Lecture Two

MRI DESIGN: 5. Resonance and signal generation

Resonance is an energy transition that occurs when an object is subjected to a frequency the same as its own. Resonance is induced by applying a **radiofrequency (RF) pulse**:

- at the same frequency as the precessing magnetic moment's hydrogen spins;
- at 90° to B_0.

This causes the hydrogen spins to resonate (receive energy from the RF pulse), whereas other types of MR active nuclei do not resonate. As their gyromagnetic ratios are different from that of hydrogen, their precessional frequencies are also different from that of hydrogen. They only resonate if RF at their specific precessional frequency is applied. As RF is only applied at the same frequency as the precessional frequency of hydrogen, only hydrogen spins resonate. The other types of MR active nuclei do not. Two things happen to the hydrogen spins at resonance: *energy absorption and phase coherence.*

Energy absorption

The energy and frequency of electromagnetic radiation (including RF) are related to each other and, consequently, the frequency required to cause resonance is related to the difference in energy between the high- and low-energy populations and thus the strength of B_0 (Table 5.1). The spin-up, low-energy hydrogen spins absorb energy from the RF pulse (excitation pulse) and move into the high-energy population. At the same time, the spin-down, high-energy spins give energy away and return to the low-energy state. As there are more low-energy spins, the net effect is of energy absorption. This absorption of applied RF energy at 90° to B_0 causes a *net increase* in the number of high-energy, spin-down nuclei compared to the pre-resonant state (Figure 5.1).

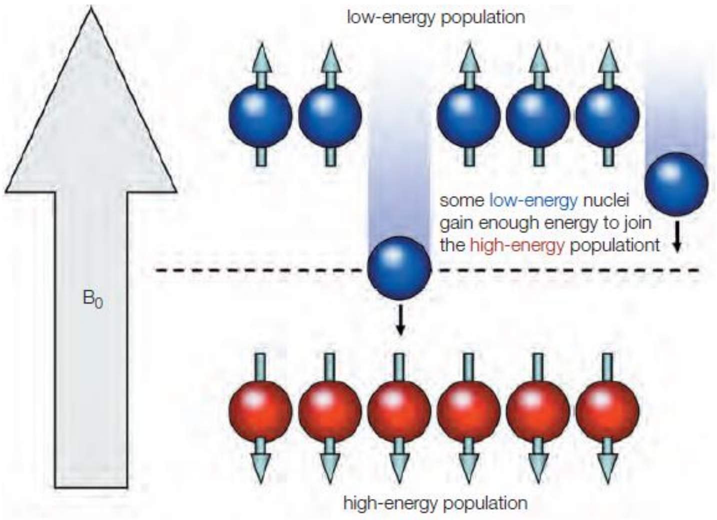


Figure 5.1 Energy transfer during excitation.

If just the right amount of energy is applied, the number of nuclei in the spin-up position equals the number in the spin-down position. As a result, the NMV (which represents the balance between spin-up and spin-down nuclei) lies in a plane at 90° to the external field (the **transverse plane**) as the net magnetization lies between the two energy states. As the NMV has been moved through 90° from B_0, it has a **flip or tip angle** of 90° (Figure 5.2).

Table 5.1 Common equations of resonance.

Equations		
$E = h\,\omega_0$	E is the energy of a photon (Joules, J) h is Planck's constant (6.626×10^{34} J/s) ω_0 is the frequency of an electromagnetic wave (Hz)	Planck's constant relates the energy of a photon of electromagnetic radiation to its frequency. Photons are both particles that possess energy and at the same time behave like waves that have frequency (wave particle duality).
$\Delta E = h\omega_0 = h\gamma B_0$	ΔE is the energy difference between the spin-up and spin-down populations h is Planck's constant (6.626×10^{34} J/s) ω_0 is the precessional or Larmor frequency (MHz) γ is the gyromagnetic ratio (MHz/T).	This equation shows that when the energy of the photon matches the energy difference between the spin-up and spin-down populations, energy absorption occurs. This is proportional to the magnetic field strength B_0.

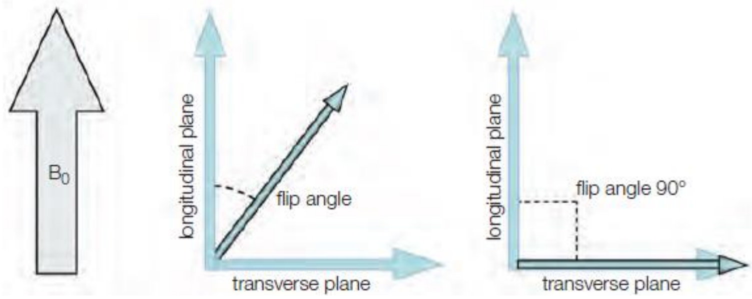


Figure 5.2 The flip angle. What flip angle gives maximum transverse magnetization?

Phase coherence

The magnetic moments of the spins move into phase with each other. As the magnetic moments of the spins are in phase in both the spin-up and spin-down positions and the spin-up nuclei are in phase with the spin-down nuclei, the net effect is one of precession, so the NMV precesses in the transverse plane at the Larmor frequency.

Important note:

When a patient is placed in the magnet and is scanned, hydrogen spins do not move. Spins are not flipped onto their sides in the transverse plane and neither are their magnetic moments. Only the magnetic moments of the spins move, aligning either with or against B_0. This is because hydrogen can only have two energy states, high or low. It is the NMV that lies in the transverse plane, not the magnetic moments, nor the spins themselves.

The MR signal:

A receiver coil is situated in the transverse plane. As the NMV rotates around the transverse plane as a result of resonance, it passes across the receiver coil, inducing a voltage in it. This voltage is the **MR signal** (Figure 5.3).

After a short period of time the RF pulse is removed. The signal induced in the receiver coil begins to decrease. This is because the in-phase component of the NMV in the transverse plane, which is passing across the receiver coil, begins to decrease as an increasingly higher proportion of spins become out of phase with each other. The amplitude of the voltage induced in the receiver coil therefore decreases. This is called **free induction decay** or **FID**:

- 'free' because of the absence of the RF pulse;
- 'induction decay' because of the decay of the induced signal in the receiver coil.

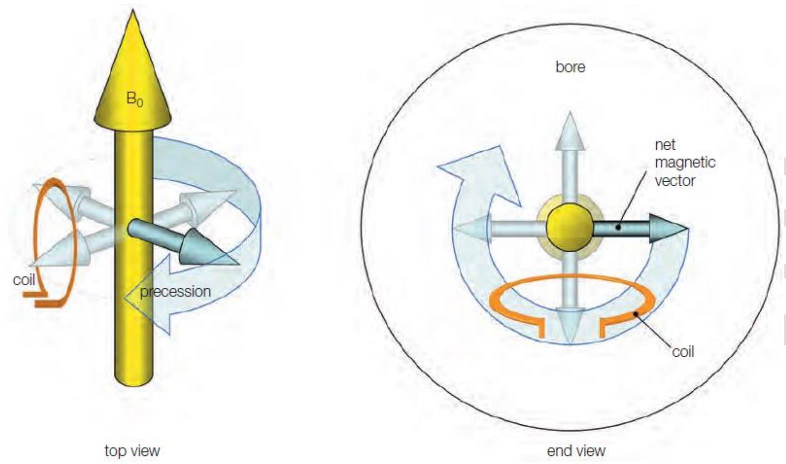


Figure 5.3 Generation of the MR signal. Why would you expect it to be alternating?

KEY POINTS

✓ The application of RF energy at the Larmor frequency causes a net absorption of energy (excitation) and changes the balance between the number of spins in the low- and high-energy populations.

✓ The orientation of the NMV to B_0 depends on this balance. If there are a similar number of spins in each population, the NMV lies in a plane at 90° to B_0 (transverse plane).

✓ Resonance also causes the magnetic moments of all spins to precess in phase. The result is coherent transverse magnetization that precesses in the transverse plane at the Larmor frequency.

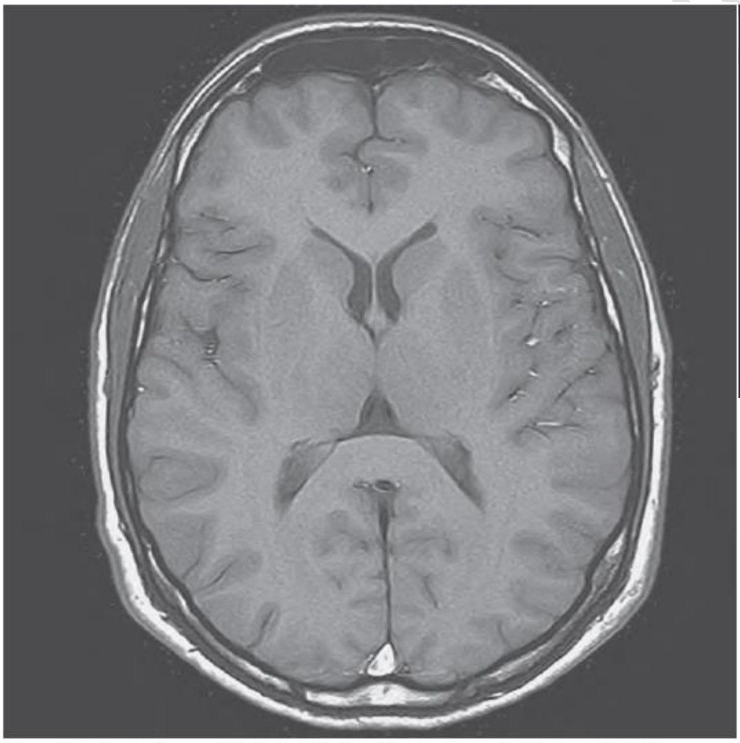
✓ If a receiver coil (conductor) is placed in the transverse plane, the movement of the rotating coherent transverse magnetization causes a voltage to be induced in the coil.

✓ When the RF excitation pulse is removed, the magnetic moments of all spins dephase and produce a FID.

MRI DESIGN: 6. Contrast Mechanisms

What is contrast?

An image has contrast if there are areas of high signal (white on the image), as well as areas of low signal (dark on the image). Some areas have an intermediate signal (shades of grey, between white and black). The NMV can be separated into the individual vectors of the tissues present in the patient, such as fat, cerebrospinal fluid (CSF), grey matter and white matter (Figure 6.1). The contrast to noise ratio (CNR) is an important image quality parameter and relates to the difference in signal between two adjacent areas. Images demonstrating a good CNR contain large differences in signal intensity. Images demonstrating poor CNR do not.



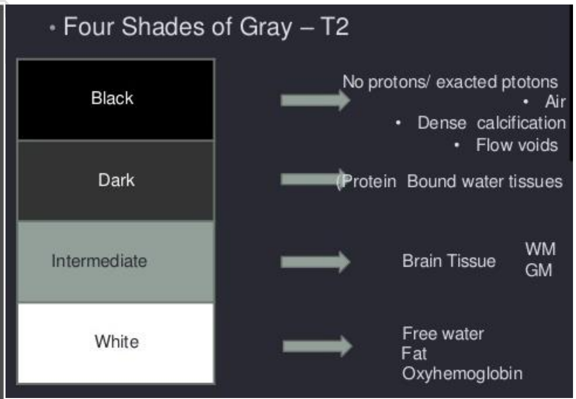


Figure 6.1 An axial image of the brain. Note the difference in contrast between CSF, fat, grey and white matter.

The determinant of signal intensity in MRI is the magnitude of precessing coherent transverse magnetization that cuts through the windings of the receiver coil when the signal is measured. This is because the amplitude of voltage induced in a conductor depends on the amplitude of the transverse magnetic field.

A tissue has a *high signal (white, hyper-intense)* if it has a *large transverse component of magnetization* when the signal is measured. If there is a large component of transverse magnetization, the amplitude of the magnetization that cuts the coil is large, and the signal induced in the coil is also large.

A tissue has a *low signal (black, hypo-intense)* if it has a *small transverse component of magnetization* when the signal is measured. If there is a small component of transverse magnetization, the amplitude of the magnetization that cuts the coil is small, and the signal induced in the coil is also small.

A tissue has an intermediate signal (grey, iso-intense) if it has a medium transverse component of magnetization when the signal is measured.

Image contrast is determined by the difference in signal intensity between tissues. This is controlled by various parameters (Table 6.1).

Table 6.1 Common equations of contrast mechanisms.

Equations		
$SI= PD\ e^{-TE/T2}(1-e^{-TR/T1})$	SI is the signal intensity in a tissue PD is proton density TE is the echo time (ms) T2 is the T2 relaxation time of the tissue (ms) TR is the repetition time (ms) T1 is the T1 relaxation time in the tissue (ms)	This equation shows why the signal intensity from a tissue depends on intrinsic and extrinsic contrast parameters. In gradient echo sequences the flip angle is added to this equation and T2 is referred to as T2*

Extrinsic contrast parameters

These parameters are controlled by the operator. They are:

- **Repetition time (TR)**: This is the time from the application of one RF pulse to the application of the next for a particular slice. It is measured in milliseconds (ms). The TR affects the length of a relaxation period in a particular slice after the application of one RF excitation pulse to the beginning of the next (see Figure 6.2).
- **Time to echo (TE)**: This is the time between an RF excitation pulse and the collection of the signal. The TE affects the length of the relaxation period after the removal of an RF excitation pulse and the peak of the signal received in the receiver coil. It is also measured in ms (Figure 6.2).
- **Flip angle**: This is the angle through which the NMV is moved as a result of an RF excitation pulse (Figure 5.2).
- **Turbo-factor (TF)** or **echo train length (ETL)**: the number of echoes acquired after each excitation.
- **Time from inversion (TI)**: the time between the 180° inverting pulse and the 90°-pulse
- **'b' value**: parameter that defines gradient strength and duration, hence determines the degree of diffusion weighting.

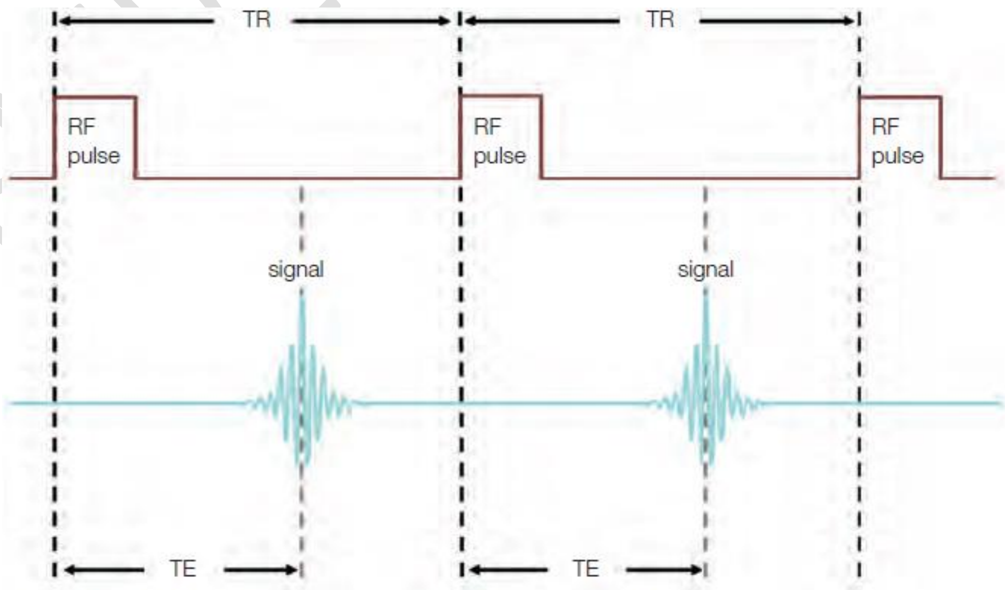


Figure 6.2 A basic pulse sequence showing TR and TE intervals.

Intrinsic contrast mechanisms

These parameters are inherent to the tissue and are not controlled by the operator. They are:

- T1 recovery time.
- T2 decay time.
- proton density.
- flow: the quantity of blood (cm^3/sec) passes a point at certain time.
- apparent diffusion coefficient (ADC): is a measure of the magnitude of diffusion (of water molecules) within tissue, and is commonly clinically calculated using MRI with diffusion-weighted imaging (DWI)

The composition of fat and water

All substances possess molecules that are constantly in motion. This molecular motion is made up of rotational and transitional movements and is called **Brownian motion**. The faster the molecular motion, the more difficult it is for a substance to release energy to its surroundings.

Fat comprises hydrogen atoms mainly linked to carbon that make up large molecules. The large molecules in fat are closely packed together and have a slow rate of molecular motion due to the inertia of the large molecules. They also have low inherent energy which means they are able to absorb energy efficiently.

Water comprises hydrogen atoms linked to oxygen. It consists of small molecules that are spaced far apart and have a high rate of molecular motion. They have a high inherent energy which means they are not able to absorb energy efficiently.

Because of these differences, tissues that contain fat and water produce different image contrast. This is because there are different **relaxation** rates in each tissue.

KEY POINTS

- ✓ The Contrast between tissues occurs because there is a different signal intensity between different tissues.
- ✓ Signal intensity depends on the amplitude of signal.
- ✓ Resonance also causes the magnetic moments of all spins to precess in phase. The result is coherent transverse magnetization that precesses in the transverse plane at the Larmor frequency.
- ✓ If a receiver coil (conductor) is placed in the transverse plane, the movement of the rotating coherent transverse magnetization causes a voltage to be induced in the coil.
- ✓ When the RF excitation pulse is removed, the magnetic moments of all spins dephase and produce a FID.

Note:

Precession: is the slow movement of the axis of a spinning body around another axis due to a torque acting to change the direction of the first axis.