1 Hardware Overview

Instrumentation: Magnets

To obtain a magnetic resonance (MR) signal from tissues, a large static magnetic field is required. The primary purpose of the static magnetic field (known as the B_0 field) is to magnetize the tissue. The magnet technology utilized is either referred to as: Permanent, Resistive or Superconductive. Regardless of the style or type of magnet used, the B_0 field must be stable and homogeneous, particularly in the central area of the magnet (isocenter) which is where the anatomy to be imaged should be placed.

- The vertical field magnet design uses two magnets, one above the patient and one below the patient.
- The frame, which supports the magnets, also serves to "return" the magnetic field.
- Generally, vertical magnets have a reduced fringe field compared with conventional horizontal field magnets.

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- The "open design" of these systems is often marketed as being less confining to the patient who may be anxious or claustrophobic.
- "Open MRI" is marketing terminology and has no basis or meaning in science.
- The radio-frequency (RF) transmit coil and gradient coils for vertical field magnets (discussed in more detail later) are flat coils located on the "face" of the magnets.
- The *receiver* or surface coils used with vertical field magnets are solenoid in design.
- For vertical field magnets, field strength and homogeneity can be increased by reducing the gap between the two magnets. The disadvantage to reducing the gap is the obvious reduction in patient area.

Regardless of whether the field is vertical or horizontal, there are three primary types of technology utilized tor MRI system magnets: permanent, resistive, and superconducting.

Permanent Magnets

- MRI systems based on permanent magnet technology use materials which are, as the name implies, permanently magnetized to produce the main external magnetic field (B_O).
- Increasing the amount of material used increases the field strength, in addition to size and weight.
- Permanent magnets generally have field strengths of 0.06 to 0.35 Tesla.
- Generally, vertical field permanent magnets have a relatively small fringe field.
- Because of the small fringe field, permanent magnets are often easy to sight, though their weight can be an issue.
- Permanent magnets are sensitive to ambient room temperature.
- Changes in scan room temperature can cause the field strength to vary several gauss per degree.

- Because changes in field strength result in changes in resonant frequency, image quality can vary if the field drifts significantly.

Resistive Magnets

- Resistive magnets are generally used in either a vertical or transverse field system.
- Larger resistive magnet-based systems can have field strengths up to 0.6 Tesla.
- Whenever electrical current is applied to a wire, a magnetic field is induced around the wire.
- To produce a static field (i.e. not alternating), direct current is required.
- Resistive systems generally also contain an iron core around which the wire is wound.
- Increasing the amount of current or turns of wire increases the field strength and results in heat in the wire.
- Resistive magnets require a constant current to maintain the static field.
- Cooling of the coils is also required as the by-product of electrical resistance is heat.
- Resistive magnets can easily be turned off when not in use (permanent and superconductive magnets cannot be turned off).
- The earliest type of magnets used in MRI were resistive.
- Resistive magnets can also be temperature-sensitive.

Superconductive Magnets

- Superconductive magnets are similar to resistive magnets because they use direct current actively applied to a coil of wire to produce the static magnetic field.
- The main difference is that the coils are immersed in liquid helium (cryogen) to remove the resistance.
- When the temperature of any conductor is reduced, electrical resistance decreases.

- Without the resistance, the electrical current can flow within a closed circuit without external power being applied (i.e. no voltage is needed for current to flow).
- The flow of electrical current without resistance is known as superconductivity.
- Most superconductive magnets are solenoid in design and thus, result in a horizontal magnetic field.
- Recent innovations in magnet design allow for vertical field systems using superconductive magnets.
- Superconductive magnets are capable of achieving higher field strengths compared to permanent and resistive magnet technology.
- Small-bore horizontal magnets used to image small animals and tissue samples can have field strengths of 10 Tesla or higher.
- Superconductive magnets currently approved for use by the FDA (US) in clinical settings include field strengths from 1.0 Tesla to 7.0 Tesla.
- Higher field strengths produce greater fringe fields.
- To reshape and/or reduce the fringe field for siting purposes, magnetic shielding is employed.
- Passive magnetic shielding uses metal (iron) in the scan room walls.
- Active magnetic shielding uses additional coils as part of the magnet design.
- Helium is not stable as a liquid. The temperature of liquid helium is 4 Kelvin. In order to maintain that temperature, it must be kept in a vacuum. Helium will boil at 4.2 K. If the temperature within the vessel containing the magnet coils and liquid helium rises only slightly, or if the vacuum were to be lost, then the liquid helium will boil and expand at a ratio of approximately 1:750.
- The resultant helium gas will burst through a pressure-sensitive containment system and should vent outside the scan room through a duct system attached to the magnet.

- In the absence of the supercooled environment, the current in the magnet coils will experience resistance, and the static field will be lost.
- This sudden and violent loss of superconductivity is referred to as a *quench*.
- The major advantage of superconducting technology is high field strength, which results in inherently high signal-to-noise ratio (SNR).
- The high SNR can be "traded" for rapid scan times and increased spatial resolution.
- The major disadvantage of superconducting technology is the high cost associated with acquisition, siting, and maintenance.

B_0 Homogeneity

Regardless of the type or style of magnet used for an MR system, the magnetic field must be as homogeneous as possible. This characteristic is particularly critical within the central area of the magnet (isocenter) where imaging takes place. The homogeneity is maximized through a process known as *shimming*. Shimming can be accomplished either *actively, passively,* or through a combination of both.

- Active shimming implies the use of additional coils within the magnet vessel or structure.
- Current applied in the shim coils either adds or subtracts from the static magnetic field to produce a field that is as homogeneous as possible.
- Passive shimming implies the use of small bits of ferrous material.
- In the case of a horizontal field magnet, the ferrous material is placed around the bore.
- In the case of a vertical field system, the material is placed on the face of the main magnets.

Instrumentation: RF Subsystem

Transmit

- The primary purpose of the RF subsystem is to transmit the RF pulses or RF field (known as the B1 field) and to receive the MR signal from tissue being examined.
- The B1 field is used to provide the necessary RF energy to cause the net magnetization of the tissues to tip and rotate through the transverse plane where the receiving coils are located.
- The RF subsystem consists of coils that transmit and/or receive the RF signals and the electronics that power them.
- Most RF subsystems in use today are digital rather than analog.
- Digital RF systems provide for finer control of the RF pulses produced in the MRI process.
- RF coils can be designed to transmit only, receive only, or transmit and receive. The decision as to which design will be used is largely determined by the manufacturer or the overall MR system design.
- The most common type of RF receiving coils in use today are receive-only multichannel coils (sometimes referred to as "phased-array" coils).
- In superconductive, horizontal field systems, a large *body coil* is located within the magnet enclosure. In general, the body coil operates either as a transmit-only coil or as a transmit-and-receive (T/R) coil.
- Body coils are used to acquire information over a large field-of-view (FOV).
- The primary disadvantage of using the integrated body coil as a receive coil is an inherently low SNR.
- Generally, a larger coil will result in lower SNR. Conversely, a small coil will result in higher SNR.

- To increase the SNR, smaller surface (local) coils can be placed over or around the region of interest.
- Local coils can be either a T/R coil or a receive-only coil, again, largely based on the manufacturer's preference.
- If the local coil is a receive-only coil, then the integrated body coil transmits RF.
- Reducing the size of the local coil increases the SNR, but the area of coverage is reduced.

Local (Surface) Coils

The primary purpose of local coils is to increase the SNR. The main difficulty is to do so without excessive restriction of coverage of the area of interest. As mentioned, as the coil size is increased, the SNR is reduced. Currently, there are three main categories or types of local coils: linear, quadrature, and phased-array coils.

- The first type of local coils used in MRI were linear in design.
- Quadrature designs use additional loops and circuitry to improve the efficiency with which the MR signal is induced in the coil.
- Typically, quadrature coils produce an increase in the SNR of approximately 40% compared with a linear coil of the same size.
- Vertical field magnets require the use of solenoid coils because of the orientation of B_0. Generally, the solenoid configuration is more efficient compared with a liner coil of similar size.
- It is possible to combine coils electronically to improve signal uniformity through a region of interest.
- When two coils are combined in a manner such that they use the same receiver electronics, this is referred to as a *Helmholtz pair.*

- The Helmholtz pair has been used in coils designed to image the cervical spine, neck, and bilateral temporomandibular joints.
- Although a Helmholtz pair can improve the signal homogeneity across a region of interest, the SNR is not necessarily increased, which is primarily a result of coupling between the coils.
- Phased-array (multi-channel) coils allow for increased area of coverage without a reduction in the SNR.
- Typically, a phased-array coil consists of an array of coils designed to cover a particular area of the anatomy such as the spine, abdomen, or extremities.
- The major distinguishing characteristic of phased-array coil is that each active coil in the array is electronically connected to its own receiver.
- Multiple receivers can contribute to the increased coverage possible with a phased-array/multi-channel coil.
- With phased-array coils, one not only realizes the coverage of the entire array, but also the SNR characteristic of each coil within the array.
- RF coils must be "tuned" for the specific Larmor frequency of the MR system for which they are designed and cannot be used on systems operating at a different field strength.
- Generally, the tuning is set by the manufacturer and cannot be changed on site.

Instrumentation: Gradient Subsystem

The primary purpose of the gradient subsystem is to select the slice and imaging plane and to spatially encode the MR signal spatially. The gradient subsystem consists of gradient coils and the electronics that power them. The term gradient means slope or incline. A gradient magnetic field is, therefore, a magnet field that varies in intensity over distance. During the *imaging* process, gradient magnetic fields are also varied over time.

- Gradient magnetic fields are superimposed over the primary magnetic field.
- Gradient magnetic fields are produced as current is applied to the gradient coils.
- There are three sets of gradient coils in MR systems.
- The coil that is used to vary the intensity of the magnetic field in the head-to-foot direction is referred to as a *z gradient coil*.
- The coil that is used to vary the intensity of the magnetic field in the right-to-left direction is referred to as an *x gradient coil*.
- The coil that is used to vary the intensity of the magnetic field in the anterior-to-posterior direction is referred to as a *y gradient coil*.
- The term *amplitude* refers to the severity or steepness of the slope of the gradient magnetic field.
- A high-amplitude gradient will have a steep slope and will, therefore, greatly vary the intensity of the magnetic field in a given direction.
- *Polarity* (either positive or negative) refers to whether the gradient magnetic field is creating a field greater than or less than the frequency of B_0.
- The maximum amplitude of gradient magnetic fields is described in units of millitesla per meter (mT/m) or Tesla per meter (T/m).
- Higher gradient amplitudes offer the benefits of thinner slices and smaller FOVs.
- The speed at which a gradient magnetic field attains its maximum amplitude is identified by its *rise time*.
- Rise time is expressed in units of microseconds (μsec).
- Another way to express gradient performance is *slew rate*.

- Slew rate is defined as the maximum amplitude divided by the rise time.
- Slew rate is expressed in units of Tesla/meter/second (T/m/sec).
- Increased slew rates offer the benefit of reduced echo times (TE), increased number of slices per repetition time (TR), shorter TR for three-dimensional (3D) sequences, and improved image quality with echo planar and fast-spin-echo sequences.