Basic Principles of MRI

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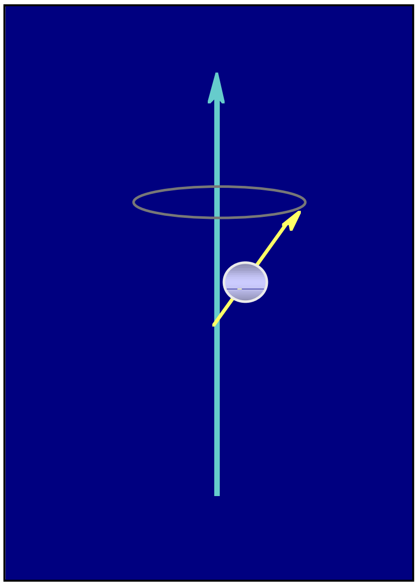
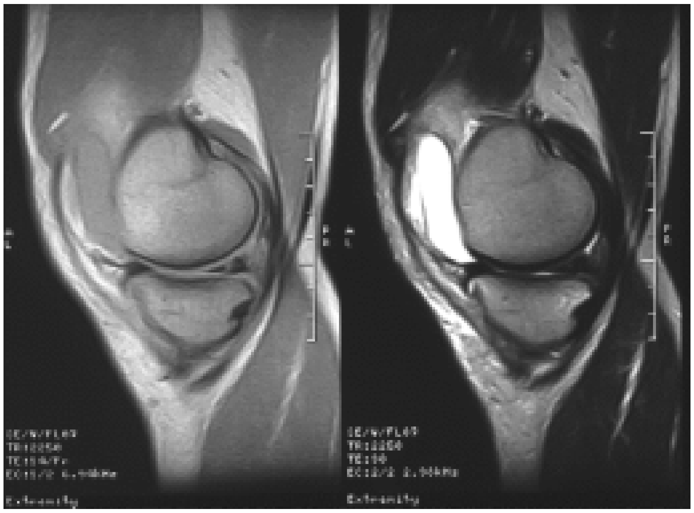


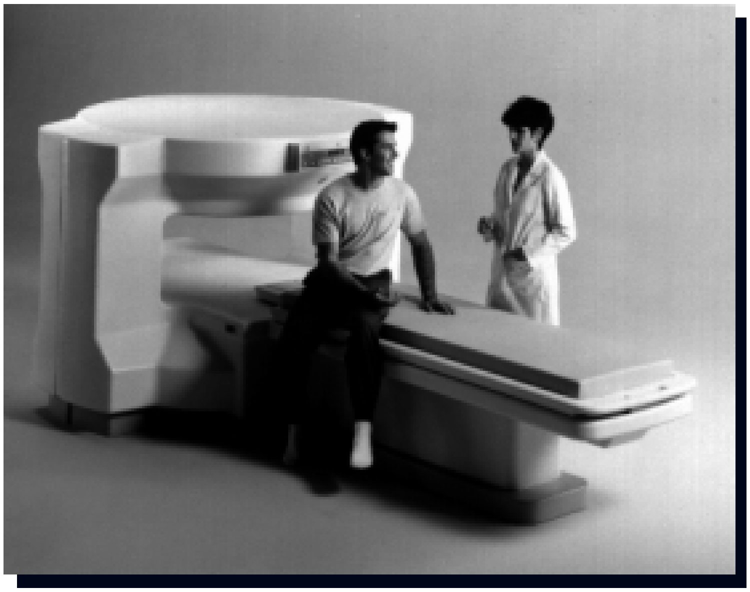


Clinical Magnetic Resonance Imaging (MRI) uses the magnetic properties of hydrogen and its interaction with both a large external magnetic field and radiowaves to produce highly detailed images of the human body. In this first module, we will discuss some basic principles of magnetism, the magnetic properties of the hydrogen nucleus, and its interaction with the externally applied magnetic field (B0).

In its early days, MRI was known as NMR. This stands for Nuclear Magnetic Resonance. Although the name has changed (primarily due to the negative connotation of the word “nuclear”), the basic principles are the same. We derive our images from the magnetic resonance properties of nuclear particles (specifically hydrogen).

In order to perform MRI, we first need a strong magnetic field. The field strength of the magnets used for MR is measured in units of Tesla. One (1) Tesla is equal to 10,000 Gauss. The magnetic field of the earth is approximately 0.5 Gauss. Given that relationship, a 1.0 T magnet has a magnetic field approximately 20,000 times stronger than that of the earth. The type of magnets used for MR imaging usually belongs to one of three types; permanent, resistive, and superconductive.

A permanent magnet is sometimes referred to as a vertical field magnet. These magnets are constructed of two magnets (one at each pole).



The patient lies on a scanning table between these two plates. Advantages of these systems are: 1) Relatively low cost, 2) No electricity or cryogenic liquids are needed to maintain the magnetic field, 3) Their more open design may help alleviate some patient anxiety, 4) Nearly non-existant fringe field. It should be noted that not all vertical field magnets are permanent magnets.

Resistive magnets are constructed from a coil of wire. The more turns to the coil, and the more current in the coil, the higher the magnetic field. These types of magnets are most often designed to produce a horizontal field due to their solenoid design (figure 2).

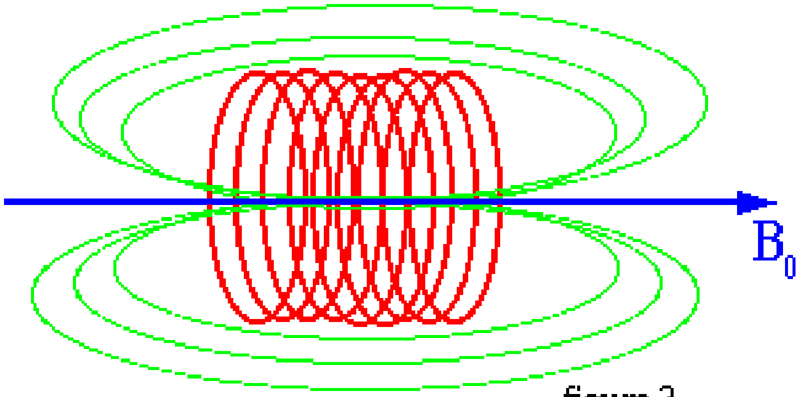


figure 2

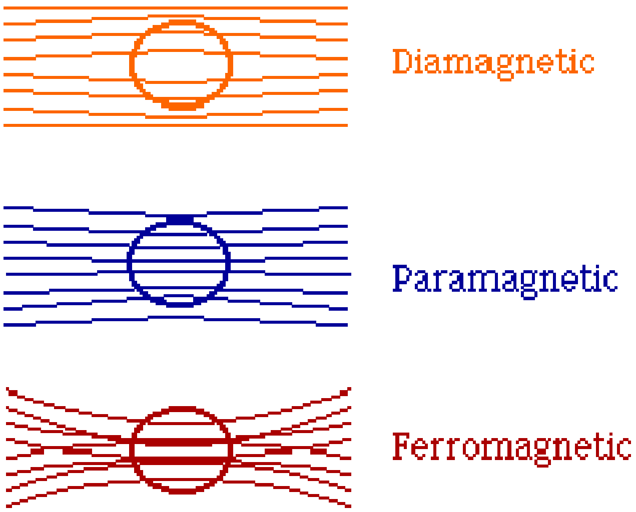
As previously mentioned, some vertical field systems are based on resistive magnets. The main advantages of these types of magnets are: 1) No liquid cryogen, 2) The ability to “turn off” the magnetic field, 3) Relatively small fringe field. Below is an example of a vertical field resistive system:

Superconducting magnets are the most common. They are made from coils of wire (as are resistive magnets) and thus produce a horizontal field. They use liquid helium to keep the magnet wire at 4 degrees Kelvin where there is no resistance. The current flows through the wire without having to be connected to an external power source. The main advantage of superconducting magnets is their ability to attain field strengths of up to 3 Tesla for clinical imagers, and up to 10 Tesla or more for small bore spectroscopy magnets. Below is an example of a superconductive MR system:

Magnetic Properties of Matter

Magnetism is a fundamental property of matter. The three types of magnetic properties are: diamagnetic, paramagnetic, and ferromagnetic. These three properties are illustrated in figure 3.

Figure 3



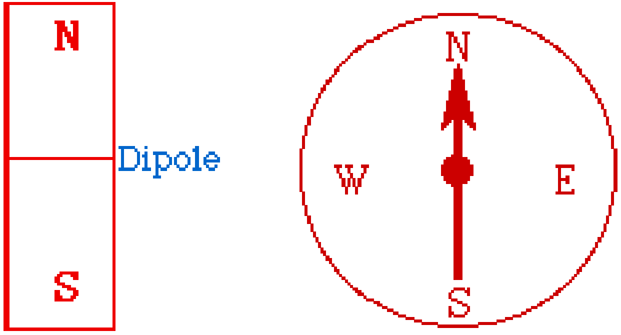
Outside a magnetic field, diamagnetic substances exhibit no magnetic properties. When placed in a magnetic field, **diamagnetic** substances will exhibit a negative interaction with the external magnetic field. In other words they are not attracted to, but rather slightly repelled by the magnetic field. These substances are said to have a **negative magnetic susceptibility**.

Paramagnetic substances also exhibit no magnetic properties outside a magnetic field. When placed in a magnetic field, however, these substances exhibit a slight positive interaction with the external magnetic field and are slightly attracted. The magnetic field is intensified within the sample causing an increase in the local magnetic field. These substances are said to have a **positive magnetic susceptibility**.

Ferromagnetic substances are quite different. When placed in a magnetic field they exhibit an extremely strong attraction to the magnetic field. The local magnetic field in the center of the substance is greatly increased. These substances (such as iron) retain magnetic properties when removed from the magnetic field. Objects made of ferromagnetic substances should not be brought into the scan room as they can become projectiles; being pulled at great speed toward the center of the MR imager. An object that has become permanently magnetized is referred to as a permanent magnet.

A permanent magnet, such as a bar magnet, has two poles and is referred to as a dipole (figure 4).

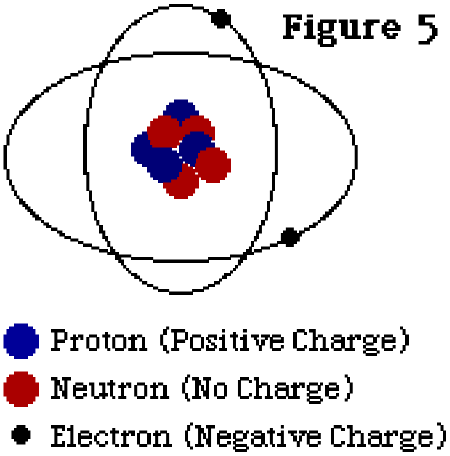
Figure 4



Atomic Structure

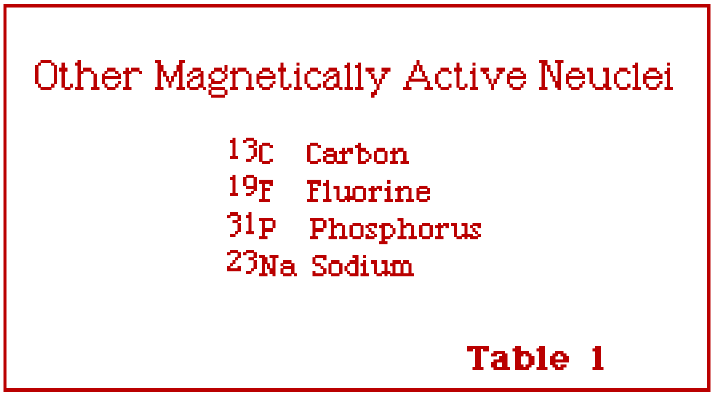
The nucleus of an atom consists of two particles; protons and neutrons. The protons have a positive charge and the neutrons have a neutral charge. The atomic number represents the number of protons in the nucleus. The atomic mass number is the total number of protons and neutrons. Orbiting the nucleus are the electrons, which carry a negative charge (figure 5).

Figure 5



All of these particles are in motion. Both the neutrons and protons spin about their axis. The electrons, in addition to orbiting the nucleus, also spin about their axis. The spinning of the nuclear particles produces angular momentum. If an atom has an even number of both protons and neutrons, then the angular momentum is zero. If an atom has an uneven number of neutrons or protons, then the atom has a certain angular momentum. The angular momentum is expressed as a vector quantity having both magnitude and direction.

In addition to spin angular momentum, certain nuclei exhibit magnetic properties. Because a proton has mass, a positive charge, and spins, it produces a small magnetic field much like a bar magnet. This small magnetic field of the proton is referred to as the magnetic moment (figure 6). The magnetic moment is also a vector quantity having both magnitude and direction and is oriented in the same direction as the angular momentum. The ratio between the angular momentum and the magnetic moment gives us a constant known as the gyromagnetic ratio, which is specific to each magnetically active nuclei. There are several nuclei, which are magnetically active (table 1).



Other Magnetically Active Neuclei

^{13}C	Carbon
^{19}F	Fluorine
^{31}P	Phosphorus
^{23}Na	Sodium

Table 1

Hydrogen has a significant magnetic moment and is nearly 100% abundant in the human body. For these reasons, we use only the hydrogen proton in routine clinical imaging, and that is where we will focus our attention from here on.

The nucleus of the hydrogen atom contains a single proton. Because of this, as previously mentioned, it possesses a significant magnetic moment. The proton will behave as a tiny bar magnet(figure 6).

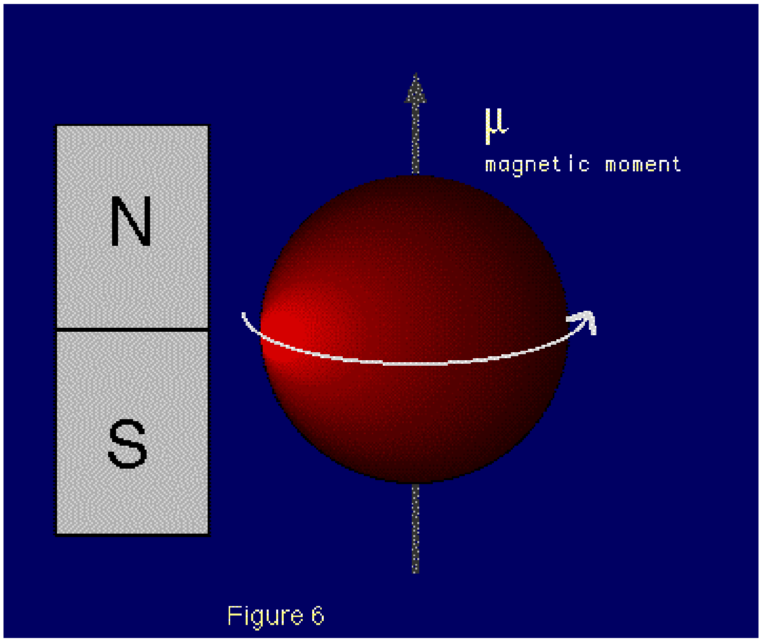


Figure 6

Because of the spin characteristics of the proton, if it is placed in a large external magnetic field, it will assume one of two possible positions. It will align (at a slight angle) in either a parallel or anti-parallel with the direction of the magnetic field (figure 7).

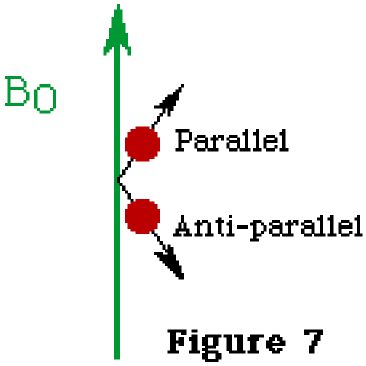


Figure 7

In addition to aligning with B0, the proton will precess at some frequency. The frequency at which the proton precesses is given by the Larmor Equation (figure 8).

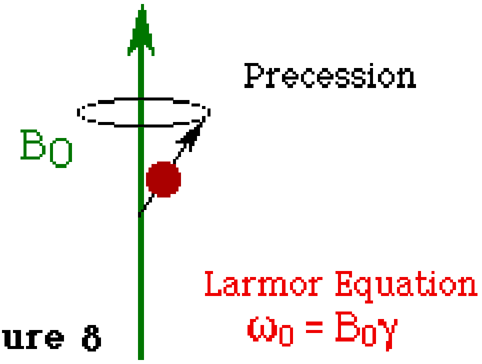


Figure 8

The Larmor Equation tells us that the precessional frequency is equal to the strength of the external static magnetic field (B0) multiplied by the gyromagnetic ratio (g). Increasing B0 will increase the precessional frequency and conversely, decreasing B0 will decrease the precessional frequency. This is analogous to a spinning top. It will precess due to the force of gravity. If the gravity were to be decreased (as it is on the moon), then the top would precess slower.

Placing many protons in a magnetic field, we find that some align anti-parallel and a slight majority aligns parallel. Protons aligned in the parallel orientation are said to be in a low energy state. Protons in the anti-parallel orientation are said to be in a high-energy state (figure 9).

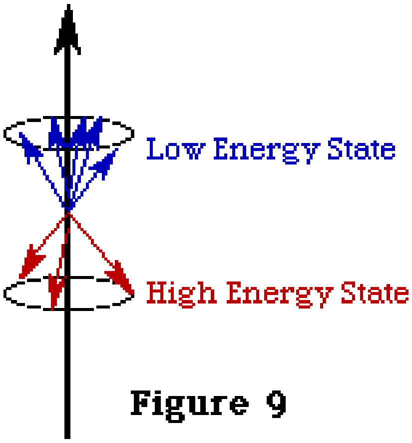


Figure 9

The energy differential between the high and low energy states is proportional to the strength of the externally applied magnetic field B0.

The greater the strength of the external field, the greater the energy differential between the two spin states (figure 10).

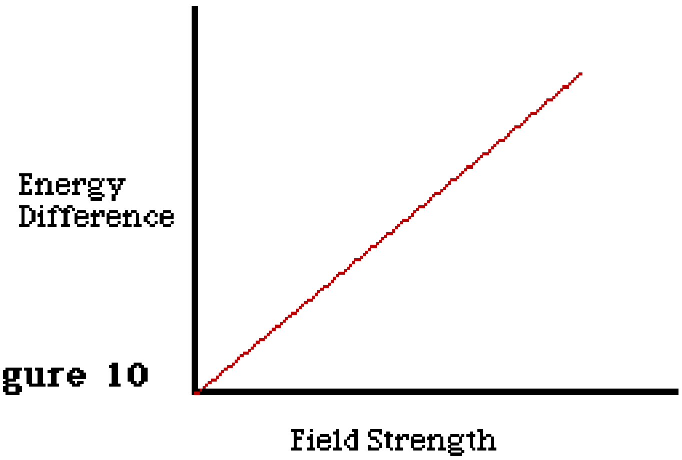


Figure 10

Also related to the strength of B0 is the number of spins in the low energy state. The higher the B0, the greater the number of spins aligned in the low-energy state. The number of spins in the low energy state in excess of the number in the high-energy state is referred to as the spin excess. The magnetic moments of these excess spins add to form the net magnetization and thus the tissue placed in the magnetic field becomes magnetized. The net magnetization is also represented as a vector quantity. As previously mentioned, **a larger B0 will produce a greater spin excess**. Therefore, a larger B0 will produce a larger net magnetization vector (figure 11).

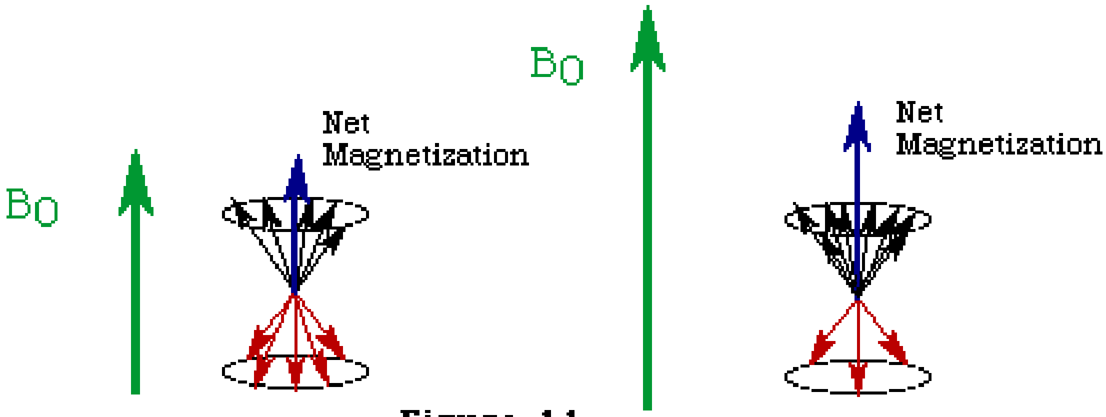


Figure 11

Once the tissue has become magnetized, that is the spins are in either the high or low energy state, a condition is reached known as thermal equilibrium. It should be noted that at equilibrium, the individual spins creating the net magnetization do not precess in phase. This is because of slight differences in precessional frequencies caused by, among other things, magnetic field inhomogenities and differences in small local magnetic fields generated within each particular molecule. As a result, the net magnetization is aligned parallel with B0 but does not precess (figure 12).

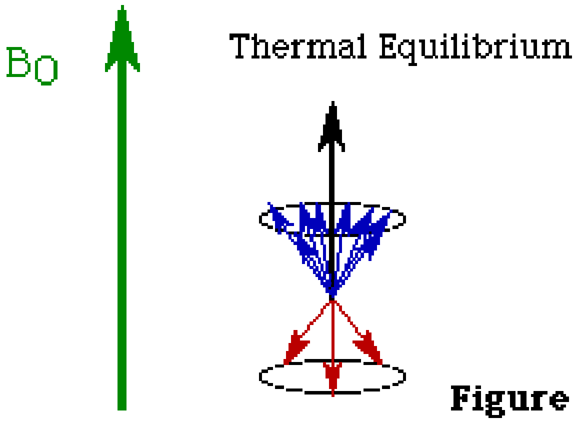


Figure 12

Hydrogen exists in many molecules in the body. Water (consisting of two hydrogen atoms and one oxygen) comprises up to 70% of body weight. Hydrogen is also present in fat and most other tissues in the body. The varying molecular structures and the amount of hydrogen in various tissues effect how the protons behave in the external field. As an example, because of the total amount of hydrogen in water, it has one of the strongest net magnetization vectors relative to other tissues. Other structures and tissues within the body have less hydrogen concentration and become magnetized to a lesser extent. In other words, their net magnetization is less intense (figure 13).

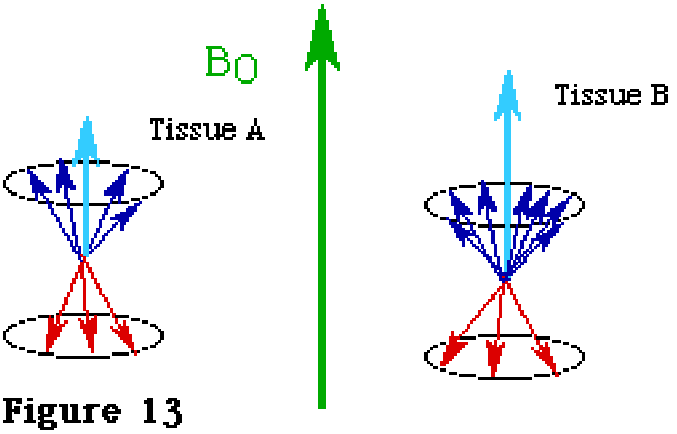


Figure 13

The amount of mobile hydrogen protons that a given tissue possesses, relative to water (specifically CSF), is referred to as its spin density (proton density).

This is the basis with which we begin to produce images using Magnetic Resonance. The hydrogen nucleus contains one proton and possesses a significant magnetic moment. In addition, hydrogen is very abundant in the human body. By placing the patient in a large external magnetic field, we magnetize the tissue (hydrogen), preparing it for the MR imaging process. In the next section, we will look at how this magnetization behaves in the presence of an RF field.

Creating an MR Signal

A radio wave is actually an oscillating electromagnetic field. The RF field is also referred to as the B1 field. It is oriented perpendicular to the main magnetic field (B0). If we apply a pulse of RF energy into the tissue at the Larmor frequency, we first find the individual spins begin to precess in phase, as will the net magnetization vector. As the RF pulse continues, some of the spins in the lower energy state absorb energy from the RF field and make a transition into the higher energy state. This has the effect of “tipping” the net magnetization toward the transverse plane. For the purpose of this explanation, we will assume sufficient energy is applied to produce a 90-degree flip of the net magnetization. In such an example, it is said that a **90-degree flip angle**, or a **90-degree pulse** has been applied (figure 14).

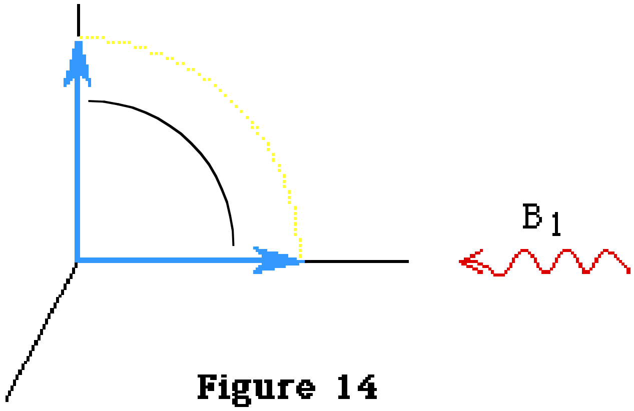
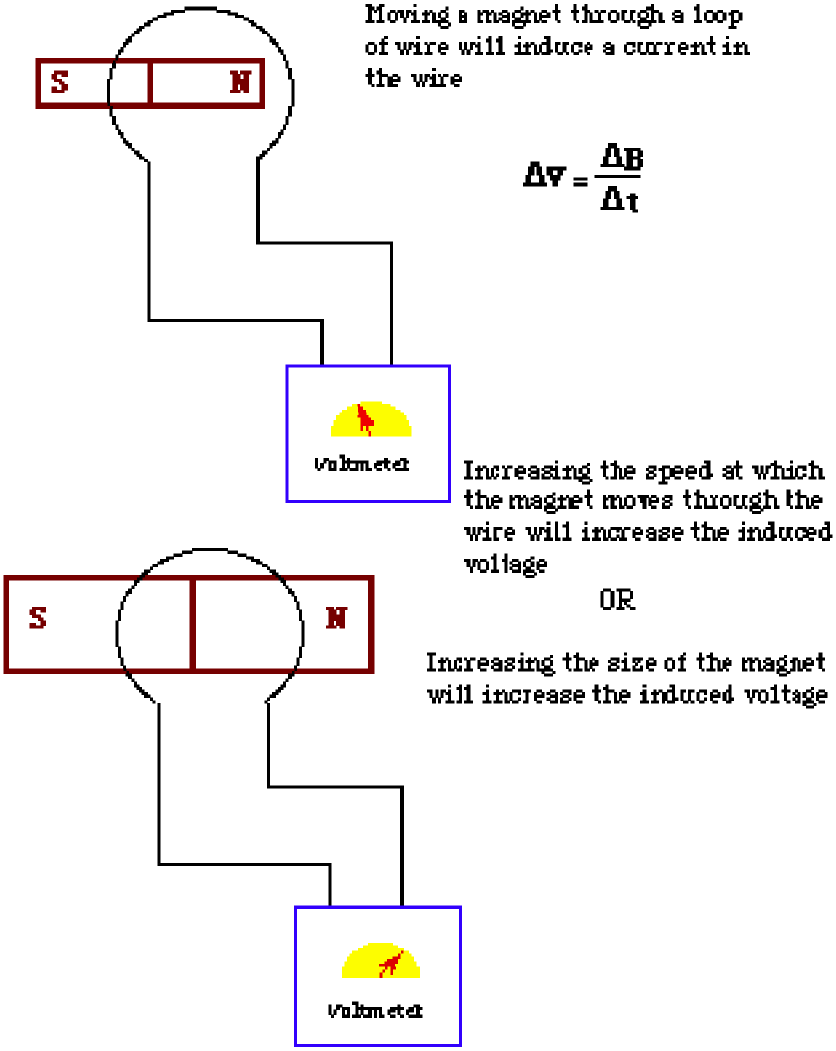


Figure 14

Oriented perpendicular to B0 is a receiver coil. As the magnetization (now referred to as transverse magnetization, or Mxy) precesses through the receiver coil, a current or signal is **induced** in the coil. The principle behind this signal induction is Faraday's Law of Induction. This states that if a magnetic field is moved through a conductor, a current will be produced in the conductor. If we increase the size of the magnetic field, or increase the speed with which it moves, we will increase the size of the signal (current) induced in the conductor (figure 15).

Figure 15



Faraday's Law of Induction:
Moving a magnet through a loop of wire will induce a current in the wire

$$\Delta v = \frac{\Delta B}{\Delta t}$$

Increasing the speed at which the magnet moves through the wire will increase the induced voltage

OR

Increasing the size of the magnet will increase the induced voltage

In order to detect the signal produced in the coil, the transmitter must be turned off. When the RF pulse is discontinued, the signal in the coil begins at a given amplitude (determined by the amount of magnetization precesssing in the transverse plane and the precessional frequency) and fades rapidly away. This initial signal is referred to as the Free Induction Decay or FID (figure 16).

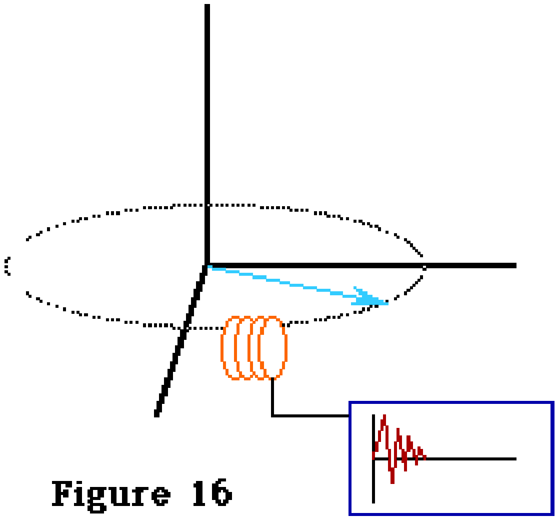


Figure 16

The signal fades as the individual spins contributing to the net magnetization loose their phase coherence, making the vector sum equal to zero (figure 17–”overhead view” of the x-y plane).

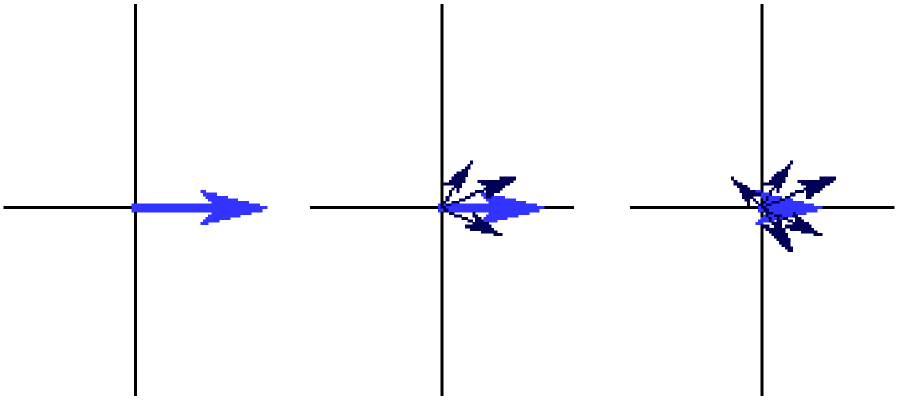


Figure 17

The FID decays at a rate given by the tissue relaxation parameter known as T2* (T2-star).

At the same time, but independently, some of the spins that had moved into the higher energy state give off their energy to their lattice and return to the lower energy state, causing the net magnetization to regrow along the z axis. This regrowth occurs at a rate given by the tissue relaxation parameter known as T1 (figure 18).

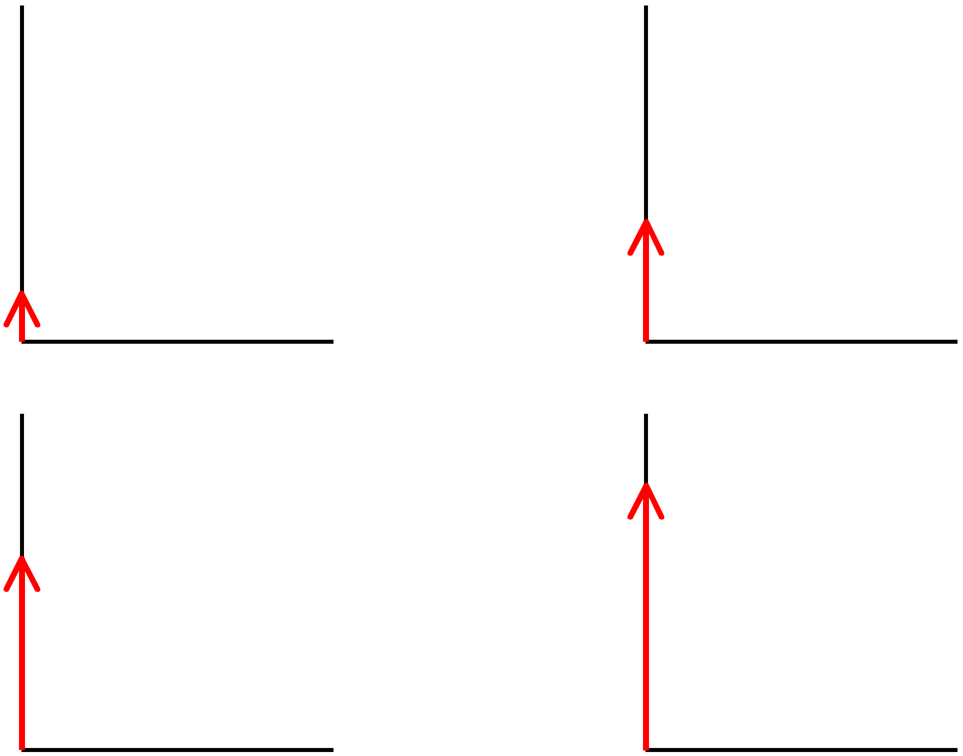


Figure 18