Magnetic Resonance Imaging

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The field of medicine has seen a rapid change over the last century due to medical advances. From diagnostics to pharmaceuticals, doctors and nurses in hospitals today work with technologies that would have seemed impossible at the turn of the 20th century. Many of these technological advances have come directly from the fields of physics and chemistry and their integration with biological processes. One of the most influential technologies in the field of diagnostics was the discovery of magnetic resonance imaging, commonly referred to as MRI. This paper will briefly discuss the discovery of the techniques behind magnetic resonance imaging and the design of the machines used in patient care. The paper will then detail the unique physical properties MRI machines take advantage of to image the human body and recent techniques that are being used to enhance this imaging technique.

The discoveries related to the science behind magnetic resonance imaging have left a trail of Nobel Prizes in Physics and Medicine in its wake. It all started in the late 1920s and 1930s when Isidor Isaac Rabi and his research group found that they could manipulate and detect the transition of the magnetic moments of certain atomic nuclei from high-energy, antiparallel alignments to low-energy, parallel alignments in an external magnetic field bathed with radio waves of a specific frequency. Rabi won the Nobel Prize in physics in 1944 as a result of his experiments. This was a great discovery for the field of physics and chemistry, but only applied to the study of magnetic properties and the structure of molecules, atom and nuclei and did not have any clear medical application (University of Manchester). In 1952, two researchers named Felix Bloch and Edward Purcell shared the Nobel Prize in physics for independently showing that condensed matter, rather than isolated molecules, exhibited the same phenomena described by Rabi's experiments. This established the physics foundation for the medical application of magnetic resonance imaging. Discoveries continued to mount up and, finally, in 1973, Dr. Paul

Lauterbur published a paper detailing his experimental results with imaging (spatial localization) of two test tubes of water using magnetic resonance (University of Manchester). The ability to produce images of objects containing water was the foundation for the medical application of magnetic resonance in the areas of diagnostics and, eventually, led to the MRI machines seen in hospitals and clinics today.

The basic design of the typical MRI machine starts with the part patients see from the outside. Externally, the MRI machines have an overall cylindrical or square prism shape with a cylindrically shaped hollowing in the center. This hollow area inside the machine, called the bore, is where the patient lies while the imaging process takes place. Figure 1 shows the cutaway of a typical MRI machine:

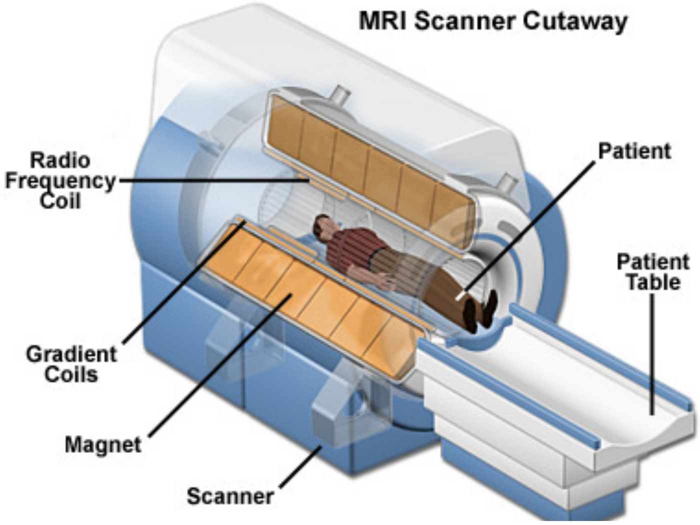

Figure 1: Diagram of MRI Machine (The Mesothelioma Library)

A typical MRI machine can create magnetic fields with strengths varying between 0.3T to 2T and must be homogeneous to avoid signal loss and preserve image resolution (Hornak 2010). Fundamentally, the MRI machine can be thought of as a large solenoid that creates a uniform field parallel to the direction the patient lays. This homogenous magnetic field, B_0, is generated based on the principles of the Biot-Savart Law and its application to current loops. The Biot-

Savart law shows that the strength of the magnetic field is proportional to the current flowing through the wires of the solenoid, requiring the amount of current passing through the wire to be much higher than traditional wire could withstand due to resistivity. Instead, the wire used in MRI machines is composed of superconducting wire, usually niobium-titanium (Nb-Ti) (Seeber 1998). These coils are immersed in liquid helium, which lowers their temperature to around 4.2K, allowing them to become superconductive and provide the necessary, uniform magnetic field strength. The second crucial components of the MRI machine are the gradient field coils that change the magnetic fields along each of the three axes. The Z-axis lies along the center of the hollow area where the patient lies, while the X-axis lies on the plane level with the floor and the Y-axis lies from the bottom to the top of the machine. The coils along the Z-axis are current-carrying coils that carry currents in opposite directions, thus creating an overall gradient magnetic field between the coils. The coils along the X- and Y-axis are known as figure-8 coils and they create a gradient field along the X- and Y-axes due to the direction of current through the loops (Hornak 2010). These gradient fields can be switched off and on rapidly in order to image the tissue of the patient. The next components of the MRI machine are the radio frequency coils that detect the radio frequencies given off by the atoms in the tissue during the imaging process. These coils vary on their location and function according to the particular MRI machine and the particular imaging being done, but are contained within the planes of the gradient coils (Hornak 2010). Accompanying these components is a computer with software to interpret the radio frequencies and their spatial orientation data. These are the basic components of a typical MRI machine and, together, they function to image the patient's tissues.

The physical principles behind the operation of an MRI machine are very complex and require knowledge of atomic structures and the concepts behind electromagnetism. The first concept necessary for understanding the process of magnetic resonance imaging is the concept of net magnetization in an external magnetic field. To understand this, the response of an individual atom with a non-zero magnetic moment to an external magnetic field must be understood. Naturally, the nucleus of certain atoms rotates about a specific axis that lies perpendicular to the direction of rotation. This non-zero nuclear spin only comes from atoms that have an unbalanced ratio of protons and neutrons in their nuclei. This rotation of the nuclei generates a magnetic field by the principle that moving charge creates a magnetic field; this magnetic field creates a net dipole in the atom. One such atom that possesses a non-zero spin and a magnetic moment is the hydrogen atom, which has a spin number of ½. Hydrogen is the atom that magnetic resonance imaging takes advantage of because it occurs naturally in the human body in large quantities, specifically in water and fat tissue (Brown, Semelka 2005). The next concept behind why nuclear magnetic resonance works lies in the fact that the axis of rotation of atomic nuclei, and, thus, the rotation of the magnetic moments, precesses around a random axis. This random axis can be manipulated by placing the atom in a uniform magnetic field. Since magnetic moments tend to align with the magnetic field lines, the axis of precession of many of the nuclei becomes the direction of the external magnetic field, B_0 (Kuperman 2000). This precession around the homogeneous magnetic field is shown in the following figure:

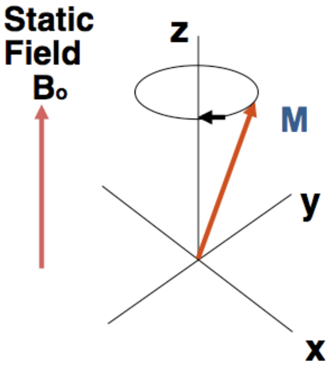

Figure 2: Precession of Moment Around B0 (Tools and Tutorials)

Since the direction of least energy for the moments to rotate is parallel to B_0, the direction of net magnetization, M_0, of a field of magnetic moments from atomic nuclei is in the direction of B_0 (Kuperman 2000). This magnetization of a sample is the basis for how and MRI generates magnetic resonance signals. This net magnetization is shown in the following figure:

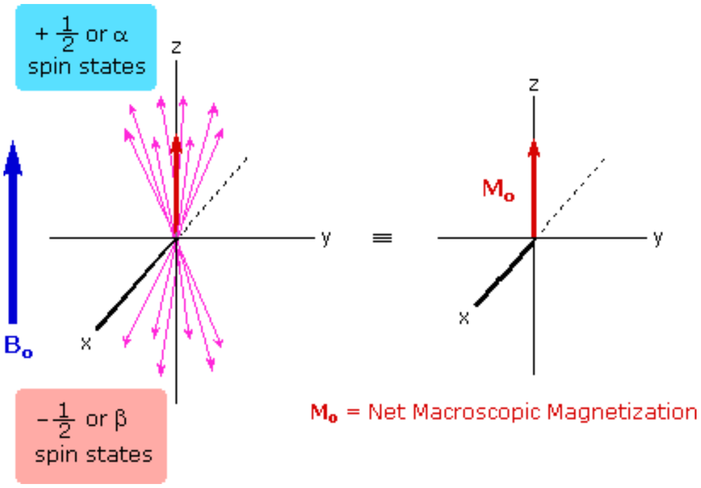

Figure 3: Net Longitudinal Magnetization of a Sample (UC Davis)

As the field strength increases, the magnitude of M_0 increase is proportional to the magnetic susceptibility of the tissue, χ, as shown by the following equation: $M_0 = \chi B_0$ (Brown, Semelka 2005). Conveniently for MRI technology, hydrogen has one of the largest responses to an applied external magnetic field, making it an excellent atom to use for imaging the human body (Brown, Semelka 2005). The manipulation of this net magnetization magnitude sets the foundation for how MR signals are created.

Once a net magnetization can be established in a sample, the net magnetization, M_0, can be manipulated by a specific radio frequency. The physics behind how this works can be explained through the precession frequencies of the atoms and their interactions with these radio frequencies. In an external magnetic field, B_0, the frequency of the precessions is given by the Larmor equation: $\omega_0 = \gamma B_0/2\pi$ which relates the angular frequency of the precessions, ω_0, to the strength of B_0 (Brown, Semelka 2005). The proportionality constant, known also as the gyromagnetic ratio, γ, is equal to 42.56 MHz in a magnetic field of 1T. Using the Larmor equation, and the gyromagnetic constant, the Larmor frequency in a 1.5 T field is 63.8 MHz and 127.6 MHz in a 3T field (Duggan-Jahns). This frequency varies greatly with the strength of the magnetic field. The frequency of the precession of the nuclei, therefore, establishes the particular frequency of radiofrequency waves that are needed to manipulate the magnetic moments away from the axis parallel to B_0. The Larmor frequency, ω_0, is exactly proportional to the change in energy, ΔE, needed to excite the protons in the nuclei to jump to a higher energy level. This higher energy level causes the orientation of the spin to be anti-parallel to the field. These two energies, either parallel to B_0 or anti-parallel to B_0, are the only energy levels possible for nuclei like hydrogen with a spin number of ½ (Kuperman 2000). This higher energy level is only maintained while the radiofrequency is putting enough energy into the deflection of the axis from the axis of equilibrium. If the radiofrequency is a pulse, it allows the magnetic moment to realign with the magnetic field, B_0, and, in turn, they emit energy at a frequency, ω_0 (Kuperman 2000). As discussed in the paragraph regarding net magnetization, the hydrogen atoms in tissues are mostly aligned in a general direction at any point in time within the magnetic field, $B_{0.}$ Thus, there is a relatively significant amount of absorption and emission of energy happening simultaneously within the tissue, creating an overall changing magnetic field when the radiofrequency is pulsed over time. By Faraday's Law, a changing magnetic flux will create a voltage within a coil of wire. This changing flux can be used to induce a voltage in the receiver coil of an MRI machine and the time rate of change can be analyzed. Using a mathematical operation known as Fourier transformations, the signal amplitudes can be analyzed by a computer to specific properties of the emitted energy from the protons in the hydrogen nuclei.

Now that a background for the radiofrequency pulses and the subsequent energy release has been established, the next crucial goal for MRI is getting image contrast. This means that the image that the MRI machine generates has to show the differences between specific tissues in the body and provide an image that can be used for diagnostic purposes such as detecting cancer or tissue abnormalities. This image contrast comes from the fact that different areas of the body contain different amounts of the hydrogen atoms used in magnetic resonance. The hydrogen in the body comes from many different molecules but most of the hydrogen atoms come from water molecules, which comprise up to 70% of body weight. Hydrogen atoms are also found in the molecules of fat tissue and most other tissues. Therefore, rather than looking at individual atoms, magnetic resonance imaging looks at entire samples of tissue and does the appropriate computations with average measurements. Relative to other tissues in the body, water has the most pronounced response to an external magnetic field, and, therefore, has a stronger net magnetization than other tissues. This stronger net magnetization correlates to a stronger radiofrequency emission from these areas of the body with high concentrations of water. Using this difference in emitted radiofrequency strength between different tissues, an image can be generated by a computer showing regions of different tissue (Faulkner). This difference in the emitted radiofrequency signal comes from the relaxation times of the protons in the hydrogen nuclei of the various tissues of the body. Relaxation is defined as "…the process by which protons release the energy that they absorbed from the [radiofrequency] pulse" (Brown, Semelka 2005). There are two relaxation times that are used in magnetic resonance imaging are known as T1 relaxation time and T2 relaxation time. First of all, T1 relaxation time is defined as the time required for a magnetic moment, M_0, to return to its longitudinal orientation with the external field, B_0. When a radiofrequency pulse is applied to a sample, it causes the change in longitudinal orientation to change as described earlier. Once the radiofrequency pulse is discontinued, the orientations of the moments of each individual atom begin to lose phase coherence and return to their equilibrium position. As they return to longitudinal equilibrium, the net magnetization of the sample grows along the longitudinal axis. This rate of return of the net magnetization shows an exponential growth pattern, given by the following equation: $M(\tau) = M_0\left(1 - e^{\left(-\frac{\tau}{T1}\right)}\right)$ where τ is the time following the radiofrequency pulse and T1 is a time constant. This relationship is shown in Figure 4 with the independent variable as T1 and the dependent variable as the net longitudinal magnetization.

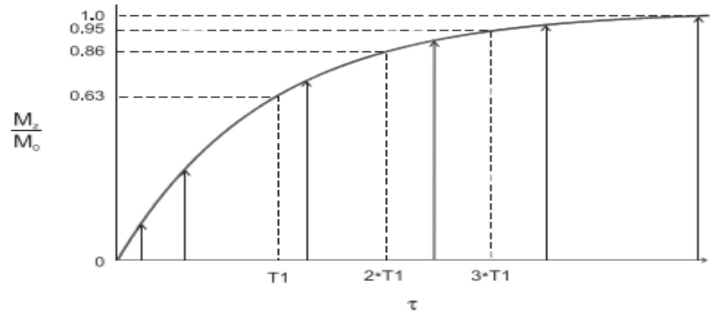

Figure 4: Graph of Net Longitudinal Magnetization vs. T1 (Brown, Semelka 2005)

This rate of net magnetization growth along the longitudinal axis is known as the T1 relaxation time (Faulkner). However, the total T1 relaxation time is too slow relative to the time between pulses so another parameter must be used for practical reasons. The second relaxation parameter, T2, is defined as the total transverse relaxation time of the sample (Brown, Semelka 2005). This time constant describes the magnetization along the XY plane and how it returns to its equilibrium value as the moments relax their precession axes back in the direction of B_0. For explanation purposes, it can be assumed that enough energy, in the form of a radiofrequency pulse, is imparted on the atoms to flip their moments perpendicular to the longitudinal axis in the XY plane. Once the pulse is discontinued, the moments start to rotate back towards the longitudinal axis and the net magnetization along the XY plane, transverse net magnetization, begins to decrease. The time constant, T2, is also known as the “spin-spin relaxation time” and is always less than, or equal to, T1. T2 relaxation time occurs at a rate proportional to *e*. This means that T2 is the time to reduce the transverse net magnetization by a factor of *e* (Hornak 2010). This relationship is shown in Figure 5 with the independent variable as T2 and the dependent variable as the net magnetization along the XY plane.

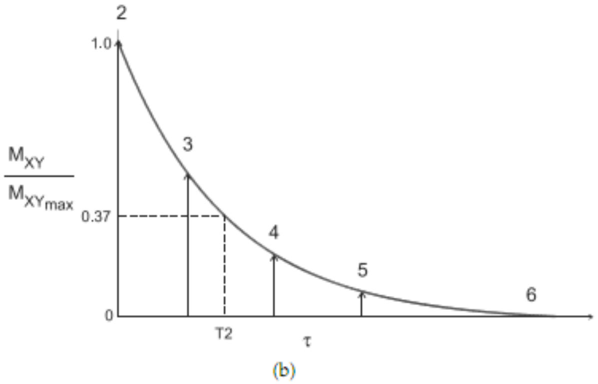

Figure 5: Graph of Net Transverse Magnetization vs. T2 (Brown, Semelka 2005)

These two relaxation times, T1 and T2, can be explained as separate processes but in reality, they occur simultaneously. These two relaxation times create a quantitative way to predict the properties of the tissue the MRI machine is imaging.

The final physical principle that must be understood to obtain a basic understanding of how an MRI machine works is how the application of gradient magnetic fields creates the information needed for spatial localization. With the physics explained thus far, an MRI machine would not be able to effectively function as an imaging device because it would not show any meaningful data regarding the location of various tissues. This problem is solved through the use of several smaller gradient field magnets that alter the homogeneous field, B_0, generated by the large solenoid of the MRI machine. Instead of switching the magnetic moments of every hydrogen atom equally in the patient’s body, these gradient fields can be established in various directions based on the direction in which the image slice needs to be oriented. This gradient magnetic field, called B_1, changes the magnetic field with respect to position. The most effective gradient field used in MRI is a one-dimensional gradient field (Brown, Semelka 2005). By changing the magnetic field in one dimension only, it allows for a slice selection of the tissue being imaged by only exciting the magnetic moments of the hydrogen nuclei within the slice, while the nuclei outside the slice remain in precession around B_0 (Kuperman 2000). If this one-dimensional slice is done along two or three axes, images in two- and three-dimensions can be created. The gradient fields can be quantified mathematically by Fourier transforms in each direction, as previously mentioned, the location of the pulses received by the pickup coils can be displayed as a meaningful image in two-, or even three-, dimensions.

The applications of MRI machines have revolutionized the medical world since its widespread use in diagnostic imaging. Since it was first used in imaging the body, everything from the magnets to the RF coils has been constantly updated, improving imaging time from a staggering 5 hours for the first patient MRI in 1977 to around 30 minutes for a modern MRI scan (Rainbow). The main application of MRI is to image the body for soft tissue diagnostics since it does not image bone well. One unique imaging tool that MRI images provide is contrast between different types of tissue. By comparing known properties of hydrogen content of various tissues, tissues can be easily identified on an image. This is particularly useful in finding abnormalities in tissue such as bleeding, defects, and cancer. For example, when imaging the brain, the difference between gray and gray matter and cerebral spinal fluid can be seen through the contrast between the shades of black and white on the image; unhealthy or cancerous white matter also shows up contrasting to healthy white matter (Rainbow). In recent years, new techniques for contrasting tissue have been developed. One of the most interesting techniques has been the discovery of fMRI, known as functional MRI. This MRI technology analyzes the oxygen content of tissue in the brain and shows the differences in oxygen at different time intervals. This allows doctors to see how the brain is functioning given various stimuli, allowing for diagnoses for diseases of the brains such as Alzheimer's disease (Columbia University). MRI technology has given doctors unparalleled access to the tissue within patients' bodies and allowed for increasingly accurate diagnostics over the years.

In conclusion, MRI technology has opened the door for doctors to view the tissue inside patients without performing risky exploratory surgery. The basis of this technology found its roots in chemistry and physics, and through utilizing physical principles on the atomic level and their electromagnetic interactions, produces remarkably clear images of the patients' soft tissue. This technology allows doctors to diagnose diseases and abnormalities faster through utilizing physics and has saved thousands of lives each year through accurate diagnostics.

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