PHYSICS OF NUCLEAR MAGNETIC RESONANCE

Nuclear magnetic resonance was first described and measured beams by Isidor Rabi in 1938. Eight years later, in 1946, Felix Bloch and Edward Mills Purecll refined the technique for use on liquids and solids, for they shared the Nobel Prize in physics in 1952.

Purcell had worked on the development and application of RADAR during world war ll. His work during that project on the production and detection of radiofrequency energy, and on the absorption of such energy by matter preceded his discovery of NMR.

They noticed that the magnetic nuclei, like ^{1}H and ^{31}P, could absorb RF energy when placed in a magnetic field of a strength specific to the identity of nuclei. When this absorption occurs, the nucleus is described by being in resonance. Interestingly, for analytical scientists, different atoms within a molecule resonate at different frequencies at a given field strength. The observation of the resonance frequencies of a molecule allows a user to discover structural information about the molecule.

The development of nuclear magnetic resonance as a technique of analytical chemistry and biochemistry parallels the development of electromagnetic technology and its introduction into civilian use.

1- Basic MR Theory:

In the nucleus of every atom, individual protons and neutrons spin about an axis. This property, called spin angular momentum, is the basis of nuclear magnetism. Since atomic nuclei have charge, this spinning motion produces a magnetic moment along the spin axis. In most nuclei, the particles are paired so that the net magnetic properties cancel. However, if the number of protons or neutrons is odd, complete cancellation is not possible. Nuclei with unpaired proton or neutron such as ^{1}H, ^{13}C, ^{23}Na, among others, exhibit a net magnetic effect. The relative strength of this magnetic moment is a property of the type of nucleus and therefore determines the MR detection sensitivity. The hydrogen ^{1}H nucleus, which is highly abundant is biological systems, has the strongest magnetic moment.

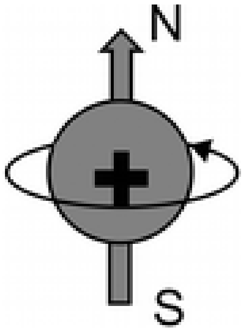
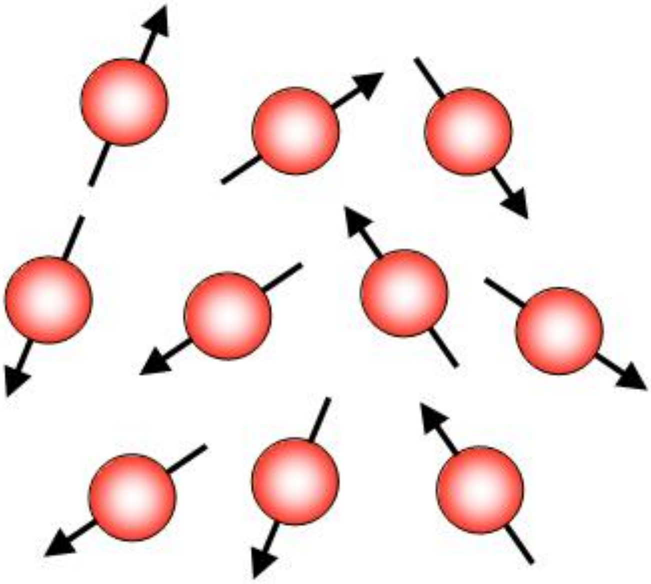


Figure (1): Hydrogen proton, the positively charged hydrogen proton(+) spin about its axis and acts like a tiny magnetic N=north, S=south.

Since the individual magnetic moments (or axis of spin) are randomly oriented, biological tissue does not normally exhibit a net magnetization (Figure 2).



Figure(2): Random oriented nuclear magnetic moment

However, in the presence of external static magnetic field B_o, the individual magnetic moments tend to align either parallel or anti parallel to the direction of the applied field, similar to the way a permanent bar magnet will align itself with the field or a compass needle aligns with the earth's magnetic field.

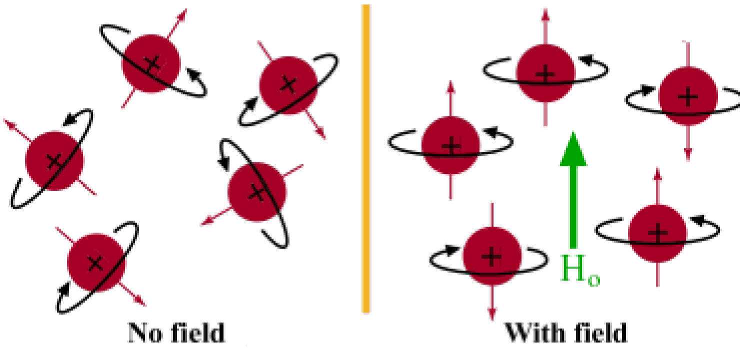


Figure (3): a-without external magnetic field, b- with presence external magnetic field

Since a parallel alignment to the field is the lower energy state, it is preferred and slightly more nuclei will align parallel rather than anti parallel to the field. As a result, the tissue will exhibit a net magnetization not unlike that of piece of iron in a magnetic field, although not as strong.

The individual spins do not align exactly parallel to the applied filed, but at an angle to it(Figure4).

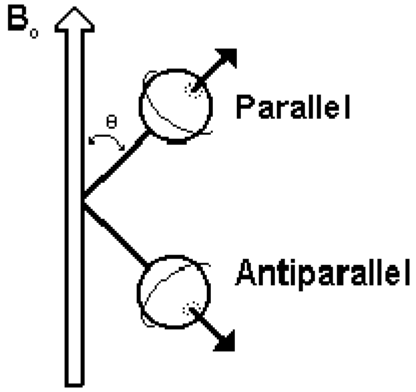
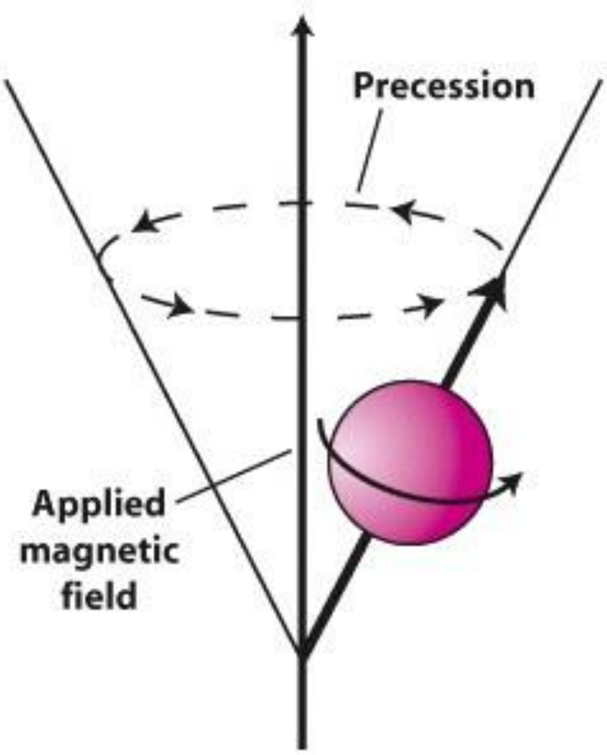


Figure 2
Nuclear magnetic moments
in the presence of an external field

Like spinning top, the individual spins cause the moment to précises about the axis of B_o(Figure4) the frequency with which the moment précises given by the Larmor equation below.



Figure(5): A spinning nucleus precessing

$$F = B_o\gamma$$

Where:

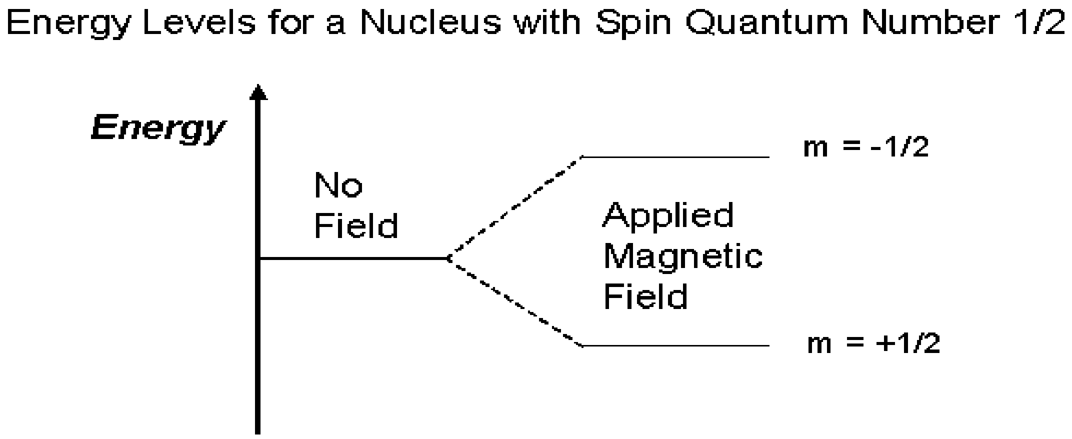
B_o= Strength of the applied filed.

γ= gyromagnetic ratio (related to the strength of the magnetic moment for the type of nuclei).

F= the frequency of precession (Larmor frequency).

For hydrogen atom γ=4257 Hz/Gauss, at B_o= 1.5 Tesla. The Larmor frequency is 63.855MHz.

Quantum mechanics tell us that a nucleus of spin I will have 2I+1 possible orientation. A nucleus with spin 1/2 will have 2 possible orientations. In absence of an external magnetic field, these orientations are of equal energy, if magnetic field is applied, then the energy levels split. Each level is given a magnetic quantum number m.



Figure(6) : Higher energy anti parallel to magnetic field m=-1/2, lower energy parallel m=+1/2.

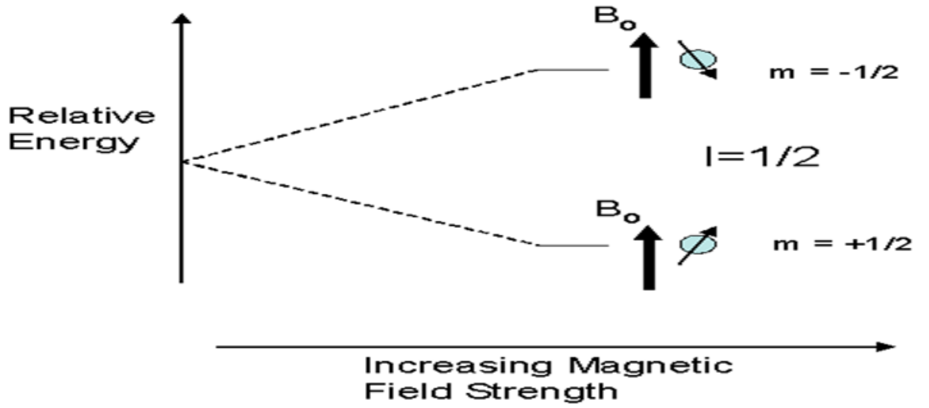
The difference in energy between levels (the transition energy) can be found from:

$$\Delta E = \gamma h B_o/2\pi$$

A nucleus(of spin 1/2) in a magnetic field is lower energy level.

2-Absorption of radiation by a nucleus in a magnetic field:

In order to create an MR signal which can be detected, a resonance condition must be established. In other words, there must exist a situation of alternating absorption and dissipation of energy, is the external static magnetic field B_o nuclei can be shifted from the parallel to anti parallel alignment by the application of radio frequency energy.



Figure(7): Nuclei can be shifted from paralle to anti parallel alignment by the application of radio frequency energy.

Application of radio frequency (RF) magnetic field at the Larmor frequency results in energy absorption,

while RF energy applied at other frequencies has no effect. If we consider an RF magnetic field. B_1, applied perpendicular to B_o, the system will absorb energy and begin to precess about the B_1 axis.

If the RF energy is pulsed, the net magnetization is rotated to a certain angle away from the B_o axis. This angle is referred to the flip angle and is proportional to the duration and amplitude of the RF pulse. Upon termination of the RF pulse, the nuclei return to there original alignment parallel to the applied static field and energy emitted in the form of a weak RF signal. The frequency of the emitted signal depends on the strength of the applied static magnetic field as well as the type of nuclei producing the signal. Detection and analysis of this signal provide insight into the chemical composition of the material. The process of alternating absorption and emission of RF energy by the material termed magnetic resonance (MR).

At the end of the applied RF pulse, the RF signal emitted by the material is at its maximum intensity. The signal intensity diminishes rapidly (within a few hundred milliseconds) as the higher energy state (the anti parallel state) is depopulated and the nuclei return to their original state.

This RF signal is picked up by a receiver coil. The waveform of this signal is an exponentially damped

sine wave and is called the free induction decay (Figure7).

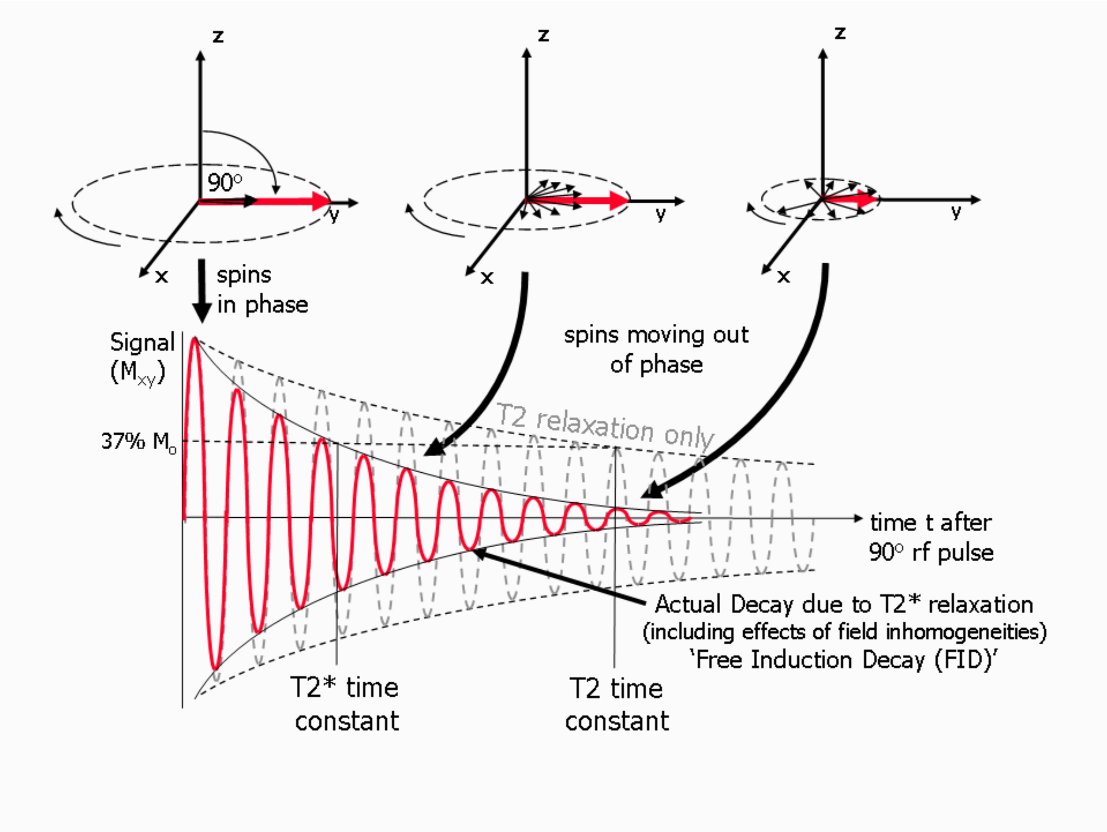
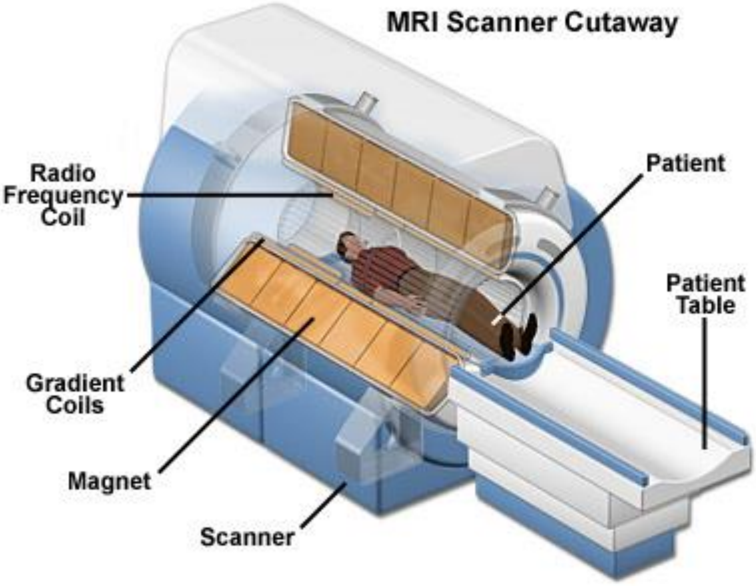


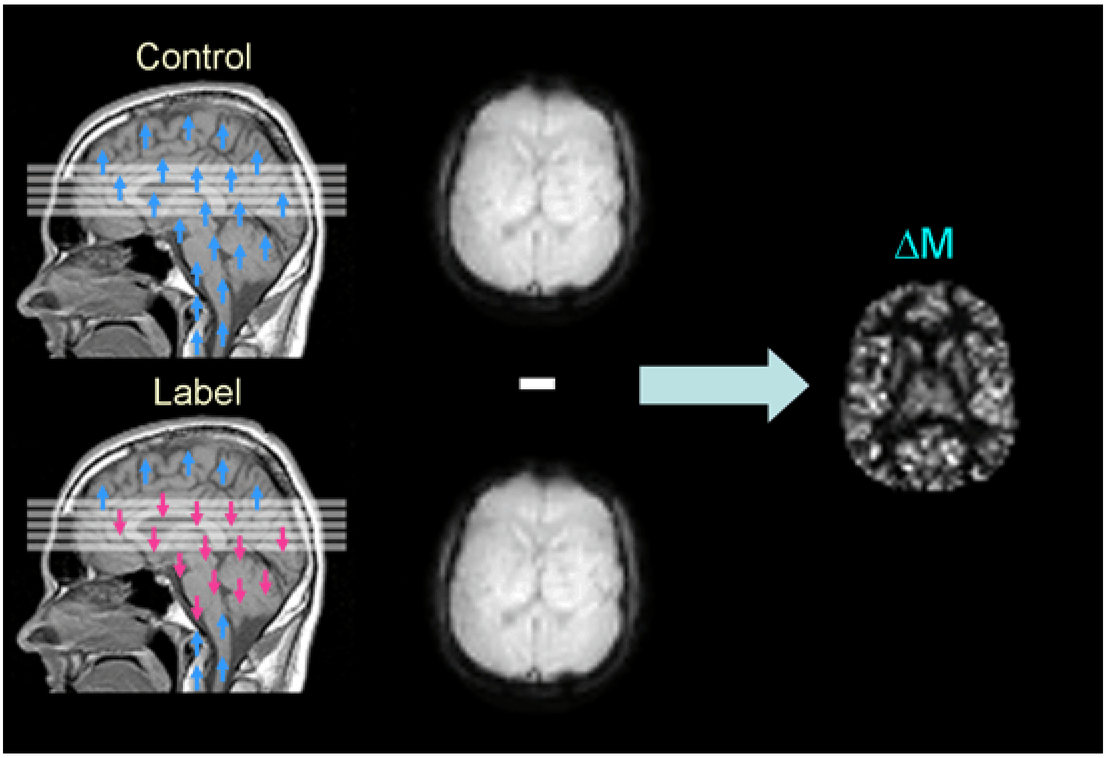
Figure7: The voltage signal induced in the receiver coil versus time.

In order to produce an image, each MR signal must be referenced to a specific region of tissue. This is accomplished by applying a gradient magnetic field in which the field strength varies linearly with position. The gradient gradually varies the magnetic field strength resulting in a corresponding shift in the RF frequency needed to stimulate the tissue.

Since emitted RF signals will also demonstrate a shift in frequency, the excited tissue from which signals originated can be localized.

Using computer-aided reconstruction program, similar to that used in computer tomography, the signals attributed to individual volume elements of tissue can be resolved and reconstruction is the two dimensional Fourier transform.



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