Magnetic Resonance Imaging

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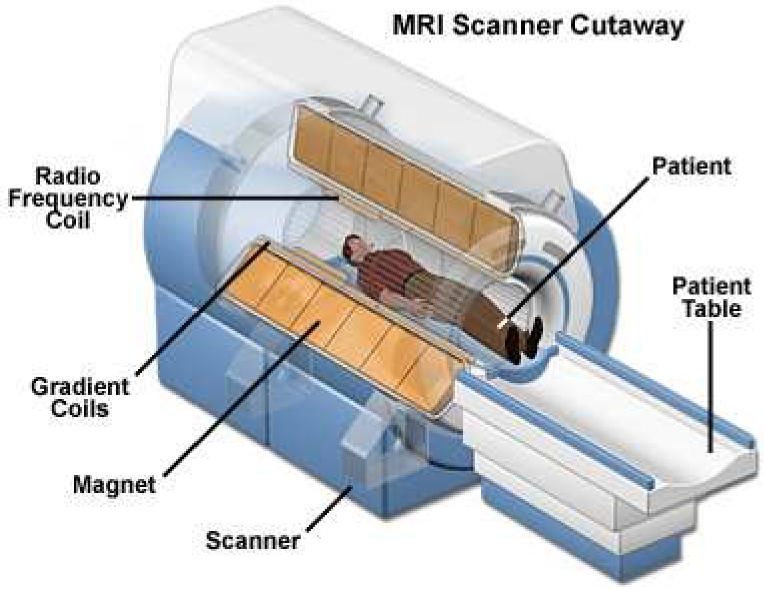
Technology and innovation have shaped the world of modern medicine in ways that seemed like dreams fifty years ago. Each day, scientists and engineers discover and develop new ways to improve the quality of life for the human population, and every time someone goes to the hospital for something as normal as a routine check up or something as drastic as an emergency room visit, these technologies and inventions are utilized. One discovery that has revolutionized diagnostics and saved countless lives is Magnetic Resonance Imaging, or MRI. The machine designed for magnetic resonance imaging uses fundamental physics and chemistry principles to accomplish the task of detecting diseased tissue such as tumors, internal bleeding, injury to soft tissue, and infection without the need for surgery (1). This paper will first cover the function and applications of magnetic resonance imaging along with the vital components in a magnetic resonance imaging scanner, and then the physics of magnetic resonance imaging will be explained.

The entire procedure of an MRI scan is non-invasive and the machine uses strong magnets and radio waves instead of the radiation that x-rays and computed tomographic scans use (4). Magnetic resonance imaging helps save lives and prevent further injury or bodily harm by detecting subtle but potentially detrimental problems in the human body that computed tomographic (CT) scans, ultrasounds, and x-rays cannot accomplish. For example, a simple scan of the patient's head can indicate the presence of a tumor or an aneurysm, nerve damage, or problems in the eyes or ears. Scans of the heart and surrounding blood vessels can detect potential heart attacks or cancer, and images taken of the lungs can show if a person experiencing chest discomfort has internal damage or cancerous tissue. If a patient is experiencing abnormalities in the abdomen or pelvis, a scan could be made to observe the organs in that area, including reproductive organs. Bone and joint issues in a person are more easily diagnosed with a magnetic resonance image than with an x-ray because the picture resulting from an MRI scan shows the bone and surrounding soft tissues in a high resolution, so even tiny tears or fractures are obvious (1).

The discovery of the principles of magnetic resonance imaging took place in 1946 separately by Felix Bloch and Edward Purcell, and both men received a Nobel Peace Prize in 1952 for their outstanding scientific contribution (2). After Bloch and Purcell had announced their findings, there were several experiments conducted in which pulsed nuclear magnetic resonance created spin echoes, but the precursor to modern magnetic resonance imaging took place in 1973 when Paul Lauterbur "produced images (of two glass tubes filled with water) reconstructed from a series of 1-D projections obtained using a magnetic field gradient" (3). In 1977 a laboratory in the United Kingdom produced the first image of a human thorax, then in 1978 they developed an image of a head. These discoveries proved impressive, but it was not until two years later when the first "clinically useful" image of a person succeeded, and this achievement sparked interest for companies to begin truly investing in the creation of magnetic resonance imaging technology for doctors and hospitals (3).

The most common machines on the market today have a large cylindrical frame with an opening in the middle, as shown in the figure below. The patient lies down on a movable table (labeled as “Patient Table” in the diagram below) that can be maneuvered by a computer to within a 1 mm accuracy range (2). Magnetic resonance imaging needs three different magnets to accomplish the task of outputting a high resolution image. The machines typically use a superconducting magnet (an electromagnet composed of superconducting wire) which is kept at a temperature near absolute zero by liquid helium. The low temperature of the liquid helium causes the wire to have almost zero resistance, so that the current travelling through the wire will continue to flow as long as the temperature of the wire is the same as the liquid helium.

Figure 1. Diagram of an MRI Scanner



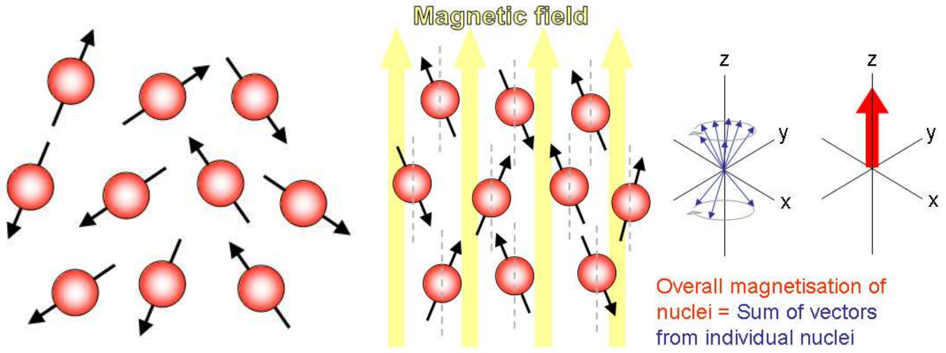
http://www.magnet.fsu.edu/education/tutorials/magnetacademy/mri/images/mri-scanner.jpg

The liquid helium also keeps the wires from becoming too hot, as the large amount of current passing in the superconducting magnet would normally generate a large amount of heat and therefore be a fire hazard. The superconducting magnet generates the B_0 magnetic field because the electric current flowing through the wire has moving charges which by laws of physics, creates a magnetic field. This magnetic field is the main field that is extremely strong (between 0.3 Tesla and 2 Tesla) and uniform (6). It is important for B_0 to be homogenous to avoid distortion of the image and to prevent signal loss from occurring. The main field generates the initial longitudinal magnetization in the patient and also keeps the Larmor precession of the hydrogen atom spins at a constant angular frequency (6). Within this magnet are the gradient coils that alter the magnitude of B_0 in the X, Y, and Z directions. The linear field gradients are turned on and off in intervals less than 1 msec and they are important in spatial localization of the magnetic resonance imaging. To obtain ideal results and optimal spatial localization, the z-gradient is made of two coils wound on a cylinder coaxial with the main magnetic field that each carry equal and opposite currents. The x and y gradients are composed of two alike coils that are each uniquely perpendicular to the z axis, and gradient coils will perform better when their size is reduced (6). Inside the gradient coils is the radio frequency coil which generates the B_1 magnetic field to excite the proton spins (this topic will be dealt with in further depth in a few paragraphs) and it then receives signals in return from the excited hydrogen atoms in order to send data to the computer. The computer compiles the "slices" of images taken from the X, Y, and Z planes and then forms a detailed picture of the subject that can be viewed digitally or printed out for further review (2). The scanner component of the magnetic resonance imaging machine takes the radio frequency signals that have been converted into electrical current and then digitizes them.

The first important concept of magnetic resonance imaging is the fact that the human body is composed primarily of water, and water molecules contain hydrogen and oxygen atoms. Along with being present in water, hydrogen atoms are found in lipids that make up fat in a person's body. The protons in the hydrogen's nuclei are the main focus of the physical principles in magnetic resonance imaging because atomic nuclei possess paramagnetic properties due to the neutrons and protons, and these particles have intrinsic spins and associated magnetic moments (5). Every nucleus contains a proton that precesses (or "wobbles") about an axis which generates a magnetic field due to the principle that moving particles create magnetic fields (7). Without the presence of an external uniform magnetic field, the hydrogen protons spin about random axis. The magnetic moment of the nucleus is given as $\mu = \gamma\hbar I$ where $\hbar I$ is the angular momentum of the nucleus and γ is the gyromagnetic ratio constant (7). The gyromagnetic ratio constant for hydrogen is 42.58 MHz/T (2). The allowed energy when the nuclei have a spin of ½ is dependent upon the direction of the hydrogen atom's magnetic moment in relation to the external field (B_0), and it is demonstrated by $E = -\gamma\hbar B_0 / 2$ if μ is parallel to B_0 and $E = \gamma\hbar B_0 / 2$ if μ is anti-parallel to B_0 (7). Each precessing proton rotates at a certain rate called the Larmor frequency, and water tends to naturally rotate faster than other biological molecules due to its small size (9). The Larmor frequency is directly proportional to the main magnetic field strength as given by the following equation: $\omega_0 = \gamma B_0$ where ω_0 is the precessional frequency of the proton, γ is the gyromagnetic ratio, and B_0 is the main magnetic field. These proton spins and moments are important principles in magnetic resonance imaging.

After locating and understanding the function of each component of a magnetic resonance imaging apparatus, one can clearly see that the process is based largely off of magnetism and radio waves. As stated earlier, the large superconducting magnet creates a magnetic field much greater than that of the Earth's, and this uniform magnetic field is called B_0. Combining this external magnetic field B_0 with the principle of nuclear spin in relation to the hydrogen atoms in a person's body discussed in the previous paragraph, a portion of the physics of magnetic resonance imaging can be described. In the same way that a bar magnet aligns to a position of equilibrium and minimal energy in a uniform magnetic field due to a couple acting on it, the nuclear magnetic moment of a hydrogen atom found in the human body will align with the magnetic field B_0 generated by the superconducting magnet in the magnetic resonance imaging machine (5). This reaction is shown in the figure below:

Figure 2. Demonstration of Hydrogen Positioning



a) Random hydrogen alignment b) Hydrogen position after B_0 introduced

http://www.cardiff.ac.uk/biosi/researchsites/emric/basics.html

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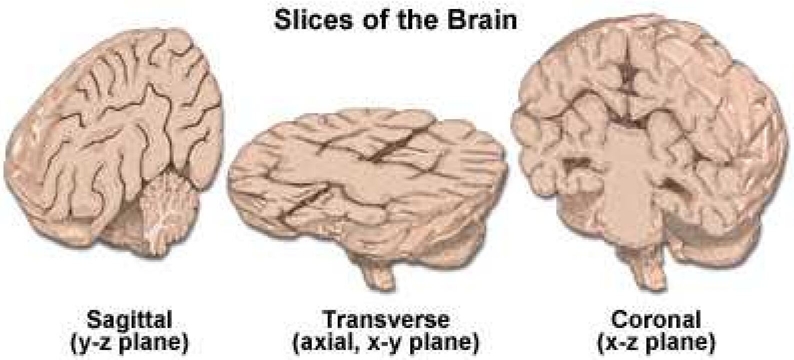
The sum of the individual vector moments in the group of hydrogen atoms shown in the figure above points in the upward (z in this coordinate system) direction and makes up the overall magnetization (8). Although most protons align in the low energy configuration, about 9 out of 2 million in an MRI powered by a 1.5 tesla magnet are positioned in the opposite manner (7). The protons that are aligned in the higher energy configuration are then excited by radio frequencies, as will be discussed in the next paragraph. The interaction between nuclei with a nonzero magnetic moment (the hydrogen atoms) and an external magnetic field (B_0) is a basic principle contributing to the overall function of the magnetic resonance imaging process (6).

The next major principle of physics following magnetic fields that is important to magnetic resonance imaging is the concept of radio frequency. The magnetic laws that govern the precessing of the hydrogen protons are extremely crucial for magnetic resonance imaging to operate correctly, but this combined with the radiofrequency component of the process is what makes this technology so powerful. After creating the initial main magnetic field, the radiofrequency coils excite the magnetization in the patient’s bodily hydrogen atoms that are aligned in the north-north south-south configuration (higher energy) (7). The protons absorb energy from the radio frequency pulse, but when the pulse vanishes the excited atoms release the energy they had absorbed and transmit a signal that is received by the radiofrequency coils (6, 7). The excitation occurs when the coils transmit the B_1 magnetic field and then the same (or sometimes different) radiofrequency coil collects the signals from the spinning atoms (2). In order for the signs emitted from the excited protons to be useful in medical diagnostics, the signals must be converted into an electric current that is digitized by the scanner (7).

The output of the magnetic resonance imaging machine shows the water content in a given area. If there is not as much water in a certain area, there will be less hydrogen protons sending signals back to the radio frequency coils (7). Every apparatus will display the hydrogen proton data differently, but usually there will be multiple shades of gray present to indicate densities in the tested area. An image generally contains 250 different shades of gray, so a radiologist can detect even minor deviations from normal tissue, blood vessels, and bone (7).

Figure 3. Example of Images

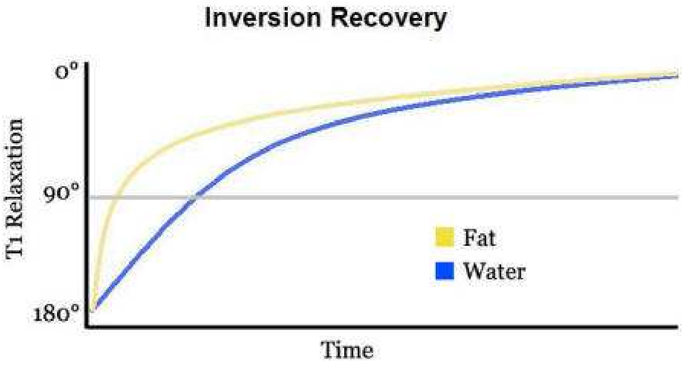


http://www.magnet.fsu.edu/education/tutorials/magnetacademy/mri/fullarticle.html

The images above show the different planes and perspectives produced in each plane. The computer pieces together the images to form a 3 dimensional image and individual cross sections can also be analyzed.

Another key to magnetic resonance imaging in relation to radio frequency transmission and reception are the T_1 and T_2 relaxation periods. After the radio frequency pulse from the radio frequency coils occurs, T_1 is the length of time it takes for the protons to regain longitudinal magnetization (9). The relationship between the original magnetic field (M_o) orientation and the realigned field (M_z) is given in the following equation: $M_z = M_o * (1 - e^{-t/T_1})$, and it changes with time (2). Below is a graph demonstrating Inversion recovery during the T_1 relaxation period:

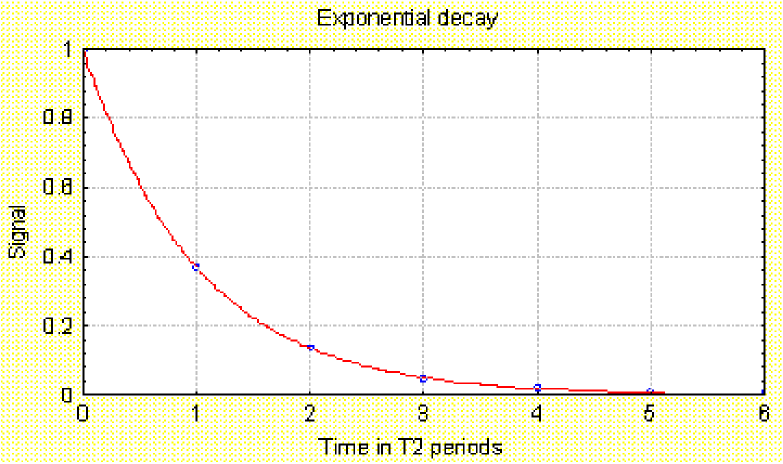
Figure 4. Recovery During T_1 Relaxation



http://mriworld.org/PulseSequences/Diagrams/Diagram%20Inversion%20Recovery.jpg

Water molecules generally move too quickly for effective T_1 relaxation and larger particles such as proteins move too slowly, however liquid cholesterol has a natural frequency close to that used in magnetic resonance imaging, so the presence of cholesterol will appear brighter than everything else on an image taken during T_1 relaxation (9). Another useful application of T_1 relaxation is in detecting hemorrhages in brain tissue. A subacute hemorrhage has a smaller T_1 relaxation time than the healthy tissue, therefore the hemorrhage will show up brighter on the image and doctors are able to take appropriate action to treat the patient. T_1 is also known as spin-lattice relaxation and it is based on an exchange of spin energy with thermal motions of the molecules in the patient (5). In contrast to T_1 relaxation, T_2 relaxation involves transverse magnetization and focuses on how long the protons remain in phase after a 90 degree radio frequency pulse. The fundamentals behind this relaxation phase (which is also fittingly known as spin-spin relaxation) root from static magnetic fields caused by protons on other molecules in the body, and they are due largely to dipole-dipole interactions (9). Below is a graph that shows the amount of protons in phase of a T_2 relaxation period, demonstrated by an exponential decay function because T_2 relaxation involves destroying the net magnetization in the x-y plane of the rotating frame (5):

Figure 5. Exponential Decay in T_2 Relaxation



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The equation for T_2 relaxation is given by $M_{XY} = M_{XYo}\, e^{-t/T_2}$ where M_{XY} is the transverse magnetic field that is reduced until it is equal to M_{XYo} or M_o, the main magnetic field (2). T_2 relaxation produces bright results on the image when the proton density in the tested area is high, and T_1 creates similar results when the molecules have similar natural frequencies to that of the main magnetic field. To determine which one to use, the tissues under observation and their relaxation times must be taken into account (9).

Magnetic Resonance Imaging provides a straightforward tool to diagnose diseases and other problems in the body, and it uses fundamental laws of physics to produce high-resolution images in order for this to occur. This invention eliminates the need for surgery in identifying possible ailments a person exhibits, and it is extremely accurate and safe. As is generally the case with technology, improvements can always be made, and scientists along with engineers create new developments every year to better magnetic resonance imaging. Magnetic resonance imaging has saved countless lives and allowed for doctors to observe and explore parts of the human body in a living subject that have previously been unavailable.

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Pictures:

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