physics of diagnostic radiology

Lecture 9

First semester

2025-2024

Shimming

MRI requires a very high homogeneous static magnetic field. In order to produce high-resolution images, the magnetic field inhomogeneity produced in a high performance MRI scanner. After manufacturing, the magnet must be adjusted in some points to produce a more uniform field by making small mechanical and/or electrical adjustments to the overall field. This process is known as **shimming**. Because the magnet itself is not homogeneous, it is necessary to improve or ―shim‖ the homogeneity of the static magnetic field (Bo). A **shim** is a device used to adjust the homogeneity of a magnetic field by two methods: (1) Passive shimming (2) Active shimming.

Passive shimming: The mechanical adjustments, which add small pieces of iron or magnetized materials, are typically called passive shimming. Passive shimming involves pieces of steel with good magnetic qualities. The steel pieces are placed near the permanent or superconducting magnet. They become magnetized and produce their own magnetic field.

Active shimming: The electrical adjustments, which use extra exciting currents, are known as active shimming. Active shimming is performed with coils with adjustable current. Active shimming requires passage of electric current through coils with unique geometric configurations.

In both cases, the additional magnetic fields (produced by coils or steel) add to the overall magnetic field of the superconducting magnet in such a way as to increase the homogeneity of the total field.

1.2 Radio Frequency Coils

Radio Frequency (RF) coils are needed to receive and/or transmit the RF signals used in MRI scanners. RF coils system comprises the set of components for transmitting and receiving the radiofrequency waves involved in exciting the nuclei, selecting slices, applying gradients and in signal acquisition. RF coils are vital component in the performance of the radiofrequency system. They one of the most important components that affects image quality and obtaining clear images of the human body. RF coils for MRI can be categorized into two different categories: volume coils and surface coils.

1.2.1 Volume RF Coils

The design of a volume coil is to provide a homogeneous RF field inside the coil which is highly desirable for transmit, but is less ideal when the region of interest is small. The large field of view of volume coils means that by receiving the noise that they receive from the whole body, not just the region of interest. Volume coils need to have the area of examination inside the coil. They can be used for transmit and receive, although sometimes they are used for receive only. These coils are requiring a great deal of RF power because of their size, so they are often driven in quadrature in order to reduce by two the RF power requirements. Figure 5 shows two volume coils. The head coil is a transmit/receive coil; the knee coil is receive only.

Figure 5: Two volume coils (a) Head coil (b) Knee coil

1.2.2 Surface Coils

Surface coils have very high RF sensitivity over a small area of interest. As the name already implies, surface coils are placed over or around the surface of the anatomy of interest to the patient directly such as the temporo-mandibular joint, the orbits or the shoulder. The coil consists of single or multi-turn loops of copper wire. They have a high **Signal to Noise Ratio** (SNR) and allow for very high-resolution imaging because their small field of view and hence they only detect noise from the region of interest. The disadvantage is that they lose signal uniformity very quickly when you move away from the coil. Surface coils make poor transmit coils because they have poor RF homogeneity, even over their region of interest. Figure 6 shows a few examples of surface coils.

Figure 6: few examples of surface coils.

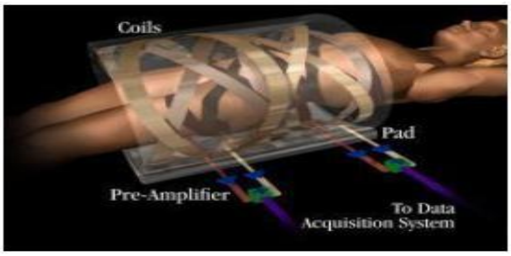
1.5. Type of the arragment of Coils

1.5.1 Quadrature Coils

The quadrature coil consists of two coils, which are placed at right angles to one another that mean oriented **90** degrees relative to each other. Therefore, the MRI signals received by each, coil is 90 degrees out of phase with each other. The quadrature coil operates in the circular polarization circularization mode. Nowadays, most volume coils are Quadrature coils.

1.5.2 Phased Array Coils

Phased array coils consist of multiple surface coils with small diameter which are combined to record the signal simultaneously and independently, so a greater level can be explored. Surface coils have the highest signal-to-noise ratio (SNR) than that delivered by one large diameter but have a limited sensitive area. By combining 4 or 6 surface coils it is possible to create a coil with a large sensitive area (see figure 7).



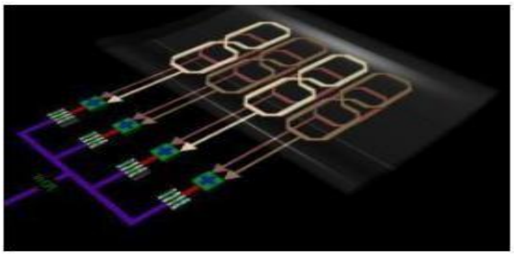


Figure 7: QD Body Array coil Spine Array coil

Other Hardware

1.6. Faraday shield

The frequency range used in MRI is the same as used for radio transmissions. That's why MRI scanners are placed in a **Faraday** cage to prevent radio waves to enter the scanner room, which may cause artifacts on the MRI image. To function properly, an MRI scanner needs to sit in a specialized room or chamber shielded against Radio Frequency (RF) interference. Without such protection the very weak RF signals that emanate from the patient when scanned would be overwhelmed. Also, to stop the radio frequencies produced by the scanner from interfering with equipment outside the cage.

1.7 Atomic Structure

All things are made of atoms, including the human body. Atoms are very small. Atoms are organized in molecules, which are two or more atoms arranged together. The most abundant atom in the body is hydrogen. This is most commonly found in molecules of water (where two hydrogen atoms are arranged with one oxygen atom, H_2O) and fat (where hydrogen atoms are arranged with carbon and oxygen atoms; the number of each depends on the type of fat).

The mass number is the sum of the protons and neutrons in the nucleus. The number of neutrons and protons in a nucleus are usually balanced so that the mass number is an even number. Nuclei with an odd mass number (a different number of protons to neutrons) are important in MRI. Protons have a positive electrical charge, neutrons have no net charge and electrons are negatively charged. So atoms are electrically stable if the number of negatively charged electrons equals the number of positively charged protons.

1.8. Magnetization

The earth electrically charged and spinning ball is floating in space. From basic of physics, that a rotating electrical charge creates a magnetic field. And sure enough, the earth has a magnetic field, which we use to find our way from one place to another by means of a compass. In short we can establish that the earth is a giant spinning bar magnet, with a north and a south pole (Figure 8).

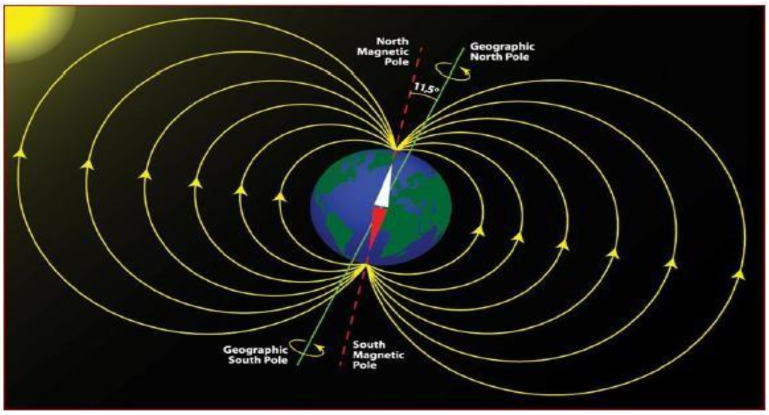


Figure 8: North and a south pole of earth.

We have many in common with earth. If we take a bit from our body and we would put it under an electron microscope we can see things that look rather familiar. We see tiny little balls, which rotate around their own axes and also have an electrical charge and they have particles floating around it. This balls which we see are atoms. And atoms have everything to do with MRI, because we use them to generate our MR image. Another thing we have in common with earth is water. Our body consists of 80% water.

Human body consists mainly of water "about 80% water". Water consists of one oxygen and two hydrogen atoms. Consider the simplest nucleus, which is hydrogen atom (the first element in the periodic table) has a nucleus contain one proton, and one electron orbital. This proton is electrically positive charged and it rotates around (spin) its axis.

Also the hydrogen proton behaves as if it were a tiny bar magnet with a north and a south pole (Figure 9). Hydrogen protons in the body thus act like many tiny magnets. The nucleus is said to be a **magnetic dipole**, and the name for its magnetism is **magnetic moment**. It is essential that there be a source of protons (protons in the nuclei of hydrogen atoms, which are associated with fat molecules and water) in order to form the MR signal.

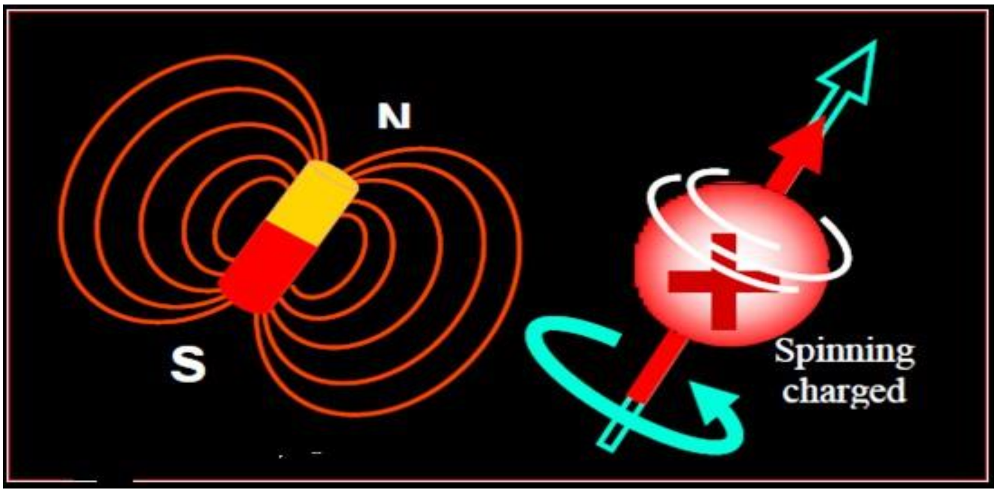


Figure 9: hydrogen proton. The positively charged hydrogen proton (+) spins about its axis and acts like a tiny magnet. *N* = north, *S* = south.

We conclude from the above that there are two reasons for taking hydrogen as a source to form the MR signal or MR imaging source.

- First off all we have a lot of them in our body. Actually it's the most abundant element we have.
- Secondly, in quantum physics there is a thing called ―Gyro Magnetic Ratio‖. It is beyond the scope of this book what it represents; suffice to know that this ratio is different for each proton. It just so happens, that this gyro magnetic ratio for Hydrogen is the largest; 42.57 MHz/Tesla.

What is the Gyro Magnetic Ratio?

1.9. Magnetic Moments

In most materials, such as soft tissue, these little magnetic moments are all oriented randomly (see figure10). That is, if one nucleus has its spin and therefore its magnetic moment pointed up, there will be another nearby nucleus with its spin pointed down. Other magnetic moments will be oriented in various directions. This random orientation causes all the spins and magnetic moments to cancel, so that the **net magnetization** is zero. Net magnetization is symbolized by **M**.

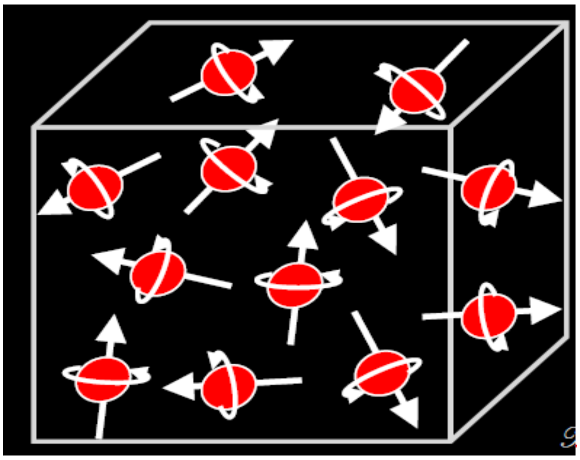


Figure 10: the magnetic moments of protons in all directions randomly**.**

If the patient however, is placed in a strong magnetic field, the magnetic moments will align themselves much as a compass needle aligns itself with the earth's magnetic field. Although all the magnetic moments are illustrated as being aligned in the same direction as the external magnetic field, in fact nearly as many align against the field as with it. It is a result of quantum mechanics that the moments must align either with the field or against it. A small excess of moments aligned with the field gives the patient a net magnetization, **M** as shown in figure 11.

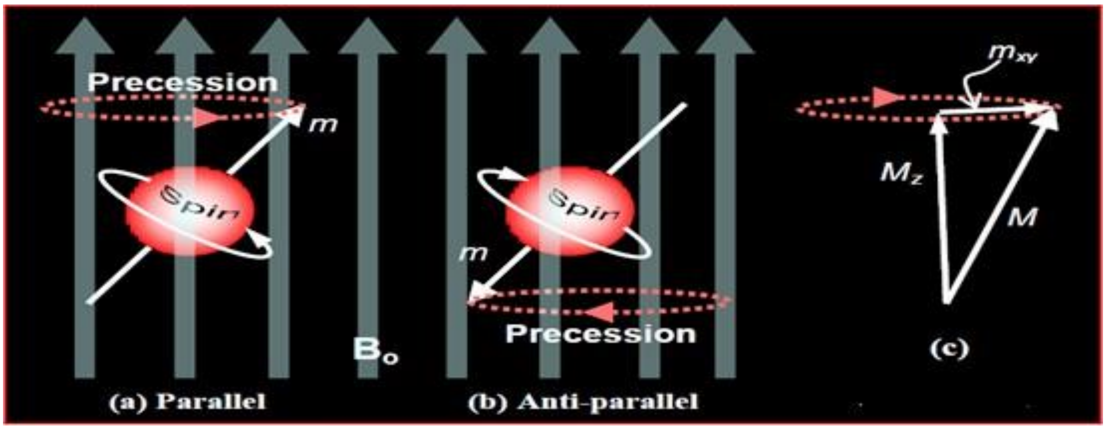


Figure 11: The hydrogen protons parallel or anti-parallel.

The atoms in any material are in constant thermal motion, and thus the nuclei are being continually banged out of alignment. At any particular time however, slightly more of the nuclei will align with the field than against it, creating net magnetization of the patient. The patient becomes a magnet.

Hydrogen is not the only element we can use for MRI. In fact any element, which has an odd number of particles in the nucleus, can be used. Some elements, which can be used, are: The protons in a molecule bunch of hydrogen a lot of tiny bar magnets spinning their own axes. As well known two north poles and two south poles of two magnets repel each other, while two poles of opposite sign attract each other. In human body these tiny bar magnets are ordered in such a way that the magnetic forces equalize. Human bodies are, magnetically speaking, in balance.

Table 1: MRI friendly elements

Isotope	Symbol	Spin Quantum number	Gyro Magnetic Ratio (MHz/T)
Hydrogen	^{1}H	1/2	42.6
Carbon	^{13}C	1/2	10.7
Oxygen	^{17}O	5/2	5.8
Fluorine	^{19}F	1/2	40.0
Sodium	^{23}Na	3/2	11.3
Magnesium	^{25}Mg	5/2	2.6
Phosphorus	^{31}P	1/2	17.2
Sulphur	^{33}S	3/2	3.3
Iron	^{57}Fe	1/2	1.4

If the person placed in the MRI scanner some interesting things happen to the hydrogen protons:

1. They align with the magnetic field. This is done in two ways, **parallel** or **anti-parallel**.

2. They **process** or —**wobble**|| around the direction of the external magnetic field (the z-axis) due to the magnetic momentum of the atom.

They process at a frequency called the Larmor frequency (When placed in a magnetic field, charged particles will process about the magnetic field. In MRI, the charged nucleus, will then exhibit Precessional motion at a characteristic frequency known as the Larmor Frequency). Larmor frequency to its importance needs to be further explained. The Larmor frequency can be calculated from the following equation:

$$\omega_o = \gamma B_O$$

Where ω_o = Processional or Larmor frequency (MHz)

γ = Gyro Magnetic Ratio (MHz/T)

B_O = Magnetic field strength (T)

For example, if the magnetic resonance imaging system 1.5 Tesla then Larmor frequency or Precessional is:

42.57 × 1.5 = 63.855 MHz

What is the Precessional frequency of 1.0 T, 0.5 T, 0.35 T and 0.2T systems?

When applied strong magnetic field of the scanner on protons, it could align with the field in two ways: parallel and anti-parallel.

Can also be called the two cases are low-energy state (parallel) and high energy state (anti-parallel). Distributions of protons for both states are not the same. To approximate the mind image can compare the protons just like a lot of people are lazy. They prefer to be in a low energy state. Protons aligned parallel which are low-energy State more than anti-parallel protons to the direction of the applied magnetic field which are a high-energy state. However, the difference between the two states is not large.

For example, the excess number of protons that aligned parallel or low energy state within a field 0.5T is only 3 per million (3 ppm = 3 parts per million), in a 1.0T system there are 6 per million in the system There 1.5T 9 per million. So, the excess number of protons is proportional with Bo.

The excess number of protons within a field 1.5T is only 9 per million which is don't seem very many, but in real life it adds up to quite a number. For example, if we calculated how many excess protons there are in a single voxel (volume element) at 1.5T.

- Assume a voxel is 2 x 2 x 5 mm = 0.02 ml
- Avogadro's number says that there are 6.02 x 10^{23} molecules per mole.
- 1 mole of water weighs 18 grams (O^{16} + $2H^{1}$), has 2 moles of Hydrogen and fills 18 ml, so…………
- 1 voxel of water has $\frac{2x6.02x10^{23}x0.02}{18} = 1.338x10^{21}$ total protons

The total number of excess protons = $\frac{1.338x10^{21}x9}{2x10^{6}}$ = $6.02x10^{15}$

Now, if like us, **net magnetization** using an easy by **vector** in order to see what is happening with them in MRI. A vector (the red arrow in the Figure 12) has a direction and a force. We imagine a frame of rotation, which is a set of axes called X, Y and Z. The Z-axis is always pointing in the direction of the main magnetic field, while X and Y are pointing at right angles from Z. Here we see the (red) net magnetization vector pointing in the same direction as the Z-axis. The net magnetization is now called M or longitudinal magnetization.

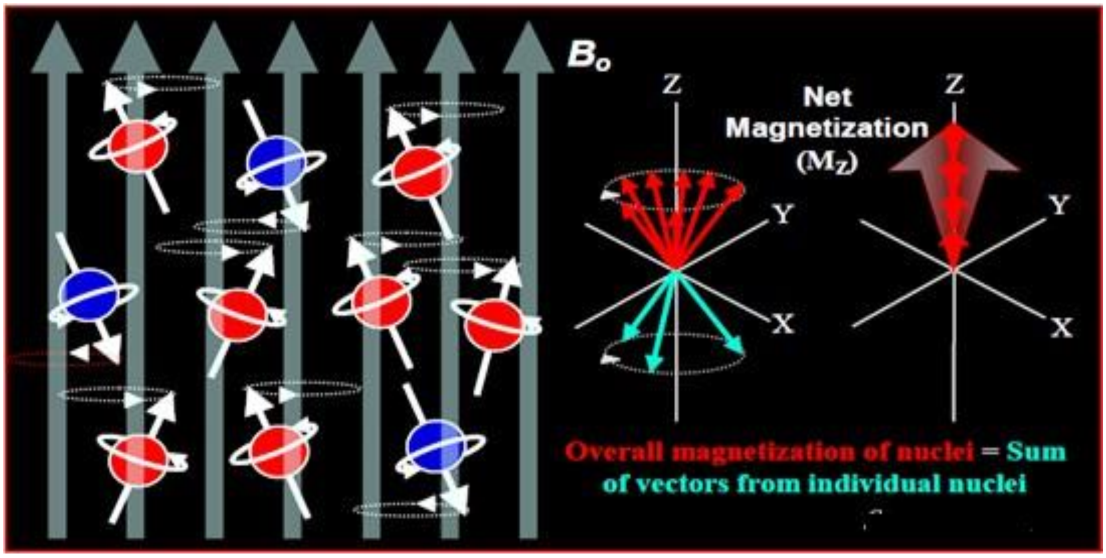


Figure 12: Direction and a force of net magnetization

Thank you