Book Review

MRI Made Easy

Shriraj Sawant

Ph.D. Scholar @BRaINLab IITGN

Introduction

What is this book about?

This book tries to explain the basics of Magnetic Resonance Imaging (MRI) as simply as possible, in a very light, illustrative, and easily digestible way. I liked the way the author used interesting analogies to make even the most complex phenomenon like proton spins approachable to someone without any background knowledge. I'll try to explain the concepts I have learned from this book in my own way.

So what is MRI?

Magnetic resonance imaging is a medical imaging method to form anatomical pictures and capture the physiological processes of the body using radiology. Speaking from a physics perspective, MRI is a medical application of the phenomenon of Nuclear Magnetic Resonance (NMR) which basically explains how the nuclei of an atom resonate with an external magnetic field and electromagnetic waves (photons). It is no wonder that MRI was earlier called NMRI but the term "Nuclear" was dropped to avoid associating any negative bias from the general public.

The simple process of generating MRI images involves, first placing the subject within the magnetic field generated by the MRI machine. Then a photon or specifically, a radio wave is sent to the subject. The subject then emits a signal which is used to generate the final MRI image. I will be explaining each of these steps in detail as we read along with this review.

In the following sections, I'll explain the basic physics and signal theory required for understanding how MRI works. First, we will understand the physics behind protons and magnetic resonance. Then we will go through how a radio wave signal can bring order to the chaos of randomly spinning protons and nuclei and how this order helps in getting an MRI signal. We will introduce some jargon used by the MRI community like Longitudinal and Transverse relaxation time, T1, T2, and T2* processes, etc. which will help us get acquainted in this field. We will then see how an image is generated by contrasting tissues with surrounding bodily fluids, how the contrast is generated, and how the basic physics principles help us achieve this. We will also see different pulse sequences in brief and how the final image is reconstructed from raw time-varying MRI signals to a 3D structural MRI image.

The Physics of MRI

Enter the proton physics....

So what are protons? They are the positively charged components of the nuclei of every atom. Whereas the negatively charged electrons shell the atom from outside the protons reside at its core along with neutrons having no electrical charge. Of course, if we want we can go even deeper into the quantum field theory and quantum chromodynamics of how protons exist but let us keep it as simple as possible and focus on the MRI aspects.

These protons are not static and don't stay idle. In fact, they are constantly moving which generates electrical currents which in turn forms a magnetic field around them. There are many causes for the dynamic motion of protons but one of the most important is the proton's inherent spin. Strictly speaking from quantum physics POV, spin is a quantum mechanical phenomenon and is not as simple as a spinning top as one might think. But for our purpose, we can assume it's similar to the spinning of everyday objects like top or even planet rotating around its axis. The most important thing which this spin causes is to make protons generate their own magnetic field.

Now in this way every proton can be imagines as tiny bar magnets. In a general state, these protons are randomly aligned in a body and on average the total magnetic field of this body is zero. But interesting things happen when we put an external magnetic field. The protons align themselves along the applied magnetic field. This can happen in two ways, the protons can be either parallel or anti-parallel to the external magnetic field. The parallel state has low energy whereas the anti-parallel state has high energy cost and is unstable in nature. That's why most of the protons prefer to stay in a parallel state since it has low energy costs but the difference in numbers of low vs high energy state protons is generally very small. This difference in numbers of parallel and anti-parallel protons induces an internal magnetic field within the body. This magnetic field is called a longitudinal field. This field is undetectable in general since it is aligned and superimposed with the external magnetic field.

Before going deeper into how this induced magnetization helps in generating MRI images let us see one more important phenomenon. Even though the protons are now aligned in one of the two possible configurations they aren't stationary. They precess and rotate around their own axis along the external magnetic field just like earth or any other planet for example. Now the rotation and precession are periodic in nature and hence they have specific frequency associated with them. This is known as Larmor frequency which says that the protons precess at the rate which is directly proportional to the strength of the applied magnetic field,

Resonance

We know that when an external magnetic field is applied the protons precess at a particular frequency which is proportional to the applied magnetic field strength. And the protons can exist in either low energy or high energy state, with the average induced magnetic field being aligned longitudinally along with the external magnetic field. Now, what happens when we send a radio wave having the same frequency as the proton's precession frequency?

Basically, some of the low energy protons jump to a high energy state by absorbing the energy of the photon. This happens only when both the radio wave frequency and precession frequency matches and is known as resonance. This effect of resonance causes the low energy protons to flip to a high energy state and that in turn decreases the longitudinal magnetic field which existed due to the difference between the no. of low and high energy state protons.

There is another important effect caused by the RF signal pulse. There are many protons that precess along the longitude of the external magnetic field. Given that the magnetic field strength is uniform all the protons will precess with the same Larmor frequency for the same material according to the gyromagnetic ratio of that material. But all of them might not be in the same phase. That is in the transverse plane the protons will be precessing in different phases and on average zeroes out the induced transverse magnetic field vector. But when an RF pulse is sent to that material, all the protons start phasing into sync and precess at the same time. This causes the transverse magnetic field vector to grow and becomes maximum when all are in phase.

Relaxation: T1 and T2 processes

We saw that when we send an RF signal pulse the longitudinal magnetization vector reduces and the transverse magnetic vector increases. We have seen the complex physics of protons and spins behind them but one can simply imagine the longitudinal vector being rotated towards the transverse plane whenever such RF pulse is sent (specifically the 90° pulse). Now, what happens when the RF signal is turned off?

What happens is the protons that were flipped to a high energy state no longer are able to stay in that anti-parallel state as it requires high energy. They slowly but steadily jump down to their earlier state. This causes the difference between the no. of high and low energy protons to fall back to their initial states and that causes to rise in the longitudinal vector. The time taken to recover the longitudinal magnetic field vector is called the longitudinal relaxation time described by the time constant T1 and this process is called the T1 process.

At the same time, the transverse magnetic field vector starts dephasing due to random fluctuations in the magnetic field background. There are many causes for it explained beautifully by quantum field theory and statistical mechanics but we don't need to dwell in such complicated places here. For our requirements, we can simply assume that the transverse vector dephases as soon as the RF signal is turned off. The time taken to reduce the transverse magnetic field vector to null is called the transverse relaxation time described by the constant T2 and this process is called the T2 process.

Both T1 and T2 processes are independent of each other and occur simultaneously. The sum effect of this process can be visualized as the transverse vector being rotated back to its original longitudinal position as soon as the RF signal is deactivated. The type of signal we get back from such a process is a decaying periodic signal and is called Free Induction Decay (FID). In general, T1 is longer than T2 and T1 vary with magnetic field strength. The stronger the magnetic field strength, the longer the T1 process is.

The Signal Acquisition and The Image Reconstruction

Getting the signal

We have understood the basic physics behind the interactions of protons, the magnetic field, and the RF pulses. Now we can move towards the MRI signal acquisition aspects and about the final image we get from the underlying complex nuclear physics. There are many parameters that control the quality of the final image obtained through MRI but the most important among those are the Time to Repeat [TR] and Time to Echo [TE]. TR is the time period between the successive repetition of RF pulse sequences. Each such RF pulse sequence can contain many different types of pulses like 90° or 180° pulse. TE is the time period between the first signal of the RF sequence (90° in the case of spin-echo sequence) and the echo received after 180° rephasing. This rephasing can be done multiple times in a single RF pulse sequence but after each such TE, the rephased signal strength decreases. This is due to the T2 process. When no such rephasing is done, the transverse vector falls even faster and that is called the T2* process. In general, the final images are weighted using either T1 or T2 processes or both.

Long TR, Short TE: The proton/spin weighted imaging

In this case, the image is neither T1 weighted nor T2 weighted. In fact, whatever signal we get is completely determined by the number of protons present in the materials or the proton/spin density. This is because the long T1 causes no difference among the signal received from different materials or tissues as all the longitudinal vectors are already recovered. Also, short T2 means there is no difference yet between the transverse field vectors of different materials.

Long TR, Long TE: The T2 weighted imaging

Same as before there are no differences between T1 of different tissues since TR is very long. But when TE is long as well, T2 process differences become more contrasting as the time period increases. This causes the image obtained to be T2 weighted.

Short TR, Short TE: The T1 weighted imaging

When TR is short enough, different tissues haven't fully recovered their longitudinal vector yet. These differences are contrasting enough to get a clear image and hence it's T1 weighted.

Short TR, Long TE: Theoretically Useless

This configuration is not used in practice because it's not possible to get any signal in this method. This is because the short TR causes very little magnetization along the transverse direction and then long TE causes that already weak signal to diminish into nothingness. The result will be nothing more interesting than the static noise we used to get in our antenna based televisions decades back.

Enhancing signal contrast

To further enhance the signal, the subjects are injected with MR contrast mediums. Basically, these are paramagnetic substances that shorten the T1 and T2 time constants of the local surroundings thus enhancing the contrast between different tissues and fluids which improves the resulting quality of the acquired MRI image. This process is called proton relaxation enhancement and one of the prominent such MR contrast mediums is Gadolinium. It is used mainly for T1 weighted imaging methods because it increases the signal for T1 processes and decreases the T2 process signals.

Frequency and Phase encoding

We understood how different parts of the final MRI image are weighted. But how do we know where the signal came from? Briefly speaking we uniquely encode each of the 3D spatial locations of the subject with frequency and phase encodings. This helps us exactly determine where the signal was emerged from. We then apply something called Fourier transform which helps us determine the magnitude of each of such frequency components. This in turn is used to determine the intensity of the pixels (or voxels) of the final reconstructed image.

The slice selection mechanism

Since the subject under MRI scan is 3 dimensional in general, we will see how each of the dimensions is spatially determined one after another. Let us see how a single 2D slice of a 3D subject is located. We know that the precessing frequency of protons is directly proportional to the applied external magnetic field strength. What if that field strength was not constant but varied along a gradient. Different field strength along a direction will cause protons in that direction to have varying Larmor frequency. This is exactly what is done in practice. To apply the gradient an additional varying magnetic field is superimposed on top of the external magnetic field. This causes each 2D slice to have different Larmor frequencies along the gradient which allows us to easily determine the location of the signal.

The voxel selection mechanism

Now within each slice, the protons have the same Larmor frequency. How do we know from which point within the slice the signal came from? We use the exact same technique as earlier. We again apply a frequency encoding gradient and this causes each of the columns (y-axis) of the 2D slice to precess with unique frequencies.

Now to determine the final dimension which is the X-axis we do something different. We apply a phase encoding gradient which unlike previous methods is applied for a limited time. This causes each of the rows (x-axis) of the 2D slice to dephase when the phase encoding gradient is on. Once turned off each of the rows of 2D slice now has unique phases. This overall helps us to uniquely determine the spatial location of each of the voxels of the 3D MRI image.

Conclusion

We finally have the final MRI image of the subject in our hand now. From placing the subject under the magnetic field to reconstructing the final image, first, we understood the basic physics necessary to understand how interactions between protons, RF pulses, and magnetic fields can be used for medical imaging. We went through proton and spin physics and understood the core phenomenon of resonance which is crucial for MRI. Then we understood the signal processing theory of MRI. We saw how different parameters of MRI can affect the quality of the image generated. We also saw how we can enhance the contrast of the signals acquired. And in the end, we saw how spatial locations of MRI signals are uniquely determined. With this, we are aimed with the basic knowledge of how MRI works and ready to research advanced topics in this field.