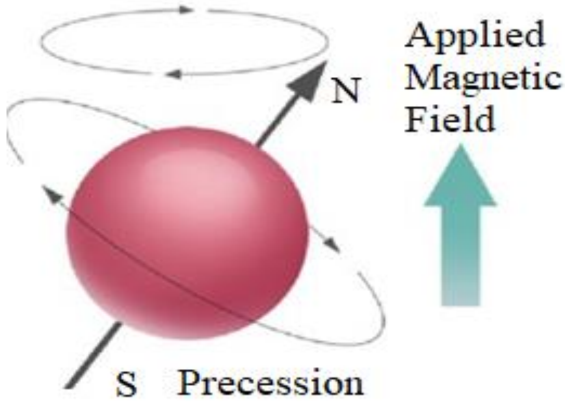




  - The RF pulses are applied through a coil that is specific to the part of the body being scanned.

Basic physics

- Fundamental concepts
  - Larmor frequency
- The magnetic moments of the nuclei do not align perfectly with the external magnetic field; instead, they **precess** around the direction of the field.



- This precession occurs at a specific frequency, known as the **Larmor frequency**, which is determined by the strength of the magnetic field and the type of nucleus

Basic physics

- Fundamental concepts
  - Larmor frequency
    - $\omega_0 = \gamma B_0$

Larmor frequency

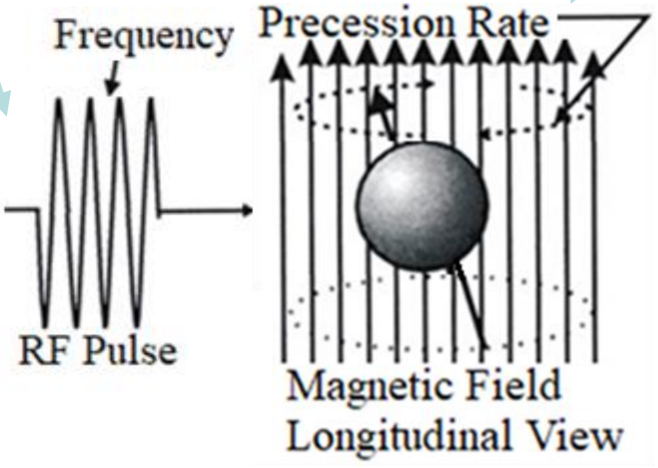
ratio (a constant specific to each type of nucleus)

strength of the external magnetic field

Basic physics

- Radiofrequency (RF) pulses
  - Resonance
- **Effect of Radiofrequency Pulse**
- When a radiofrequency pulse is applied at the **Larmor frequency**, energy is transferred to the nuclei, resulting in a tipping of the net magnetization away from the direction of the magnetic field (**B_0**).

- RF Pulse is switched off
- the protons start to realign themselves back in a low energy state



Basic physics

- Radiofrequency (RF) pulses
  - Flip angle
- **Flip Angle and MRI Principles**
- The angle by which the net magnetization is tipped is referred to as the **flip angle**. Commonly used flip angles are **90°** (for maximum signal) and **180°** (for inversion recovery techniques).
- MRI is a powerful imaging modality that relies on the principles of **NMR**, utilizing the unique properties of atomic nuclei in a magnetic field.
- By understanding the fundamental concepts of nuclear magnetic moments, Larmor frequency, RF pulses, relaxation processes, and signal detection, one can appreciate the intricate workings of MRI technology in clinical practice.

Basic physics

Signal generation in MRI

- **Relaxation processes**
  - **T1 Relaxation (Longitudinal relaxation)**
  - **T2 Relaxation (transverse relaxation)**
  - **Free Induction Decay (FID)**

Basic physics

Signal generation in MRI

Two independent processes that reduce transverse magnetization after the application of a radiofrequency (RF) and cause a return to the steady state present before excitation are:

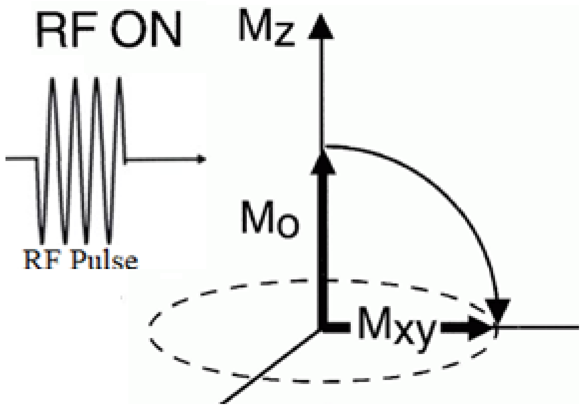
- spin-lattice interaction causes T1 relaxation
- spin-spin interaction causes T2 relaxation

In MRI, relaxation processes are crucial for signal generation and image formation.

Basic physics
Signal generation in MRI

- **Relaxation processes**

- The term **relaxation** means that the spins are relaxing back into their lowest energy state or back to the equilibrium state. (Equilibrium by definition is the lowest energy state possible.) Once the **radio frequency** (**RF**) pulse is turned **off,** the protons will have to realign with the axis of the B_0 magnetic field and give up all their excess energy.



Basic physics

Signal generation in MRI

- **Relaxation processes**
  - **T1 Relaxation (Longitudinal relaxation)**

T1 relaxation, or spin-lattice relaxation, is the process where net magnetization aligns with the external magnetic field $\mathbf{B_0}$ after an RF pulse.

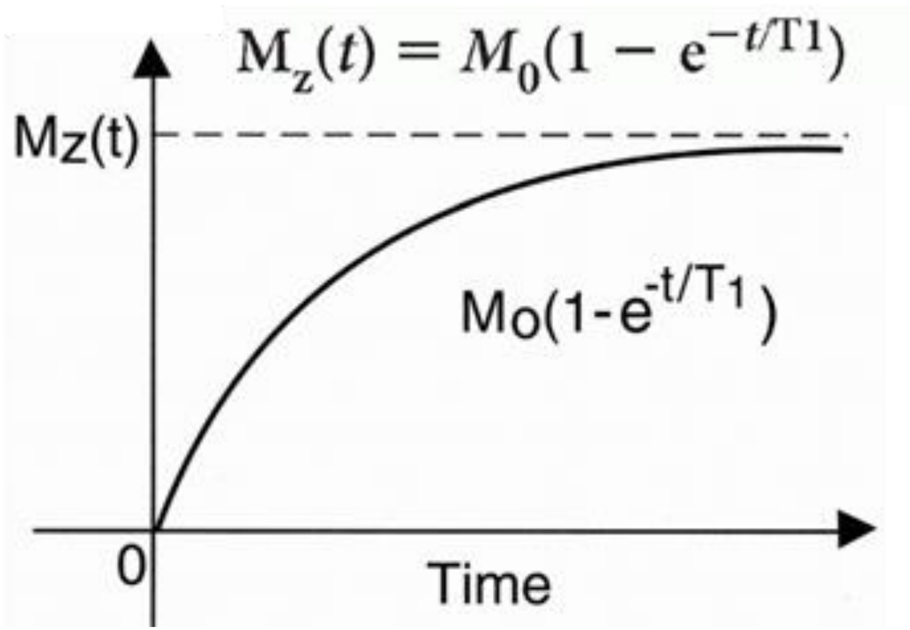
During the RF pulse, protons are excited and move away from equilibrium. After the pulse, they lose energy to their environment, realigning with $\mathbf{B_0}$.

T1 relaxation times vary by tissue type, affecting MRI contrast. For example, fat has a shorter T1 time than water, influencing signal intensity.

Basic physics

Signal generation in MRI

- **Relaxation processes**
  - **T1 Relaxation (Longitudinal relaxation)**



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Basic physics

Signal generation in MRI

- **Relaxation processes**
  - **T2 Relaxation (transverse relaxation)**

T2 relaxation (spin-spin relaxation) describes the decay of the transverse magnetization vector due to interactions among neighboring spins after protons are excited in a magnetic field.

While T1 relaxation focuses on the longitudinal component, T2 relaxation addresses the loss of coherence among spins in the transverse plane, leading to a decay in the MRI signal.

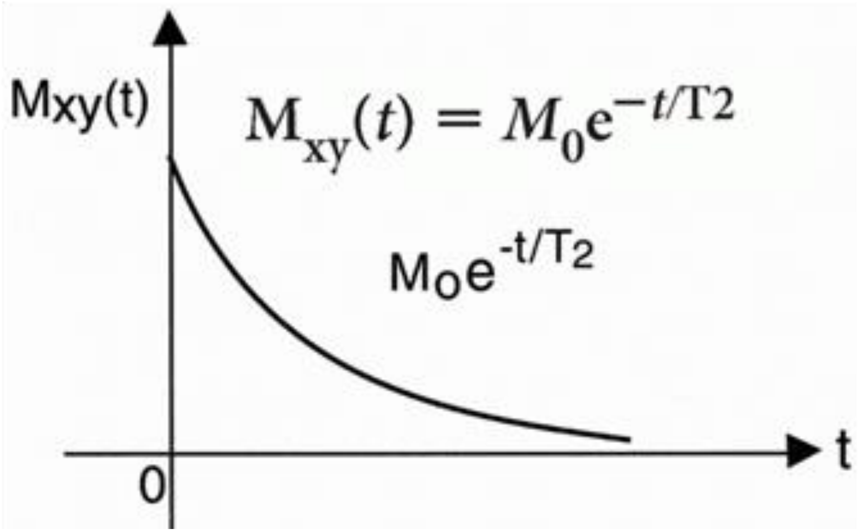
The rate of T2 relaxation varies among tissues; (high water content tissues like cerebrospinal fluid have longer T2 times, while denser tissues such as muscle have shorter times.

This variation is crucial for MRI contrast, helping radiologists differentiate tissue types and enhance diagnostic capabilities.

Basic physics

Signal generation in MRI

- **Relaxation processes**
  - **T2 Relaxation (transverse relaxation)**

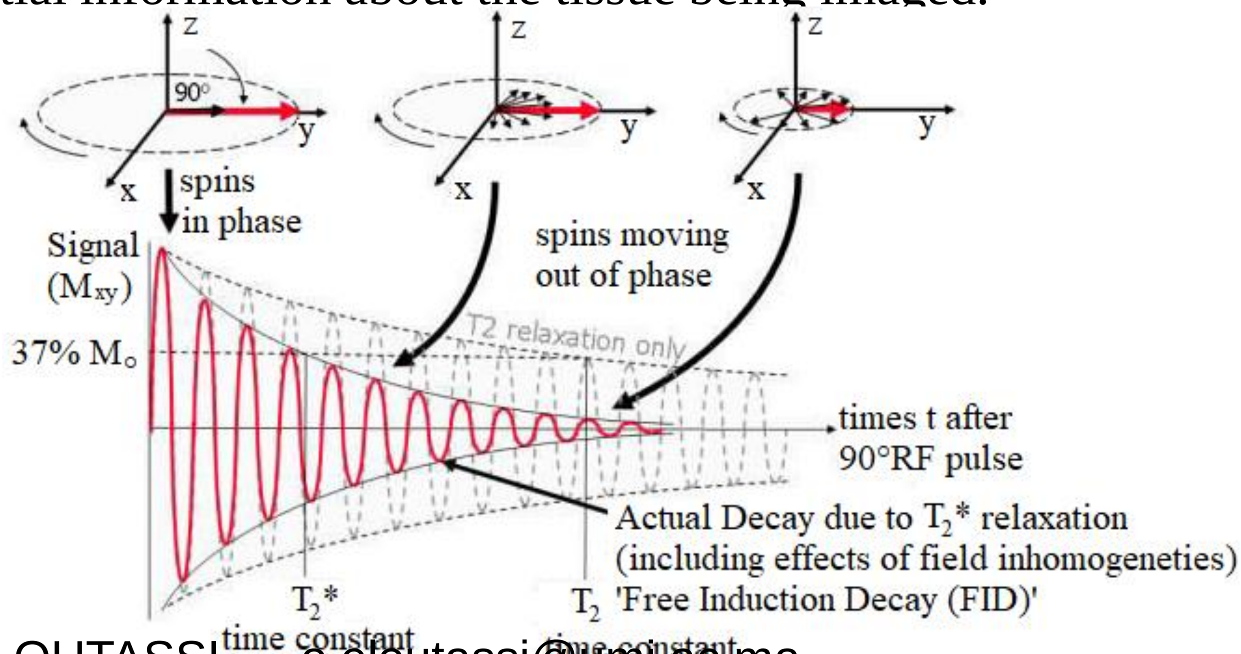


Basic physics

Signal generation in MRI

- **Relaxation processes**
  - **Free Induction Decay (FID)**

After the RF pulse, the transverse magnetization induces a voltage signal in the receiver coil, known as the free induction decay (FID) signal. This signal represents the decaying transverse magnetization and contains essential information about the tissue being imaged.



Basic physics

Signal generation in MRI

- **Image formation in MRI**
  - **Spatial encoding**
    - **Gradient magnetic fields**
  - **Slice Selection**
    - **Selective RF Pulses**
  - **Frequency and Phase Encoding**
    - **Frequency encoding**
    - **Phase encoding**

Watch this
https://www.youtube.com/watch?v=nFDzXvjF7gg

Basic physics

Signal generation in MRI

- ## Image formation in MRI

The process of image formation in Magnetic Resonance Imaging (MRI) is a sophisticated sequence of steps that ensures high-quality imaging of the body's internal structures. **Key Steps in MRI Image Formation**

Spatial Encoding: Defines the location of signals within the imaging volume.

Slice Selection: Isolates specific anatomical sections for detailed examination.

Frequency and Phase Encoding: Enhances spatial resolution and contrast, capturing tissue nuances.

Image Reconstruction: Transforms raw data into images using the Fourier transform.

Importance of MRI Image Formation: Each component works in harmony to provide accurate visualizations. This process aids in diagnosing medical conditions and enhances our understanding of human anatomy and physiology, making MRI a vital tool in modern medicine.

Basic physics

Signal generation in MRI

- **Image formation in MRI**
  - **Spatial encoding**

A critical process that allows for the localization of signals within a three-dimensional space.

Essential for creating detailed images of internal structures in the body.

Crucial for engineers involved in MRI technology development.

Informs the design of MRI systems and optimization of imaging sequences.

Enhances image quality and aids in troubleshooting existing protocols.

By mastering spatial encoding, engineers can contribute to advancements in MRI technology, leading to better diagnostic capabilities and improved patient outcomes.

Basic physics

Signal generation in MRI

- **Image formation in MRI**
  - **Gradient magnetic fields**

Additional magnetic fields applied in specific directions (x, y, and z axes) during an MRI scan

Modify the main magnetic field B_0 to create a spatially varying magnetic field.

It causes the Larmor frequency of the nuclei to vary linearly with their position.

$$\omega(x)=\gamma(B_0+G_x \cdot x)$$

Larmor frequency at position x

gyromagnetic ratio of the nucleus

strength of the main magnetic field

gradient strength along the x-axis

position along the x-axis.

Basic physics

Signal generation in MRI

- **Image formation in MRI**
  - **Slice Selection**
    - **Selective RF Pulses**

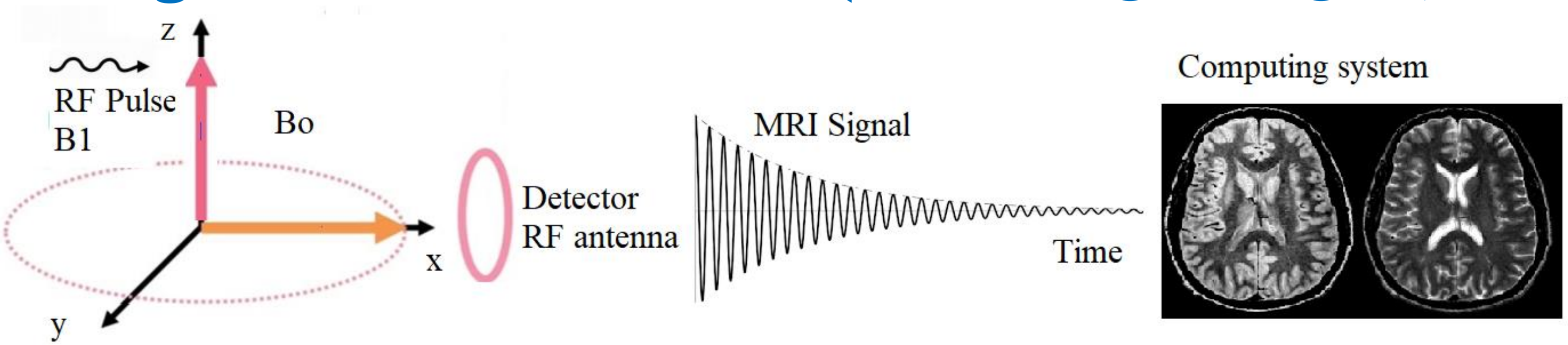
$$\Delta f = \frac{\gamma \cdot Gz \cdot \Delta z}{2\pi}$$

- Gz: the gradient strength along the z-axis
- Δz: the thickness of the slice
- Δf: bandwidth of the RF pulse

Basic physics

Signal generation in MRI

- **Image formation in MRI (Measuring the signal)**



- The moving protons vectors induces signal (sinusoidal in general) in RF antenna (detector)
- The signal is picked up by the coil and send to the computing system as mathematical data
- The coil detect the signal due to Farady curent induced by the electromagnetic changes
- The data are processed in computing system using Fourier transform configuration
- Watch this video: https://www.youtube.com/watch?v=PxqDjhO9FUs&t=166s

END