9.1 Historical Introduction

Magnetic resonance imaging (MRI) is an imaging technique used primarily in medical settings to produce high quality images of the inside of the human body. MRI is based on the principles of nuclear magnetic resonance (NMR), a spectroscopic technique used by scientists to obtain microscopic chemical and physical information about molecules. The technique was called magnetic resonance imaging rather than nuclear magnetic resonance imaging (NMRI) because of the negative connotations associated with the word nuclear in the late 1970's. MRI started out as a tomographic imaging technique, that is it produced an image of the NMR signal in a thin slice through the human body. MRI has advanced beyond a tomographic imaging technique to a volume imaging technique. This package presents a comprehensive picture of the basic principles of MRI.

Before beginning a study of the science of MRI, it will be helpful to reflect on the brief history of MRI. Felix Bloch and Edward Purcell, both of whom were awarded the Nobel Prize in 1952, discovered the magnetic resonance phenomenon independently in 1946. In the period between 1950 and 1970, NMR was developed and used for chemical and physical molecular analysis.

In 1971 Raymond Damadian showed that the nuclear magnetic relaxation times of tissues and tumors differed, thus motivating scientists to consider magnetic resonance for the detection of disease. In 1973 the x-ray-based computerized tomography (CT) was introduced by Hounsfield. This date is important to the MRI timeline because it showed hospitals were willing to spend large amounts of money for medical imaging hardware. Magnetic resonance imaging was first demonstrated on small test tube samples that same year by Paul Lauterbur. He used a back projection technique similar to that used in CT. In 1975 Richard Ernst proposed magnetic resonance imaging using phase and frequency encoding, and the Fourier Transform. This technique is the basis of current MRI techniques. A few years later, in 1977, Raymond Damadian demonstrated MRI called field-focusing nuclear magnetic resonance. In this same year, Peter Mansfield developed the echo-planar imaging (EPI) technique. This technique will be developed in later years to produce images at video rates (30 ms / image).

Edelstein and coworkers demonstrated imaging of the body using Ernst's technique in 1980. A single image could be acquired in approximately five minutes by this technique. By 1986, the imaging time was reduced to about five seconds, without sacrificing too much image quality. The same year people were developing the NMR microscope, which allowed approximately 10 μm resolution on approximately one cm samples. In 1987 echo-planar imaging was used to perform real-time movie imaging of a single cardiac cycle. In this same year Charles Dumoulin was perfecting magnetic resonance angiography (MRA), which allowed imaging of flowing blood without the use of contrast agents.

In 1991, Richard Ernst was rewarded for his achievements in pulsed Fourier Transform NMR and MRI with the Nobel Prize in Chemistry. In 1992 functional MRI (fMRI) was developed. This technique allows the mapping of the function of the various regions of the human brain. Five years earlier many clinicians thought echo-planar imaging's primary applications were to be in real-time cardiac imaging. The development of fMRI opened up a new application for EPI in mapping the regions of the brain responsible for thought and motor control. In 1994, researchers at the State University of New York at Stony Brook and Princeton University demonstrated the imaging of hyperpolarized ^{129}Xe gas for respiration studies.

In 2003, Paul C. Lauterbur of the University of Illinois and Sir Peter Mansfield of the University of Nottingham were awarded the Nobel Prize in Medicine for their discoveries concerning magnetic resonance imaging. MRI is clearly a young, but growing science.

Why MRI?

When using x-rays to image the body one doesn't see very much. The image is gray and flat. The overall contrast resolution of an x-ray image is poor. In order to increase the image contrast one can administer some sort of contrast medium, such as barium or iodine based contrast media. By manipulating the x-ray parameters kV and mAs one can try to optimize the image contrast further but it will remain sub optimal. With CT scanners one can produce images with a lot more contrast, which helps in detecting lesions in soft tissue. The principle advantage of MRI is its excellent contrast resolution. With MRI it is possible to detect minute contrast differences in (soft) tissue, even more so than with CT images. By manipulating the MR parameters one can optimize the pulse sequence for certain pathology. Another advantage of MRI is the possibility the make images in every imaginable plane, something, which is quite impossible with x-rays or CT. (With CT it is possible to reconstruct other planes from an axially acquired data set).

However, the spatial resolution of x-ray images is, when using special x-ray film, excellent. This is particularly useful when looking at bone structures. The spatial resolution of MRI compared to that of x-ray is poor. In general one can use x-ray and CT to visualize bone structures whereas MRI is extremely useful for detecting soft tissue lesions. Before beginning a study of the science of MRI, it will be helpful to reflect on the brief the hardware of MRI.

9.2 The Hardware

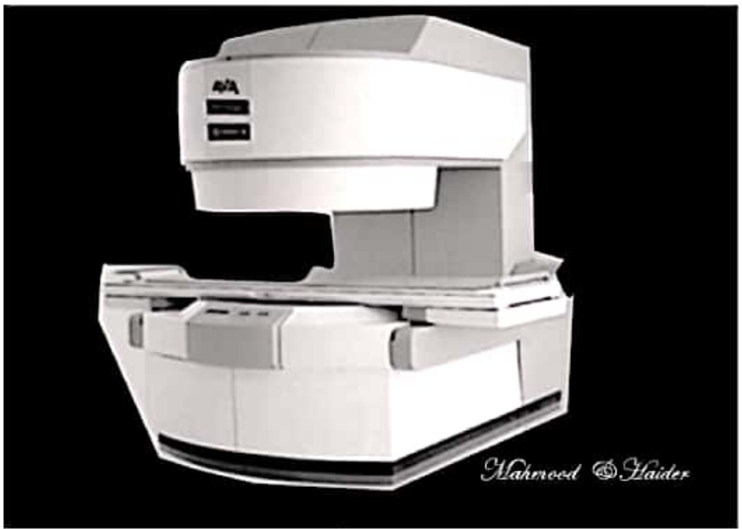
Scanners of magnetic resonance imaging (MRI) come in many varieties. There is a permanent magnet type, resistive, superconducting, and opening or bore, with or without helium, high field strength or low. The choice of magnet mainly governed by what you intend to do, and the cost. Field magnets offer high quality image better, faster scanning and a wider range of applications, but they are more cost than their counterpart's field is low.

9.3 Magnet Types

The static magnetic field (B_0) in MRI systems can be created by: **Permanent magnets** and **Electromagnets.**

9.3.1 Permanent Magnets

A **permanent magnet** that originates from permanently ferromagnetic materials, which does not lose the magnet field, that remains over time without weakening. Due to weight considerations, **these types of magnets** are usually limited to maximum field strengths of 0.4 T (the unit for magnetic field strength is Tesla: 1 Tesla = 10000 Gauss). Permanent magnets have usually an open design system (see Figure 9.1) which has ample open space which is more comfortable for the patient. So, the open design accommodates extremely large patients and dramatically reduces anxiety for all patients especially those who have claustrophobic tendencies or have larger body structures.



ADVANTAGES	DISADVANTAGES
Low power consumption Low operating cost Small fringe field No cryogen	Limited field strength (<0.3T) Very heavy No quench possibility

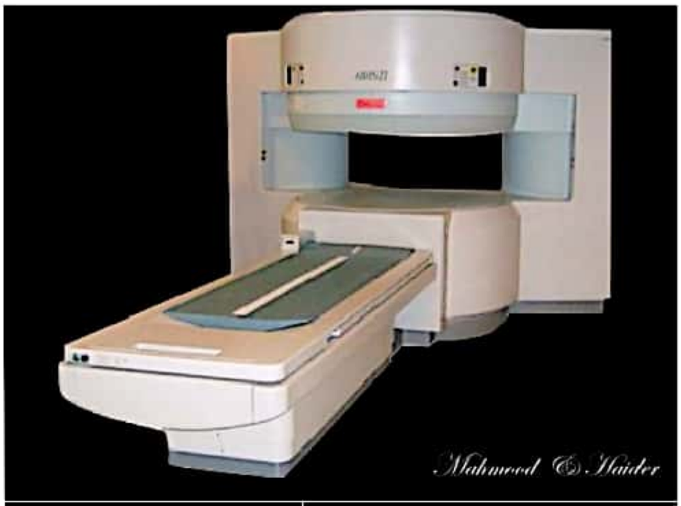
Figure 9.1: Open MRI system "OPER"

9.3.2 Electromagnets

There are two categories can be used in MR scanner: Resistive and Superconducting Magnets

9.3.2.1. Resistive Magnets

Resistive magnets are made from loops of wire wrapped around a cylinder through which a large electric current is passed. These magnets are very large that utilizes the principles of electromagnetism to generate the magnetic field, like the ones used in scrap yards to pick up cars. They are lower in cost, but need a lot of power to run that means, large current values which runs through loops of wire because of the natural resistance of the wire. Therefore they produce a lot of heat, which requires significant cooling of the magnet coils. Resistive magnets come in two general categories: iron-core and air-core. Resistive magnets are typically limited to maximum field strengths can be up to 0.6 Tesla. They usually have an open design, which reduces claustrophobia. Figure 9.2 shows Hitachi's Airis 0.3 Tesla (air-core) system.

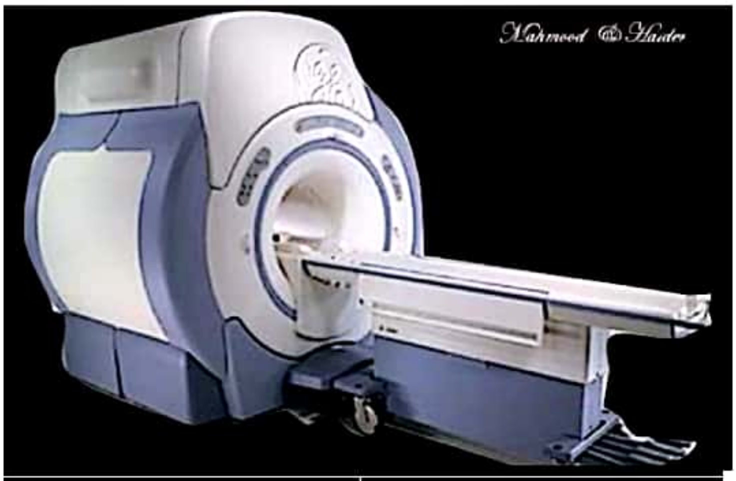


ADVANTAGES	DISADVANTAGES
Low capital cost Light weight Can be shut off	High power consumption Limited field strength (<0.2T) Water cooling required Large fringe field

Figure 9.2: Hitachi's Airis 0.3 Tesla (air-core) system.

9.3.2.2 Superconducting Magnets

Superconducting magnets are Today's most commonly used in MRIs. These superconductors, such as niobium-tin and niobium-titanium are used to make the coil windings for superconducting magnets. The magnetic field is generated by a passing electrical current through coils of wire. The wire is surrounded with a coolant, such as liquid helium, to reduce the electric resistance of the wire. At 4 Kelvin (-269 °C) electric wire looses its resistance. Once a system is energized, it won't loose its magnetic field. Superconductivity allows for systems with very high field strengths up to 12 Tesla. The ones that are most used in clinical environments run at 1.5 Tesla. Most superconducting magnets are bore type magnets. A number of vacuum vessels, which act as temperature shields, surround the core. These shields are necessary to prevent the helium to boil off too quickly. Another advantage of superconducting magnets is the high magnetic field homogeneity.



ADVANTAGES	DISADVANTAGES
High field strength	High capital costs
High field homogeneity	High cryogen costs
Low power consumption	Acoustic noise
High SNR	Motion artifacts
Fast scanning	Technical complexity

Figure 9.3: bore type magnets.

[In 1997 Toshiba introduced the world's first open superconducting magnet. The system uses a special metal alloy, which conducts the low temperature needed for superconductivity. The advantage of this is that the system does not need any helium refills, which dramatically reduces running costs. The open design reduces anxiety and claustrophobia. Figure 9.4 shows Toshiba's OPART 0.35 Tesla system, which combines an open design with the advantages related to superconducting magnets.]

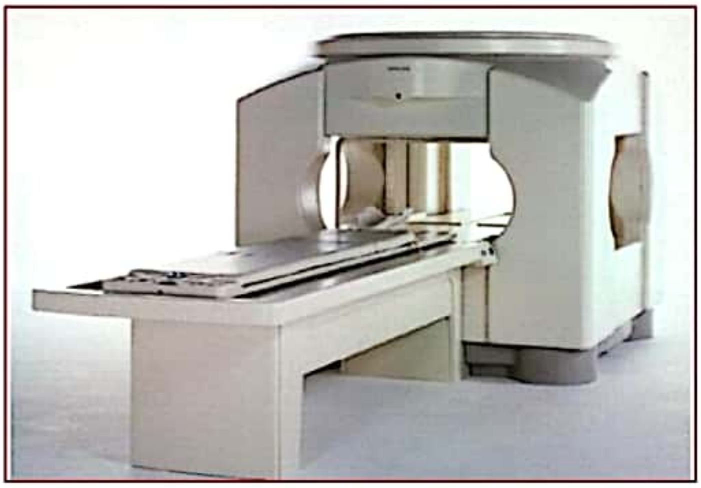


Figure 9.4: Toshiba's OPART 0.35 Tesla system, which combines an open design.

The current trend in magnet design is low field open design versus high field bore design. Obviously it would be desirable to combine the two, and only time will tell whether this can be done within reasonable manufacturing costs and technical/structural limitations.

9.4 Shimming

MRI requires a very high homogeneous static magnetic field. In order to produce high-resolution images, the magnetic field inhomogeneity produced in a high performance MRI scanner must be maintained to the order of several ppm. After manufacturing, the magnet must be adjusted in some points to produce a more uniform field by making small mechanical and/or electrical adjustments to the overall field. This process is known as **shimming**. Because the magnet itself is not adequately homogeneous, it is necessary to improve or "shim" the homogeneity of the static magnetic field (B_o). A **shim** is a device used to adjust the homogeneity of a magnetic field.

Shimming (or adjustment of the static magnetic field homogeneity) is accomplished by two methods: (1) Passive shimming (2) Active shimming

Passive shimming: The mechanical adjustments, which add small pieces of iron or magnetized materials, are typically called passive shimming. Passive shimming involves pieces of steel with good magnetic qualities. The steel pieces are placed near the permanent or superconducting magnet. They become magnetized and produce their own magnetic field.

Active shimming: The electrical adjustments, which use extra exciting currents, are known as active shimming. Active shimming is performed with coils with adjustable current. Active shimming requires passage of electric current through coils with unique geometric configurations. The shim coils are designed to correct inhomogeneities of specific geometries.

In both cases (active and passive shimming), the additional magnetic fields (produced by coils or steel) add to the overall magnetic field of the superconducting magnet in such a way as to increase the homogeneity of the total field.

9.5 Radio Frequency Coils

Until here

Radio Frequency (RF) coils are needed to receive and/or transmit the RF signals used in MRI scanners. RF coils system comprises the set of components for transmitting and receiving the radiofrequency waves involved in exciting the nuclei, selecting slices, applying gradients and in signal acquisition. RF coils are vital component in the performance of the radiofrequency system. They one of the most important components that affects image quality and obtaining clear images of the human body. RF coils for MRI can be categorized into two different categories: volume coils and surface coils.

9.5.1 Volume RF Coils

The design of a volume coil is to provide a homogeneous RF field inside the coil which is highly desirable for transmit, but is less ideal when the region of interest is small. The large field of view of volume coils means that by receiving the noise that they receive from the