Magnetic resonance imaging: Improving medical diagnosis one scan at a time

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Abstract

Magnetic resonance imaging (MRI) is a type of medical imaging that allows clinicians to examine organs inside of the human body that are made of soft tissue. It does so by taking advantage of the way biological tissue interacts with electromagnetic fields. There are many different applications of MRI that allow clinicians to examine different physiological aspects of the body, such as heart and brain function. Because of this, it has been an invaluable means of advancing the medical field by not only providing information about how our bodies work, but also by helping clinicians to detect diseases such as cancer and heart disease much earlier than before.

Introduction

The main problem a practicing physician confronts when presented with a patient is that of diagnosis. In other words, the physician has to find out the cause of the patient's problem in order to treat it effectively. How does the physician go about solving this problem? In ancient times, physicians relied on what they could see outside of the patient's body, and/or what they could hear from outside of the patient's body [1]. While there were plenty other advancements in medical diagnostics, such as examination of bodily fluids and measuring body temperature, the observations used to make diagnoses before the 1900's were either too superficial or too dangerous [1]. It was not until the invention of X-ray in 1895, and thus the birth of medical imaging, that physicians could begin to easily obtain information about structures inside of the human body to aid in their diagnoses [2]. Since then, these feats of engineering have helped improve the quality of life of countless patients by facilitating less invasive diagnoses and more effective treatments.

Magnetic resonance imaging (MRI) is one of those feats. MRI is a type of medical imaging that allows physicians to image structures inside the body and gain clear contrast between different types of tissue. MRI does this by taking advantage of the way that human tissue behaves under the presence of different types of magnetic fields. Although it is slow compared to other imaging modalities, it is one of the main ways of diagnosing various kinds of diseases such as cancer and heart disease. For this reason, it has allowed for much earlier detection of these diseases than before such technology existed. The future of MRI is very bright as the field works to improve its speed and efficacy in order to better detect and prevent harmful diseases.

Historical Overview

The idea of imaging molecules using nuclear magnetic resonance (NMR) has been around since the mid 1900's. In 1946, Felix Bloch and Edward Purcell found that when certain atoms are hit with electromagnetic waves, they become excited by absorbing some of the energy and then fall back to their original state after releasing the energy [3]. This method was used to study the magnetic properties of different compounds since each one released a unique signal [3]. As you will learn later, this released energy can be measured at consecutive time points in order to create an MR signal.

It was not until 1971 that a physician finally gave another perspective on the idea. Raymond Damadian suggested that it was possible to use NMR to analyze human tissue and locate abnormalities such as tumors[4]. This idea, which was sparked by his conjecture that normal human tissue would produce a signal different from cancerous tissue, was correct. In 1973, researcher Paul Lauterbur applied this idea and produced the first 2D and 3D MRI images with methods that were proven to be much more efficient and accurate than Damadian's proposed system [5]. Finally in 1977, the first scan was performed on a human being by Damadian and his team [2]. Thanks to great engineering minds like Damadian and Lauterbur, MRI was made into a very feasible and useful invention in just under a decade.

MRI, How Does It Work?

MRI works by means of a scanner which is composed of various electrical and mechanical components. As shown in Figure 1, the patient is placed on a table which can move in and out of a cylindrical shell. Inside the shell there are various coils and a superconducting magnet that work together in order to form electromagnetic fields which are used to excite the atoms in human tissue in various ways.

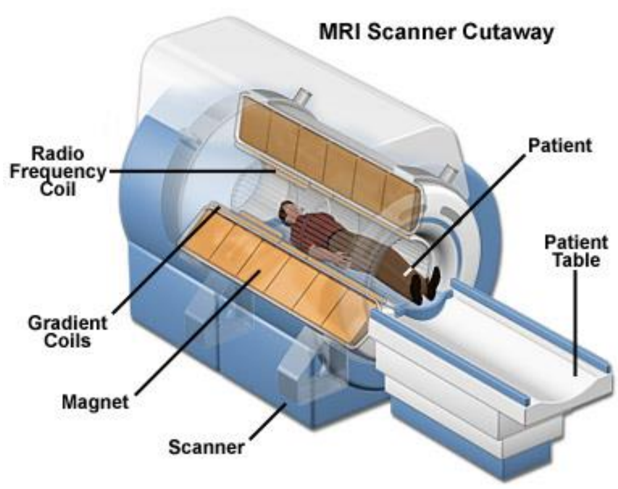

Figure 1: A cutaway of a typical MRI scanner depicting its inner components.

Source: Magnet Lab, Florida State University

MRI is possible because of a simple physical principle known as atomic resonance. Atoms with an odd number of protons and/or neutrons such as hydrogen can be excited by being hit with some form of energy, which in this case is an electromagnetic wave at the atom's resonance frequency [6]. In MRI, the radio frequency coils in the scanner produce a radio wave (also known as a pulse) which the hydrogen atoms in our tissues absorb and become excited as a result. However, as shown in Figure 2, this excitation decays away and the atoms release that energy in the form of a different radio frequency wave [6]. The magnitude of the signal emitted by these atoms is proportional to the water (H_2O) content of the structure being imaged.

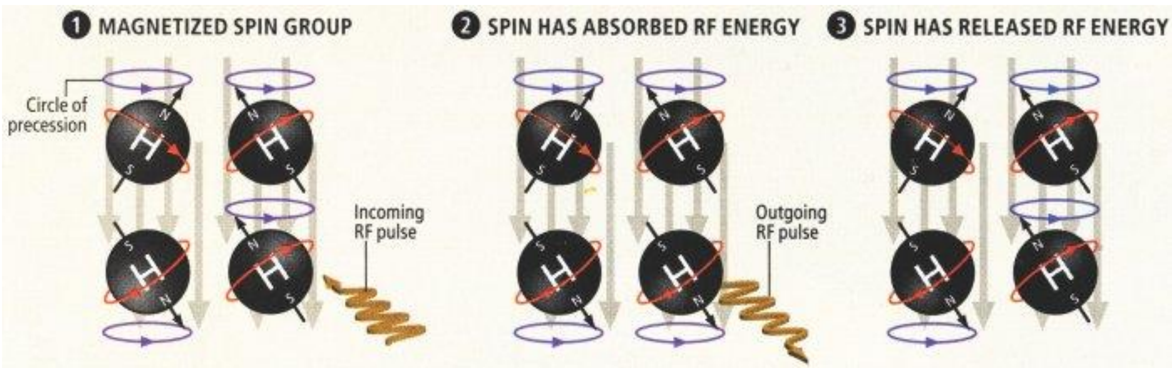

Figure 2: The hydrogen atoms are pulsed by a radio frequency signal which sends them into an excited state. This "excitement" decays and emits a signal in the process of doing so.

Source: http://miriam-english.org/files/IncredibleShrinkingScanner.html

These atoms are pulsed again and again so that the signals can be picked up by coils contained in the shell of the scanner. From this point, it becomes a matter of sending the signals to a computer so that it can formulate an image. The distribution of water content of different structures of the body is produced from these signals by applying a mathematical operation called the Fourier transform [6]. Thus, areas of the body with relatively higher amounts of water will look brighter in the final image because they emitted a stronger signal than tissues with lower amounts. Because of this, Ramadian's initial conjecture that MRI could be used to detect cancerous tissue was correct, as shown by Figure 3.

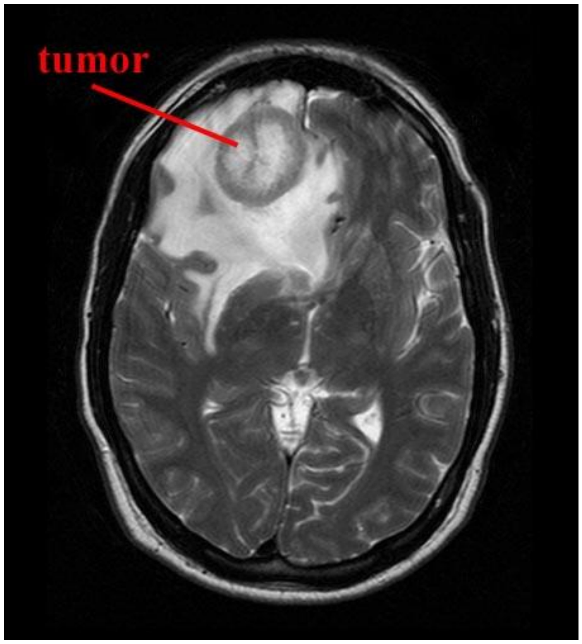

Figure 3: The figure above shows an axial slice of a brain with a cancerous tumor invading it. The tumor can be easily identified because the cancerous region in the top left produced a different signal (hence its different color) than the healthy regions surrounding it.

Source: https://www.ksu.edu/parasitology/cancer.html

Limitations of MRI

Why should we use MRI when other imaging modalities, such as computed tomography (CT) and positron-emission tomography (PET), are able to image the same type of structures? All of these medical imaging techniques allow doctors to image soft tissues such as the brain and heart due to their high water contents. However, MRI is the only one that does not require that the patient be given a dose of ionizing radiation. CT scans are performed by shooting X-rays at the patient in a radial fashion [2]. In PET scans, the patient is injected with a radioactive isotope which can then be detected by the scanner due to the gamma rays that it emits [2]. Although all of these require relatively low dosages of radiation, the scans cannot be performed too frequently due to risks of permanently damaging tissues. MRI, on the other hand, does not present any potential harms such as CT and PET.

However, MRI is relatively slow compared to other imaging modalities. Human tissue must be pulsed many times in order to be able to collect enough samples and reproduce an accurate image. This issue of speed becomes apparent in a couple of ways. One of them is that it requires patients to lie still in the scanner for up to 40 minutes for a typical clinical scan [7]. Keep in mind that during the scan, there are also very loud knocking noises caused by torques acting upon components inside the scanner. Thus, if the patient is in a bad condition, he or she may not be able to withstand being in the scanner for very long. Secondly, high resolution imaging of dynamic (moving) structures in the body such as the heart also becomes a problem. Imagine the scanner is a camera that requires a long exposure time in order to reproduce an image. Now imagine trying to take a picture of a runner trailing past you with that camera. The camera will end up producing a blurry picture since it is attempting to gather information about the runner while he or she is in different positions. Fortunately, there are methods that researchers have invented or are trying to invent in order to mitigate these effects.

Current Applications

There are countless applications and special cases of MRI that attempt to gather different types of information about the human body in order to aid in diagnosis. The following two are prominent examples, but keep in mind that there are many others.

Cardiac MRI (CMR)

The goal of Cardiac MRI (CMR) is to obtain either still or moving images of the heart and is often used to diagnose a patient with heart disease, heart failure or cardiac defects [8]. Since blood tissue has much more water than cardiac muscle, there is a lot of contrast between blood inside the heart and cardiac muscle, as seen in figure 4. This excess water allows radiologists to easily find defects in the cardiac structure and motion which are symptoms of various types of cardiac disease.

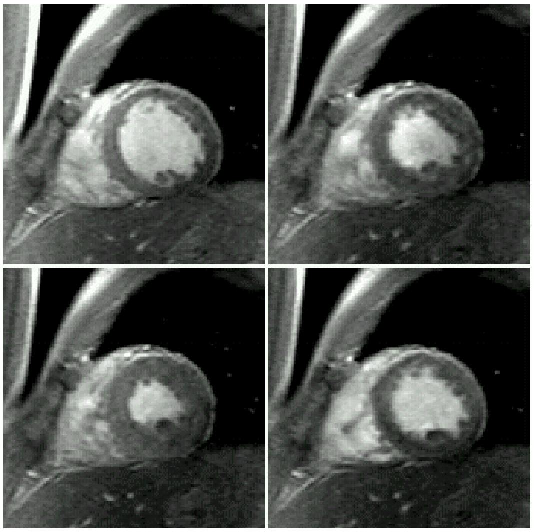

Figure 4: Above are four frames of a CMR video. The lighter (higher signal intensity) areas are the ventricle blood pools, while the darker areas represent cardiac muscle.

Source: http://www.kuleuven.ac.be/radiology/Research/Cardiac/Cardiac_Main.html

Suggestion to Illumin: Put video of a cardiac MRI scan.

However, as stated before, MRI has problems with imaging dynamic bodies, which makes it hard to obtain high quality cardiac datasets without any motion artifacts. Low resolution datasets are easy to obtain since they do not require a long exposure time like higher resolution ones do. A process called electrocardiogram (ECG) gating fixes this problem for high resolution cardiac imaging [9]. A heart that pumps blood normally moves cyclically such as a sine wave. If you were to take a snapshot of the heart at one time point, it would be exactly the same if you took another snapshot exactly one heartbeat later. ECG-gating takes advantage of this by gathering information cyclically according to the patient's heartbeat [9]. Using the camera analogy, the scanner will take half of a picture and then after the length of one heartbeat, it will take the rest of the picture. Consequently, this reduces the "exposure time" each time the scanner is trying to take a picture. This can be done for various time points to create multiple images of the heart at stages in the cardiac cycle and thus generate a video.

Functional MRI (fMRI)

Function MRI (fMRI) allows radiologists as well as researchers to quantitatively measure neural activity in specific parts of the brain. Since neurons (the type of tissue that makes up the brain) do not have their own energy supply, they require oxygen to be brought to them by blood when they are sending signals to the body. Therefore, when a particular part of the brain is active, there is more blood transporting oxygen to that part. It turns out that the signals produced from active areas of the brain are slightly different from the inactive areas. These differences in signals can be detected using blood-oxygen-level dependent imaging which can then determine which parts of the brain were active during certain types of thoughts [10]. These areas are identified and highlighted in the final reconstruction of an fMRI image as can be seen in Figure 5.

Thus, fMRI has been invaluable in studying which parts of the brain are responsible for specific thoughts and actions. It has not only been a revolutionary tool in neuroscience research, but is also extremely applicable in clinical practice. fMRI is often used to detect strokes or other types of brain injury since damaged areas will have unusually large or small amounts of activity. Knowing where these areas are located also aid surgeons who need to know which areas to operate on.

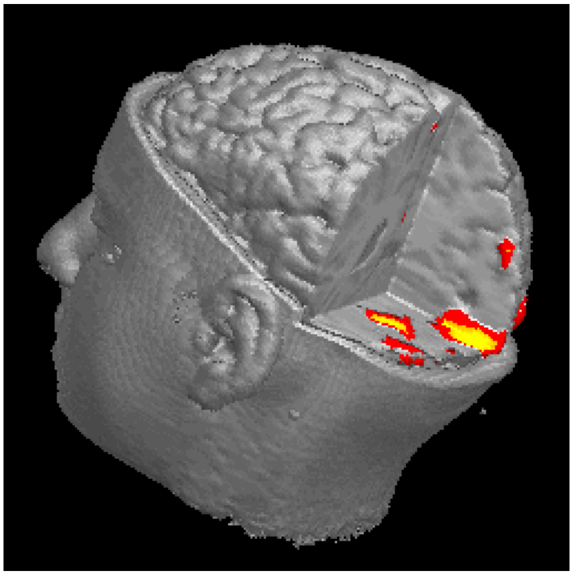

Figure 5: Above is a 3D image reconstruction showing a cross section of the brain. The bright red and yellow areas in the cross section depict high blood-oxygen levels indicating that those parts of the brain were very active while the scan was taking place.

Source: http://www.csulb.edu/~cwallis/482/fmri/fmri.html

Future Research

The field of MRI has advanced greatly since its inception, but there is still a lot of room for improvement and fine tuning. Most of the research being done has to do with improving MRI at the source by making scan times faster. Remember that scan times are slow due to the way that the scanner acquires data. Given this fact, researchers are attempting to improve MRI in two main ways: by reducing the amount of data that is necessary to reconstruct accurate images and/or changing the way the data is acquired so that acquisition times are shorter.

The first way is tricky because when less data is used to reconstruct an image, it usually results in artifacts that obscure important features of clinical images. Under sampling (acquiring less data than is necessary) is actually common in clinical settings, but usually trade-offs must be made between increasing scan speed and quality of the image. The goal of researchers working in this field is to mitigate the effects of this trade-off. Essentially, researchers use constraints which are based on information that they know about the image beforehand. This has defined the field of compressive sampling, which aims to estimate samples that are not taken by the scanner by using a priori information, thus reducing artifacts caused by under sampling [11].

Increasing MRI speed would improve all applications as well as introduce new ones. One idea which has been proposed and implemented using newer techniques is real-time MRI. In 2004, Santos proposed a framework using various fast imaging techniques that could potentially allow for physicians to view live MRI feeds of patients and thus be able to diagnose the patient then and there [12]. Various scanning parameters such as which slices of the body are being imaged could also be changed on the fly. Unfortunately, this framework and others like it still have a long road ahead to become reliable enough to be used by physicians as a means for diagnosis.

Conclusion

MRI has advanced the medical field by leaps and bounds through the insights it has given into internal body structures that were once inaccessible to physicians unless they performed dangerous, invasive surgeries. These insights have given us invaluable information towards how to help humans live just a bit longer by allowing for faster detection of diseases and more informed treatment of those diseases. As engineers continue to make it even better, MRI will continue to help us understand the human body as well as improve our quality of life.

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