MR Principles and Hardware

This document is to give an introduction in the basic principles and hardware used in a modern MRI scanner.

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1. MR Principles

Magnetic Resonance Imaging (MRI) is a powerful and versatile medical imaging technique that allows for non-invasive visualization of the internal structures of the human body. It relies on the principles of nuclear magnetic resonance (NMR), which is a physical phenomenon involving the interaction of atomic nuclei with strong magnetic fields and radio waves. MRI has become a cornerstone in medical diagnostics, enabling the examination of soft tissues, organs, and even functions of the body with remarkable detail.

Here's a short introduction to the field of MRI:

1.1. Nuclear Magnetic Resonance (NMR)

MRI is based on the same physical principles as NMR spectroscopy. In the presence of a strong magnetic field (B_0), certain atomic nuclei, particularly hydrogen nuclei (protons), align themselves with the magnetic field. When a radiofrequency pulse (B_1) is applied at the appropriate frequency, it temporarily tilts these nuclei away from their aligned position.

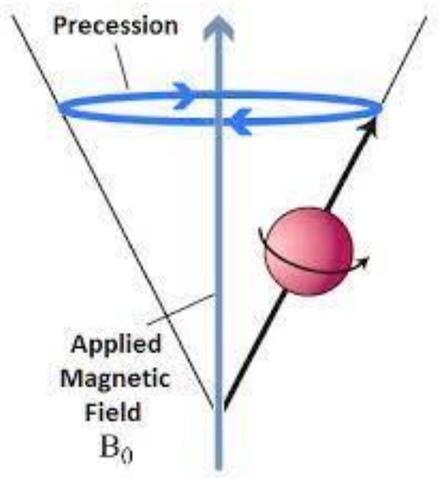

Fig. 1 The nuclei (in MRI its often hydrogen) first aligned with the magnetic field B_0 and then tilted away by a radiofrequency pulse B_1. Because of the angle between the field and the magnetic nuclei, precession starts, and the nuclei spin is rotating around the magnetic field.

1.2. Precession

After the radiofrequency pulse is turned off, the nuclei return to their original alignment with the magnetic field. During this process, the nuclei precess around the magnetic field and emit radiofrequency signals, which are detected by the MRI scanner. This emission is referred to as nuclear magnetic resonance or NMR signal.

1.3. Spatial Encoding

MRI introduces spatial encoding gradients, which vary the magnetic field across the region of interest. These gradients cause nuclei at different locations within the body to resonate at slightly different frequencies. By analyzing the differences in resonance frequencies, the MRI scanner can determine the spatial location of the emitting nuclei.

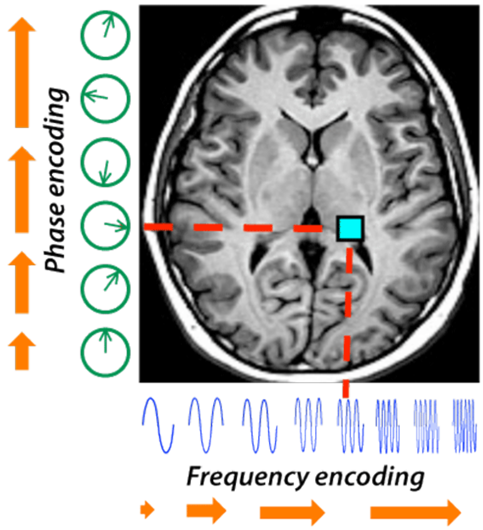

Fig. 2 Illustrations of spatial encoding in MRI by varying the gradients fields. Along the frequency encoding direction, the precession frequency is increasing left to right, enabling localization of the MRI signal. To localize the signal in the phase encoding direction, the signal needs to read out multiple times, each with a different phase applied. This enables the signal to be localized through the use of the Fourier transform.

1.4. Image Formation

The collected NMR signals are processed using complex mathematical algorithms and Fourier transformations to create detailed cross-sectional images of the body. The resulting images represent variations in the density of protons in different tissues, such as muscles, fat, and fluids, which can be seen as variations in brightness and contrast.

1.4.1. Tissue Contrast

Different tissues in the body have distinct relaxation times, known as T1 (longitudinal) and T2 (transverse) relaxation times. By manipulating the timing and repetition of radiofrequency pulses and signal acquisition, MRI can produce images with varying levels of contrast, allowing for the visualization of anatomical structures and abnormalities.

1.4.2. Functional MRI (fMRI)

Beyond anatomy, MRI is used for functional imaging, such as fMRI. This technique measures changes in blood flow and oxygenation to assess brain activity, making it valuable for studying cognitive and neurological functions.

1.4.3. Specialized MRI Techniques

MRI has various specialized techniques, including diffusion-weighted imaging (DWI), magnetic resonance angiography (MRA), and magnetic resonance spectroscopy (MRS), each tailored for specific diagnostic purposes.

1.5. Clinical Applications

MRI is widely used in clinical medicine for the diagnosis and monitoring of various conditions, including neurologic disorders, cardiovascular diseases, musculoskeletal injuries, and cancer. It provides detailed images without exposing patients to ionizing radiation.

2. MR Hardware

Magnetic Resonance Imaging (MRI) relies on a complex interplay of hardware components to create detailed images of the human body. Here's a short introduction to the key hardware components used in MRI:

2.1. Magnet

The core of an MRI system is a powerful superconducting magnet. This magnet generates a strong, uniform magnetic field that aligns the hydrogen nuclei (protons) in the body. The strength of this magnetic field is typically measured in Tesla (T) and can range from 1.5 T to 7 T in clinical systems, with even higher fields used in research.

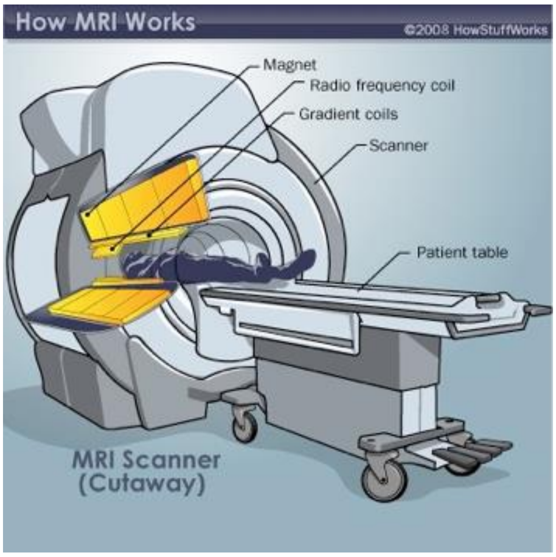

***Fig. 2** Hardware components in the MRI scanner, showing the main magnet (B_0), the radio frequency coil (B_1) and the gradient coils.*

2.2. Gradient Coils

Gradient coils are sets of smaller electromagnets used to create spatial variations in the main magnetic field. By switching the gradient coils on and off, the MRI machine can encode spatial information and produce detailed images in multiple dimensions (e.g., 2D slices or 3D volumes). The switching cause characteristic “blipping” sound and is the main cause of the loud noise in MRI.

2.3. Radiofrequency (RF) Coils

RF coils are used to transmit radiofrequency pulses and receive the resulting signals from the patient's body. There are various types of RF coils, including surface coils (placed on or near the body part of interest) and body coils (integrated into the MRI scanner itself).

2.4. Cooling Systems
The superconducting magnet needs to be maintained at extremely low temperatures to maintain their superconducting state. Liquid helium is typically used for cooling, around 2m^3, and a cryopump is used to keep the helium cold.

2.5. Gradient Amplifiers
These components are responsible for delivering the electric currents to the gradient coils, allowing for precise control of the spatial encoding process.

2.6. RF Transmit and Receive Systems
These systems include RF amplifiers and receivers for transmitting RF pulses and detecting the resulting NMR signals. They are essential for both exciting the protons and capturing the emitted signals during image acquisition.

2.7. Computers
Computers play a critical role in the operation of MRI scanners, performing tasks ranging from controlling the scanner's hardware to processing and generating images.

2.7.1. Control Computer
The control computer, sometimes referred to as host computer, serves as the "brain" of the MRI scanner. It manages the scanner's hardware components, including the magnet, gradient coils, and RF systems. It sends precise instructions to these components to control the timing and strength of magnetic fields and radiofrequency pulses. The control computer ensures that the MRI scan is executed according to the desired parameters and sequences.

2.7.2. Image Reconstruction Computer
The raw data acquired by the MRI scanner needs to be processed to create meaningful images. The image reconstruction computer is responsible for applying complex mathematical algorithms, often involving Fourier transformations, to convert the NMR signals into detailed cross-sectional images. This computer handles data manipulation and image generation.

2.7.3. Console Computer
MRI operators, such as radiologists and technologists, interact with the MRI scanner through a user interface on a console computer. This computer provides a graphical user interface (GUI) for setting scan parameters, selecting imaging sequences, and monitoring the scanning process in real time. It allows the operator to customize the MRI scan according to the patient's needs and the clinical context.

2.7.4. Post-Processing and Analysis Workstations
In addition to real-time image generation, MRI scanners often have dedicated post-processing and analysis workstations. These workstations run specialized software for advanced image processing, quantitative analysis, and 3D reconstructions. Radiologists and researchers use these tools to extract additional information from the MRI data.

2.7.5. Network and Data Storage Servers

MRI scanners are often connected to a network to facilitate data transfer and storage. These servers store patient data, images, and relevant information securely. Access to these servers may be restricted for privacy and security reasons, as patient data must be handled in compliance with healthcare regulations.

2.7.6. Safety and Monitoring Computers

MRI scanners have safety systems that continuously monitor the scanner's status and alert operators to any anomalies. These systems, often integrated into dedicated computers, are critical for ensuring patient and operator safety in the strong magnetic field environment.

2.7.7. Communication and Archiving Computers

Communication computers enable the transfer of images and reports to hospital information systems (HIS) and picture archiving and communication systems (PACS). These computers ensure that MRI results are integrated into a patient's electronic health record and can be accessed by healthcare providers.

2.8. Patient Table

The patient table is a movable platform that allows patients to be positioned within the MRI scanner. It can be adjusted to ensure that the area of interest is in the center of the magnetic field.

2.9. Control Room

The MRI scanner is operated from a separate control room to shield operators from the strong magnetic field. The control room houses the console computer that controls the scanner and processes the reconstructed data.

2.10. Safety Measures

MRI rooms are equipped with safety features, such as a safety door with an interlock system to prevent accidental exposure to the strong magnetic field. Patients and operators must also remove any ferromagnetic objects before entering the MRI room, as these can become dangerous projectiles in the presence of a strong magnetic field.