Magnetism

Lecture 9

Magnetic Resonance Imaging (MRI)

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Lecture Notes

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1. Introduction to MRI

Magnetic Resonance Imaging (MRI) is one of the most advanced non-invasive medical imaging techniques. It uses strong magnetic fields and radiofrequency (RF) waves to generate high-resolution images of internal body tissues.

Key Advantages of MRI

- **No ionizing radiation** is used (unlike X-ray and CT).
- **Excellent soft-tissue contrast**, making it ideal for imaging organs such as the brain, spinal cord, joints, and abdominal structures.
- Ability to produce **detailed 2D and 3D images**.

MRI works by exciting hydrogen protons in body tissues and detecting the signals they emit. These signals are processed to form detailed anatomical images.

2. Nuclear Magnetic Resonance (NMR) Theory

The physical principles behind MRI are based on Nuclear Magnetic Resonance (NMR), which describes how atomic nuclei—especially **hydrogen protons**—behave in a magnetic field.

The NMR process consists of **three main stages**:

2.1 Alignment

- In their natural state, protons move randomly without a preferred direction.
- When a patient is placed inside a strong magnetic field:
  - Protons align either **with** or **against** the magnetic field.
  - Slightly more protons align with the field → forming a **Net Magnetization Vector (NMV)**.
- Protons begin to **precess** around the magnetic field axis at a specific **Larmor Frequency**.
- This prepares the protons for RF excitation.

2.2 Resonance

- An RF pulse is applied at the Larmor frequency.
- When the frequencies match, **resonance** occurs:
  1. Protons absorb energy.
  2. They are displaced from alignment with the field.
  3. A **transverse magnetization** component is created.
- This transverse magnetization is the basis of the detectable MRI signal.

2.3 Relaxation

After the RF pulse stops, protons gradually return to equilibrium:

A. Longitudinal Relaxation (T1)

- Recovery of magnetization along the magnetic field axis.
- Energy is released to the surrounding lattice.

B. Transverse Relaxation (T2)

- Loss of phase coherence between spinning protons.
- Causes decay of the transverse magnetization.

During these relaxation processes, protons emit electromagnetic signals that are detected by RF coils and converted into images.

3. Main Components of the MRI System

An MRI scanner consists of several key subsystems working together to produce diagnostic images.

3.1 Patient Table / Bore

- The patient lies on a motorized table that moves into the central bore, where the magnetic field is strongest.

3.2 Main Magnetic Field (B0)

The primary magnet generates the static magnetic field needed to align hydrogen protons.

Field Strengths

- **Low field:** 0.2 – 0.5 T
- **Medium field:** 0.5 – 1.0 T
- **Clinical systems:** 1.5 T and 3.0 T
- **Research MRI:** 7 T and above

Higher field strength → better **signal-to-noise ratio (SNR)** and image resolution.

Types of Magnets

A) Resistive Magnets

- Made of copper coils carrying continuous current.
- *Disadvantages:* high heat generation, high power consumption.

B) Permanent Magnets

- Do not require electrical power.
- Common in **open MRI** systems.

C) Superconducting Magnets *(most widely used)*

- Used in 1.5T and 3T systems.
- Operate with low-temperature superconductors cooled by **liquid helium**.
- Provide stable, high-strength magnetic fields.

3.3 RF Coils (Radiofrequency Coils)

These coils are responsible for transmitting and receiving MRI signals.

- **Transmitter coils:** deliver RF pulses.
- **Receiver coils:** detect emitted proton signals.
- Specialized coils exist for the head, spine, breast, extremities, etc.

3.4 Computer System

The computer system performs:

- Signal acquisition from RF coils.
- Application of the **Fourier Transform**.
- Image reconstruction in 2D or 3D.
- Post-processing and display of images.

4. MRI Magnetic Subsystems

4.1 Main Magnet

- Generates the static field **B0**.
- Field homogeneity is crucial for image quality.
- Highly homogeneous magnets ensure accurate resonance.

4.2 Cryogenic System

Used only with superconducting magnets.

Components:

1. **Liquid Helium Tank** – maintains ultra-low temperatures.

2. **Cryocooler** – recondenses helium and reduces consumption.
3. **Vacuum Chamber** – provides thermal insulation.

Quench:
A sudden loss of superconductivity → rapid boil-off of helium → loud noise and vapor release.

4.3 Magnetic Shielding

Prevents the magnetic field from extending outside the MRI room.

- **Passive Shielding:** thick steel plates.
- **Active Shielding:** secondary coils that produce an opposing field.

4.4 Gradient Coils

- Modify the magnetic field along the X, Y, and Z axes.
- Enable spatial encoding and slice selection.
- Responsible for the loud knocking sounds during scanning due to rapid expansion/contraction.

4.5 Magnet Control Unit

Monitors and controls:

- Persistent magnet mode.
- Magnetic field stability.
- Helium pressure and temperature.
- Safety systems to prevent quench events.