Magnetic Resonance Imaging

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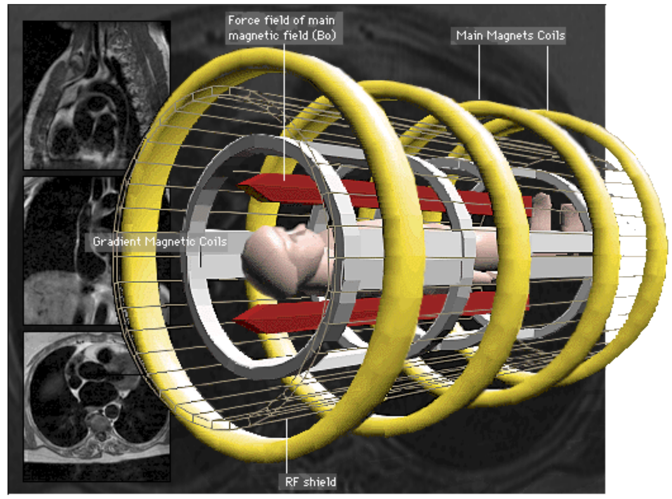
Magnetic Resonance Imaging has become a commonplace tool in the realm of medicine, allowing for a view of the human body not possible before its inception. Most all people have heard of this technique or know it at least by its abbreviation, MRI. Its mention in venues as different as medical dramas and football games shows its widespread use, but few know the true mechanism behind it. Magnetic Resonance Imaging sets its conceptual foundation in many areas of physics, combining to give us a look into the human body we would not otherwise have. This paper will explain why MRI is important, the various relevant areas of physics, how it operates, and methods for image improvement.

MRI may be the most prevalent test in medicine next to the likes of the x-ray. Its uses vary and it can be used to diagnose or identify many medically relevant things in various parts of the body. MRI uses a technique so compatible with the body that it can detect such minute inconsistencies as abnormal bleeding, minor tears in muscles or tendons, tumors, blood vessel irregularities, and even slight inflammation due to infection. An MRI also stands as a more conclusive and clear test than the CT or x-ray and is often done when the aforementioned tests provide inconclusive evidence or a clearer picture is needed[1]. Also, MRI is a safer alternative in that it doesn't require the use of ionizing radiation[2].

The most common uses for MRI are imaging of the head, bones and joints, primarily of the legs or arms, and of the chest. In the head, an MRI can show characteristic signs of a tumor as in stress points in the brain from the tumor growing in an unnatural place, or it may show the tumor itself. Also, a very important use of a cranial MRI is the detection of abnormal bleeding such as an aneurysm to prevent the sudden death often associated with bleeding in the brain.

MRIs can also show problems with the various portions of the brain that explain mental or physiological disorders and functional problems. These problems include damage to the brain caused by a stroke, the optic and auditory nerves, and even damage to the amygdala or the blood vessels of the brain showing signs of concussion. The base use for MRI in joints is obvious, to the point that most sports teams now have MRI machines as a part of their facility to quickly diagnose sports injuries. An MRI can show signs of torn cartilage, ligaments, and tendons and well as broken bones if an x-ray is not available or is not clear. Along the same lines, MRIs can show signs of arthritis, bone marrow problems, and even bone tumors. For chest MRIs, defects in the heart like plaques and abnormalities; in the lungs like cancer alveolar damage; or in the breast like cancerous tumors can be found. The frequent goal of chest MRIs is to find indications of strain, tearing, or blockage of the coronary blood vessels and is one of the most common times that a contrast dye is used so the image can model the movement and speed of flow of blood through these vessels. In addition to the uses mentioned, MRIs are also often used in the abdomen and pelvic regions for the imaging of organs of the GI and Urinary tracts as well as in the spine to check for slipped discs, nerve damage, and tumors[1].

The basics of how the MRI machine is constructed follows many of the fundamental principles of magnetism and how magnetic fields are generated and maintained. At the heart of MRI is an extremely strong donut shaped magnet, seen in the first diagram as ‘main magnetic coils’[3]. The next figure shows a more detailed look at the coils and their function as a conductor[4]. A magnetic field is generated by sending a strong electric current through the coiled wire, as a magnetic field is generated wherever there is moving charge. The magnetic force extends outward from the dipole shaped field of the magnet and is strongest at the magnets poles. When the electric current through the coiled wire is increased, the magnetic force and magnetic field also increase, as indicated by the Biot-Savart Law and the Lorentz Force equations. Since the magnetic field must be so strong in an MRI system, it requires an enormous amount of electric current. This much current through conventional wire could generate a lot of heat due to its resistance, but the MR magnet uses a special type of wire. To keep the electrical conductor, the special coiled wire in this case, in the MR superconducting magnet from overheating and to remove electrical resistance, it is super cooled using liquid helium. Liquid helium is applied to the magnets conductor in an outer shell to keep it at superconducting temperature. In some magnets, liquid nitrogen is used outside of that shell to regulate the amount of helium that boils off due to the immense heat generated in the conductor. Once current is flowing through the super cooled conductor, there's little to no electrical resistance so no additional power is needed to keep the current flowing. Therefore, the system is virtually always running and the magnetic field is always present even when the system is not being used. The magnet in the MRI is many thousands of times greater than the strength of the earth's magnetic field which is needed for the MRI to align the protons of hydrogen atoms in water and fats in the body so imaging can take place by a mechanism that will be explained later in the paper[5].



Artwork courtesy of Rebecca Cagle, National Library of Medicine-Lister Hill Center for Biocommunication

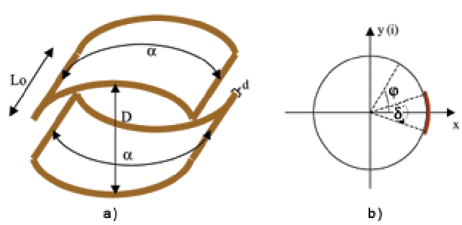
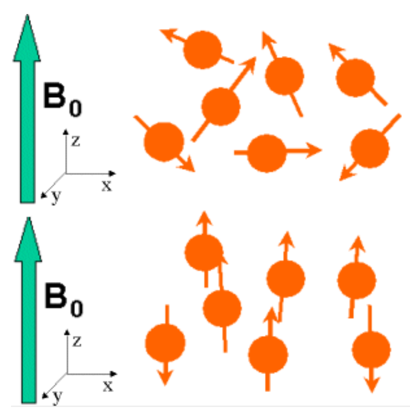


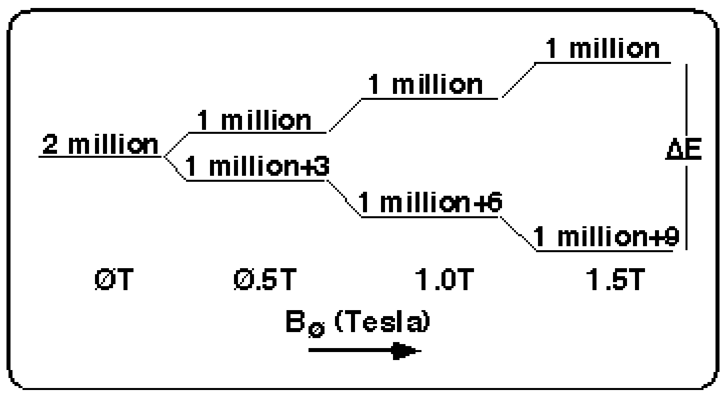
FIG. 1: a) General sketch of a four finite width rungs saddle coil configuration. The letters indicate the geometric parameters: diameter, length, angular aperture and width of the conductors; b) Representation of a unique conductor on the surface coil in the complex plane (z=0); the polar angle (φ) and the δ parameter are indicated in the figure.

A very important fact in obtaining an MRI signal is the relationship of the magnetic vectors to each other. To get a signal and therefore an image, we must measure the MRI signal perpendicular to the external applied magnetic field, $B_{0.}$ The first reason for this is if the two vectors representing protons' net magnetization and the external applied field are aligned, no signal will arise. Second, the net magnetization vector is much too small to be quantified when in the same direction as the large applied field. Lastly, since the net magnetization vector precesses, this gives a measureable signal[6,8].

In a more detailed fashion, MRIs' functionality depends directly on the cooperation of two phenomena in physics: magnetism and the generation and reception of radio waves. The first of these to be discussed is magnetism because it is the main feature of MRI and the first step in the process. As stated above, the laws of electromagnetism tell us that if a current is moving through a wire, it produces a magnetic field around that wire. Now, if a hoop or coil of wire is carrying a current, as in the MRI, a magnetic field will again be formed and will be in the direction perpendicular to the surface area of the hoop or coil. The way in which the MRI machine interacts with the body begins with the proton of the hydrogen atom. Hydrogen is targeted because of its obvious abundance in the body in H_2O and fats as $–CH_2–$ portions. While the proton of hydrogen does not have a very big electric charge, it is able to produce a magnetic field because of its ability to spin very fast[9]. Each of these hydrogen nuclei have a certain spin as represented by the spin quantum number which in quantum terms is best thought of as intrinsic angular momentum[8]. This spin produces a small magnetic field referred to as the magnetic moment. This magnetic moment will



have no fixed orientation in space when not subjected to an external magnetic field, B_0 as in the top picture in the above figure but will align with an external field, B_0 once subjected to it just like a compass aligns with the earth's magnetic field when subjected to it (bottom picture). The possible complication arises when looking at the possible spin quantum numbers for Hydrogen which are represented as a plus or minus ½ which corresponds to one spin sign aligning with the external field and the other spin quantity anti-aligning with the external field. Aligning the moment with the field represents a lower energy level than anti-aligning with the field and therefore this is why there is a very small majority of the Hydrogens that align with the external field of the MRI[2]. As shown by the following diagram, the amount of protons that align with the field is slightly greater than those that anti-align, making for a net alignment. Where there is no magnetic field, all 2 million of the protons and their



moments are in a random orientation, at .5T only 3 more protons are aligned with the field than not, and going all the way to 1.5T, 9 more protons are aligned with the field than not. All together, at 1.5T there are three times as many excess protons as there are at 0.5T and in all cases the number of protons aligned in excess is always proportional to the applied field, B_0. This may seem like a very insignificant number of protons to make a difference but when looking at how many excess protons are aligned with the external field in a voxel (volume pixel), we find that in a quantity equal to just 0.2mL where Avogadro's number is 6.02×10^{23} molecules per mole and one mole of water weighs 18 grams, we find that there are 6.02×10^{15} excess protons aligning with the field in only one voxel. With this large of a number of moments aligned with the field working together, they form a significant magnetic field which will be refered to as M_0. This seems simple enough to say but that's because the applied field is large enough that we can simply follow the classical mechanics of the system as compared to the quantum mechanics that truly define it. The basic way to state the quantum side is to say that both alignments of the protons (with and against the field) are possible and are constantly alternating for any given proton. But, since being aligned with the field is the lower energy state, at any single point frozen in time, you will see that more protons are in this lower energy state and aligned with the field. As expressed above, the larger the B_0 field, the greater number of excess protons in the direction of the field[9].

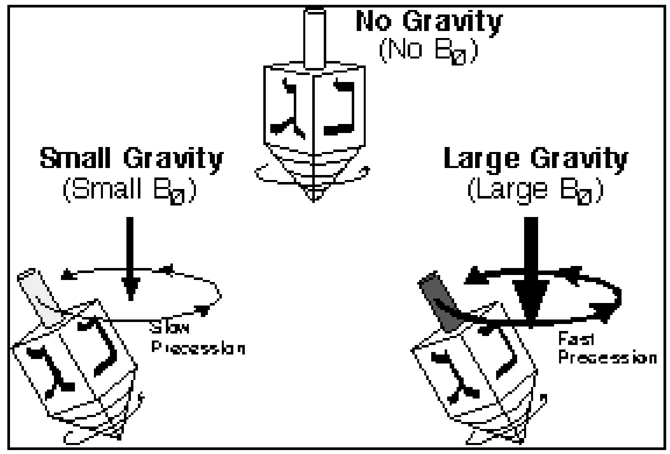
With this significant magnetic field of the protons, M_0, the energy of the system in an MRI is found using Planck's constant where Planck's Constant, *h*, multiplied by the frequency, *v*, of the waves entering the MRI is equal to the Energy of the system. The figure to the right shows this equation and shows one reason that MRIs are the safest of the many medical tests used to look into the body. Aside from the absence of radiation in MRIs, they also have one trillion times less energy in the system than a normal x-ray, not to mention that a CT has about 300-1000 times the energy of an x-ray. These large differences in energy are due to the large differences in frequency of the radio waves used in MRIs (which will be discussed later) and the frequencies used in other tests like x-rays. Moreover, it's obvious that since an MRI takes a much more detailed image than say an x-ray, that quality of result is not related to the energy used to make the image. The MRI does not take detailed images because of a high energy amount used, it does

$$\Delta E = h\mathbf{v}$$

- X-rays: $\mathbf{v} \approx 10^{19}$
- Ultra-violet: $\mathbf{v} \approx 10^{16}$
- Visible Light: $\mathbf{v} \approx 5 \times 10^{14}$
- Radio Waves: $\mathbf{v} \approx 10^{7}$ (MRI)

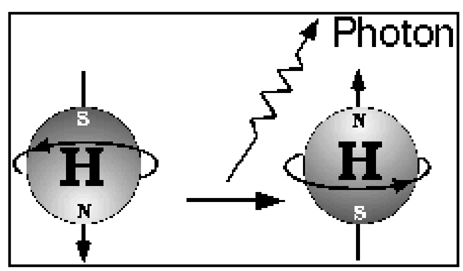
so because of the immense amount of protons found in the body therefore accounting for the large amount of protons that can be aligned with the field to make images from[9].

A physics based explanation of the frequency of a proton is given by the Larmor equation which is given as $\omega_0 = \gamma B_0$ where ω_0 is the precessional frequency and γ is the gyromagnetic ratio which is 42.56 MHz/T for protons. Much like a dreidle spins according to the amount of gravity present, a proton spins according to the applied magnetic field it is subjected to. In a situation with no gravity (in the dreidle's case) or no magnetic field in the case of the proton, the spin is uniform and it spins about one point in a perfect circle. Upon introducing a small magnetic field, the proton begins to deviate from its perfectly circular path; when this "wobbling" occurs it is more technically said to have precessed. This precession is directly proportional to the strength of the magnetic field present as shown in the Larmor equation[2,9].

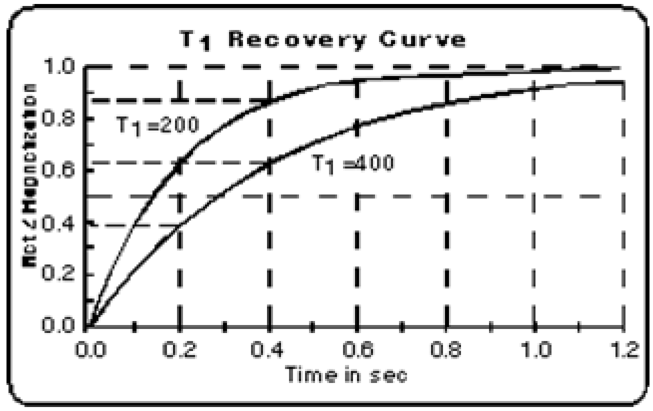


The use of magnetism in MRIs is vitally important for precessing the protons in the body for imaging but the use of radio frequencies in combination is what allows for a quantifiable result to be made into an MRI image. At this point in the progression, the proton has already aligned with the applied field, B_0 and possesses a certain precession frequency proportional to that B_0 as governed by the Larmor equation. Now, an electromagnetic radio frequency pulse or RF is applied to the aligned protons at their precession frequency in a way allowing them to absorb the energy. This absorbed energy causes the proton to move to a higher energy state. To illustrate the effect of this RF on the proton, the spin of the proton is modeled in the x-y plane where the precession frequency is either traveling clockwise or counterclockwise where the z-axis is the axis of rotation. Once the RF is applied, the M_0, defined earlier as the direction of the excess spin in accordance to the B_0 (aligning in this case), appears to spin in a vortex like fashion about the z-axis as it spirals down towards the x-y plane (or negative z-axis). The image made by the MRI machine originates with the data collected in the next few steps. Once the applied RF has been on long enough to cause the movement of the M_0, the RF signal is turned off and three things occur at the same time. First, the previously absorbed RF energy is retransmitted at the resonance frequency. This directly causes the second event: the excited spins that directed toward the negative z-axis, now begin to return to their original M_0 orientation, or in other words, the protons begin realigning with the applied magnetic field, B_0. Lastly, where the protons were initially in phase upon introduction of the RF pulse, they are now beginning to dephase[9,10].

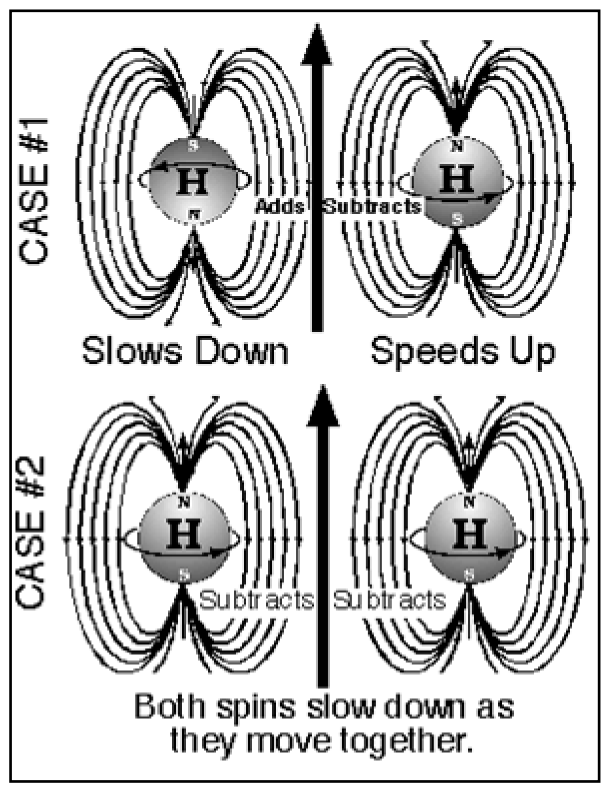
In the first of these three happenings, the absorbed RF energy is retransmitted out of the proton as the proton returns to its original M_0 state (which occurs in the second step) as shown in the photon leaving as energy in the figure to the right.



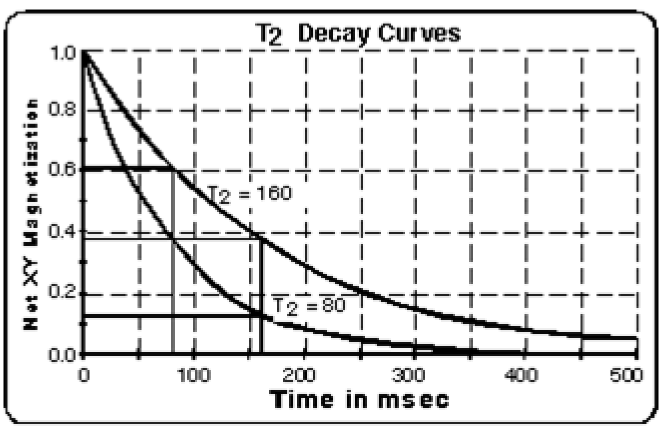
While this is happening, the vector will remain spinning at its precession frequency ω_0 as defined by the Larmor equation. As shown in the earlier chart, the energy of RF waves are very small; the electromagnetic radiation that is produced by the proton retransmitting the energy is at a similar magnitude of frequency as RF waves and therefore the act of retransmitting the RF energy comes in the form of the proton emitting RF waves, not surprisingly. These energy waves that are given off are due to the proton returning to a lower energy state (alignment with field) from the RF induced higher energy state (anti-alignment with field). Not all of this energy will be detectable as a RF wave and the relationship T_1 (or relaxation constant) between the M_0 (original alignment) to the M_z (realignment) is shown by the following equation $M_z = M_0 * (1 - e^{-t/T1})$. The graph to the right shows this equation for a proton where at a time, T_1 after the initial RF pulse is turned off, 63.2% of the protons have become realigned with the applied magnetic field, B_0[7,9].



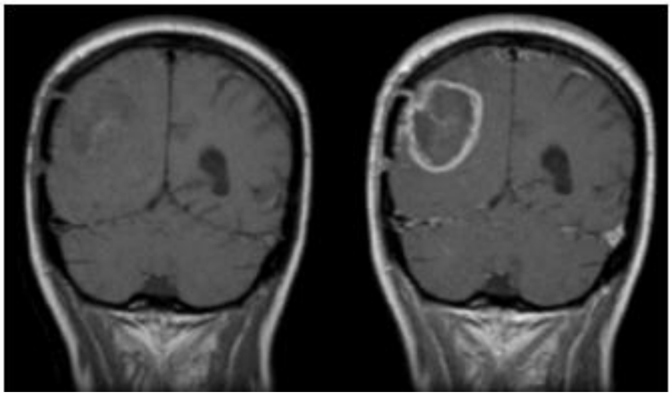
As said above, the first step is a description of what occurs energetically while step two, the returning of the protons to M_0 is occurring. But step three of this sequence is what allows the reception of data from the protons in order to produce an image. In this step, the protons go from a state where they are in phase (oriented toward the negative z-axis due to the applied RF) to a state where they are out of phase (with the input RF no longer present). At time zero, when the RF is still being applied, the protons are emitting no energy, but once they begin to realign, they give off the retransmitted energy (step 1) but at variable rates. This variable rate of returning to the original M_0 in alignment with the B_0 is picked up by the computing system and can be used to figure out various things about the medium in

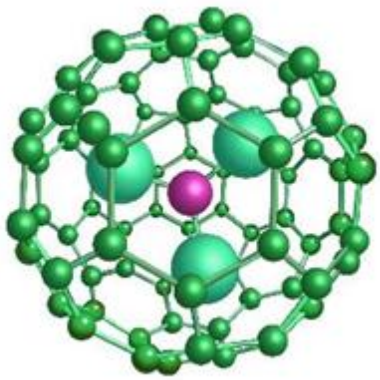


which the protons exist. A principle that is easy to overlook is that the magnetic field is not the only magnetic force on each proton but each proton also exerts a small magnetic force on other protons in close proximity. The interactions between the magnetic fields of protons allow for the deduction of how close or far apart the protons (or atoms) are in a medium therefore providing information of rigidity and conformation. This is done because the magnetic field's affect on neighboring protons is related to the distance the protons are from each other. The relationship caused by the protons' magnetic fields is called spin-spin interaction and the net result of this interaction is shown in the figure on the previous page. These interact to form the T_2 decay curve also shown below that is governed by the equation $M_{xy} = M_0 * e^{-t/T2}$, where M_{xy} refers to the moment of the protons when moving toward the negative z-axis[7,9]. Energy returning to the computer also helps show structure based on the time it takes for the energy to be retransmitted back to the machine (like sonar), as protons in different places in the body do this at different rates[11]. The combination of this data forms an image in the 2D plane that can be constructed as a cross section of the area of interest.



Even though MRIs are one of the most reliable and commonly used tests in medicine, the images are not always perfect. As has been shown throughout this paper, the MRI image is a direct result of the strength of the MRI signal given off by the protons returning to their M_0 state. Also, as seen by the various equations and explanations, this signal is directly related to the strength and manifestation of the applied magnetic field and the spin-spin interactions between the protons themselves. So, in cases where the signal of the MRI needs to be amplified to generate a better image, it makes sense that the alteration of the magnetic field would serve this result. In this situation, contrast dyes with specific magnetic properties are injected through an IV in order to alter the magnetic field and produce a better image. Since the MRI measures the orientation of magnetic fields and their time to return to normal after being struck with an RF pulse, other magnetic atoms in close proximity to this field, or the protons in this case, will alter the time it takes to return to normal. As expressed earlier, the relaxation time, T_1 is the main source of information in determining the time is takes the protons to return to alignment with the field. Introducing these paramagnetic contrast agents, like Gadolinium, essentially alters the relaxation time of the protons in water, thereby increasing the MRI signal[2]. The areas of the body which contain these agents will appear white compared to the areas that do not, resulting in an image with greater contrast as seen in the figure where the right picture has contrast[12]. Because many of these paramagnetic contrast agents are highly toxic, the charged metal must be wrapped in an organic chelate to shield its toxicity. This chelate can present a problem in rare cases where the chelate is eliminated via the kidneys, causing various kidney problems due to the toxic metal[13]. New technologies have instead begun to use carbon nanomaterials as the shells for the Gadolinium ions[14]. These “Buckyballs” are comprised of a sphere of 80 carbons, one nitrogen, and a paramagnetic metal ion at its core. The shell itself will not likely breakdown unless subjected to temperatures above 900C. This provides not only a





safer MRI contrast agent but has been experimentally found to be a 25-fold better image enhancing contrast agent[12].

Magnetic Resonance Imaging has grown to combine the fields of chemistry, medicine, and especially physics in the creation of a very useful diagnostic tool. The basic and immersive ideas of magnetism are both involved in the generation of an accurate snapshot of the human body. Also, utilizing other areas of physics like Radio Frequencies, Magnetic Resonance Imaging allows the manipulation of various principles in physics to generate an even better picture or to increase the safety of imaging techniques.

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