# 1

# Basic principles

*After reading this chapter, you will be able to:*

- *Describe the structure of the atom.*
- *Explain the mechanisms of alignment and precession.*
- *Understand the concept of resonance and signal generation.*

## INTRODUCTION

The basic principles of magnetic resonance imaging (MRI) form the foundation for further understanding of this complex subject. It is important to grasp these ideas before moving on to more complicated topics in this book.

There are essentially two ways of explaining the fundamentals of MRI: classically and via quantum mechanics. **Classical theory** (accredited to Sir Isaac Newton and often called Newtonian theory) provides a mechanical view of how the universe (and therefore how MRI) works. Using classical theory, MRI is explained using the concepts of mass, spin, and angular momentum on a large or bulk scale. **Quantum theory** (accredited to several individuals including Max Planck, Albert Einstein, and Paul Dirac) operates at a much smaller, subatomic scale and refers to the energy levels of protons, neutrons, and electrons. Although classical theory is often used to describe physical principles on a large scale and quantum theory on a subatomic level, there is evidence that all physical principles are explained using quantum concepts [1]. However, for our purposes, this chapter mainly relies on classical perspectives because they are generally easier to understand. Quantum theory is only used to provide more detail when required.

*MRI in Practice*, Fifth Edition. Catherine Westbrook and John Talbot.

Companion Website: www.wiley.com/go/westbrook/mriinpractice

In this chapter, we explore the properties of atoms and their interactions with magnetic fields as well as the mechanisms of excitation and relaxation.

# ATOMIC STRUCTURE

All things are made of **atoms**. Atoms are organized into **molecules**, which are two or more atoms arranged together. The most abundant atom in the human body is **hydrogen**, but there are other elements such as oxygen, carbon, and nitrogen. Hydrogen 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 atom consists of a central nucleus and orbiting **electrons** (Figure 1.1). The nucleus is very small, one millionth of a billionth of the total volume of an atom, but it contains all the atom's mass. This mass comes mainly from particles called **nucleons**, which are subdivided into **protons** and **neutrons**. Atoms are characterized in two ways.

- The **atomic number** is the sum of the protons in the nucleus. This number gives an atom its chemical identity.
- The **mass number** or **atomic weight** is the sum of the protons and neutrons in the nucleus.

The number of neutrons and protons in a nucleus is usually balanced so that the mass number is an even number. In some atoms, however, there are slightly more or fewer neutrons than protons. Atoms of elements with the same number of protons but a different number of neutrons are called **isotopes**.

Electrons are particles that spin around the nucleus. Traditionally, this is thought of as analogous to planets orbiting around the sun with electrons moving in distinct shells. However, according to quantum theory, the position of an electron is not predictable as it depends on the energy of an individual electron at any moment in time (this is called Heisenberg's Uncertainty Principle).

Some of the particles in the atom possess an electrical charge. Protons have a positive electrical charge, neutrons have no net charge, and electrons are negatively charged. Atoms are electrically stable if the number of negatively charged electrons equals the number of positively charged protons. This balance is sometimes altered by applying energy to knock out electrons from the atom. This produces a deficit in the number of electrons compared with protons and causes electrical instability. Atoms in which this occurs are called **ions** and the process of knocking out electrons is called **ionization**.

# MOTION IN THE ATOM

Three types of motion are present within the atom (Figure 1.1):

- Electrons spinning on their own axis
- Electrons orbiting the nucleus
- The nucleus itself spinning about its own axis.

The principles of MRI rely on the spinning motion of specific nuclei present in biological tissues. There are a limited number of spin values depending on the atomic and mass numbers. A nucleus has no spin if it has an even atomic and mass number, e.g. six protons and six neutrons, mass number 12. In nuclei that have an even mass number caused by an even number of protons and neutrons, half of the nucleons spin in one direction and half in the other. The forces of rotation cancel out, and the nucleus itself has no net spin.

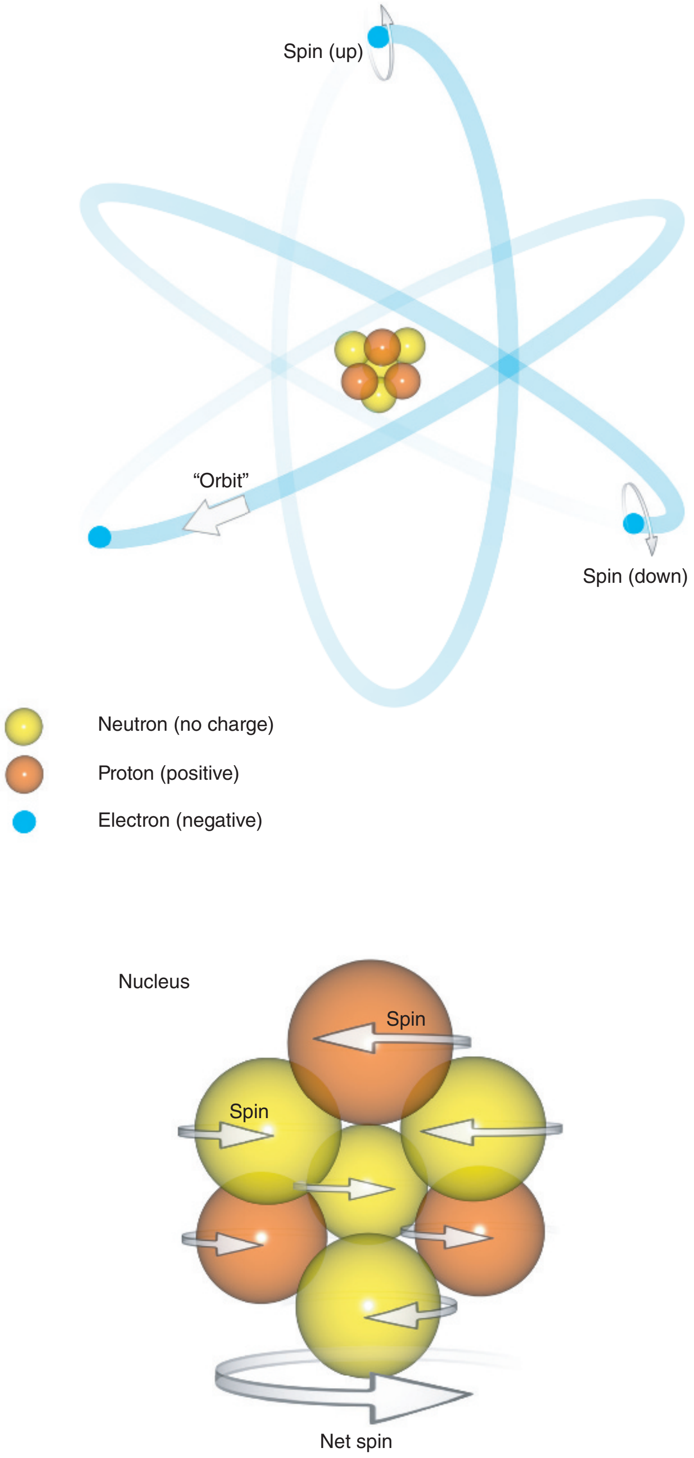


**Figure 1.1** The atom.

However, in nuclei with an odd number of protons, an odd number of neutrons, or an odd number of both protons and neutrons, the spin directions are not equal and opposite, so the nucleus itself has a net spin or **angular momentum**. Typically, these are nuclei that have an odd number of protons (or odd atomic number) and therefore an odd mass number. This means that their spin has a half-integral value, e.g. ½, $^5/_2$. However, this phenomenon also occurs in nuclei with an odd number of both protons and neutrons resulting in an even mass number. This means that it has a whole integral spin value, e.g. 1, 2, 3. Examples are $^6$lithium (which is made up of three protons and three neutrons) and $^{14}$nitrogen (seven protons and seven neutrons). However, these elements are largely unobservable in MRI so, in general, only nuclei with an odd mass number or atomic weight are used. These are known as **MR-active nuclei**.

### Learning tip:
### What makes a proton spin and why is it charged?

On a subnuclear level, individual protons are made up of quarks, each of which possesses the characteristics of alignment and spin. The net charge and spin of a proton are a consequence of its quark composition. The proton consists of three spinning quarks. Two quarks spin up and the other spins down. The net spin of the proton (1/2) is caused by the different alignment of the quarks. The net charge of the proton is caused by each spin-up quark having a charge of + 2/3, while the spin-down quark has a charge of – 1/3 (total charge + 1) [2].

## MR-ACTIVE NUCLEI

MR-active nuclei are characterized by their tendency to align their axis of rotation to an applied magnetic field. This occurs because they have angular momentum or spin and, as they contain positively charged protons, they possess an electrical charge. The law of electromagnetic induction (determined by Michael Faraday in 1833) refers to the connection between electric and magnetic fields and motion (explained later in this chapter). Faraday's law determines that a moving electric field produces a magnetic field and vice versa.

MR-active nuclei have a net electrical charge (electric field) and are spinning (motion), and, therefore, automatically acquire a magnetic field. In classical theory, this magnetic field is denoted by a **magnetic moment**. The magnetic moment of each nucleus has vector properties, i.e. it has size (or magnitude) and direction. The total magnetic moment of the nucleus is the vector sum of all the magnetic moments of protons in the nucleus.

Important examples of MR-active nuclei, together with their mass numbers are listed below:

- $^1$H (hydrogen)
- $^{13}$C (carbon)
- $^{15}$N (nitrogen)
- $^{17}$O (oxygen)
- $^{19}$F (fluorine)
- $^{23}$Na (sodium).

**Table 1.1** Characteristics of common elements in the human body.

| Element | Protons | Neutrons | Nuclear spin | % Natural abundance |
|---|---|---|---|---|
| $^{1}$H (protium) | 1 | 0 | 1/2 | 99.985 |
| $^{13}$C (carbon) | 6 | 7 | 1/2 | 1.10 |
| $^{15}$N (nitrogen) | 7 | 8 | 1/2 | 0.366 |
| $^{17}$O (oxygen) | 8 | 9 | 5/2 | 0.038 |

# THE HYDROGEN NUCLEUS

The isotope of hydrogen called **protium** is the most commonly used MR-active nucleus in MRI. It has a mass and atomic number of 1, so the nucleus consists of a single proton and has no neutrons. It is used because hydrogen is very abundant in the human body and because the solitary proton gives it a relatively large magnetic moment. These characteristics mean that the maximum amount of available magnetization in the body is utilized.

Faraday's law of electromagnetic induction states that a magnetic field is created by a charged moving particle (that creates an electric field). The protium nucleus contains one positively charged proton that spins, i.e. it moves. Therefore, the nucleus has a magnetic field induced around it and acts as a small magnet. The magnet of each hydrogen nucleus has a north and a south pole of equal strength. The north/south axis of each nucleus is represented by a magnetic moment and is used in classical theory.

In diagrams in this book, the magnetic moment is shown by an arrow. The length of the arrow represents the magnitude of the magnetic moment or the strength of the magnetic field that surrounds the nucleus. The direction of the arrow denotes the direction of alignment of the magnetic moment as in Figure 1.2.

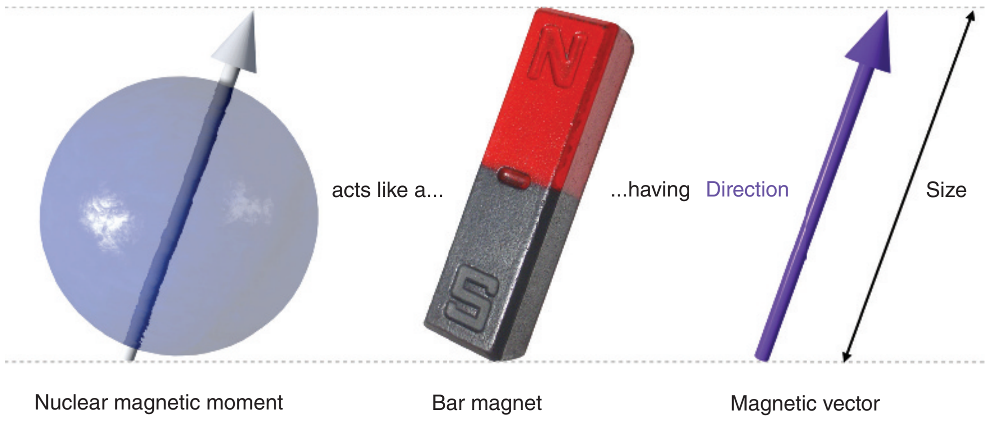


**Figure 1.2** The magnetic moment of the hydrogen nucleus.

### Learning tip:
### Use of terms – MRI active nuclei

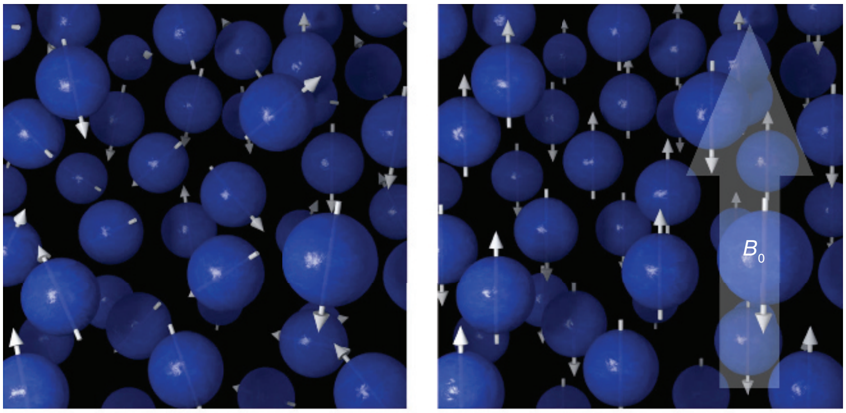
From now on in this book, the terms spin, nucleus, or proton are all used when we refer to the $^1$H nucleus, protium. However, it is important to remember that the other types of MR-active nuclei behave in a similar way when exposed to an external magnetic field. Some of these, phosphorous, sodium, and carbon, are used in certain MRI applications, but the majority use protium.

**Table 1.2** Things to remember – basics of the atom.

| |
|---|
| Hydrogen is the most abundant element in the human body |
| Nuclei that are available for MRI are those that exhibit a net spin |
| As all nuclei contain at least one positively charged proton, those that also spin have a magnetic field induced around them |
| An arrow called a magnetic moment denotes the magnetic field of a nucleus in classical theory |

# ALIGNMENT

In the absence of an applied magnetic field, the magnetic moments of hydrogen nuclei are randomly orientated and produce no overall magnetic effect. However, when placed in a strong static external magnetic field (shown as a white arrow on Figure 1.3 and termed $\boldsymbol{B}_0$), the magnetic moments of hydrogen nuclei orientate with this magnetic field. This is called **alignment**. Alignment is best described using classical and quantum theories as follows.



Random alignment
No external field

Alignment
External magnetic field

**Figure 1.3** Alignment – classical theory.

Classical theory uses the *direction of the magnetic moments* of spins (hydrogen nuclei) to illustrate alignment.

- **Parallel alignment:** Alignment of magnetic moments in the same direction as the main $B_0$ field (also referred to as spin-up).
- **Antiparallel alignment:** Alignment of magnetic moments in the opposite direction to the main $B_0$ field (also referred to as spin-down) (Figure 1.3).

After alignment, there are always more spins with their magnetic moments aligned parallel than antiparallel. The net magnetism of the patient (termed the **net magnetic vector**, **NMV**) is therefore aligned parallel to the main $B_0$ field in the **longitudinal plane** or ***z*-axis**.

## Learning tip: Magnetic moments vs hydrogen nucleus

A very common misunderstanding is that when a patient is exposed to $B_0$, the hydrogen nucleus itself aligns with the external magnetic field. This is incorrect. It is the magnetic moments of hydrogen nuclei that align with $B_0$ not hydrogen nuclei themselves. The hydrogen nucleus does not change direction but merely spins on its axis.

Quantum theory uses the *energy level* of the spins (or hydrogen nuclei) to illustrate alignment. Protons of hydrogen nuclei couple with the external magnetic field $B_0$ (termed **Zeeman interaction**) and cause a discrete number of energy states. For hydrogen nuclei, there are only two possible energy states (Figure 1.4):

- **Low-energy nuclei** do not have enough energy to oppose the main $B_0$ field (shown as a white arrow on Figure 1.4). These are nuclei that align their magnetic moments parallel or spin-up to the main $B_0$ field in the classical description (shown in blue in Figure 1.4).
- **High-energy nuclei** do have enough energy to oppose the main $B_0$ field. These are nuclei that align their magnetic moments antiparallel or spin-down to the main $B_0$ field in the classical description (shown in red in Figure 1.4).

Quantum theory explains why hydrogen nuclei only possess two energy states – high or low (Equation (1.1)). This means that the magnetic moments of hydrogen spins only align in the parallel or antiparallel directions. They cannot orientate themselves in any other direction. The number of spins in each energy level is predicted by the **Boltzmann equation** (Equation (1.2)). The difference in energy between these two states is proportional to the strength of the external magnetic field ($B_0$) ($\Delta E$ in the Boltzmann equation). As $B_0$ increases, the difference in energy between the two energy states increases, and nuclei therefore require more energy to align their magnetic moments in opposition to the main field. Boltzmann's equation also shows that the patient's temperature is an important factor that determines whether a spin is in the high- or low-energy population. In clinical imaging, however, thermal effects are largely discounted, as the patient's temperature is usually similar inside and outside the magnetic field. This is called **thermal equilibrium**.

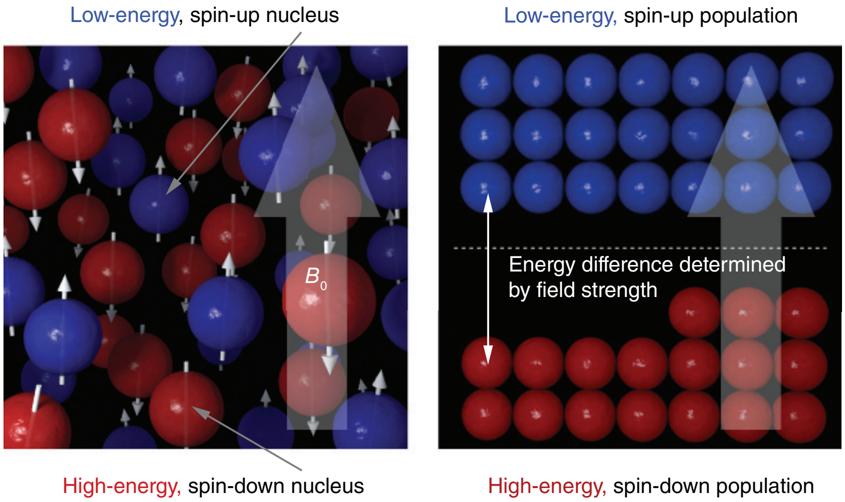


**Figure 1.4** Alignment – quantum theory.

**Equation 1.1**

| | | |
|---|---|---|
| Number of energy states = 2S + 1 | S is the spin quantum number. The value of S for hydrogen is ½ | This equation explains why hydrogen can only possess two energy states. If S = ½, then the number of energy states is 2 × ½ + 1 = 2 |

### Learning tip: What is $B_0$?

$B_0$ refers to the large magnetic field of the MRI scanner. This static magnetic field is measured in teslas (T) using the Systeme Internationale (SI). B is the universally accepted notation for magnetic flux density, and the zero annotation indicates that this is primary magnetic field of the scanner. Other magnetic fields are also used in MRI. These include graded or sloped magnetic fields (called gradients, used to produce images) and an oscillating magnetic field that causes a phenomenon called resonance. This oscillating field is termed $B_1$. It has a magnitude several orders lower than $B_0$ (milliteslas as opposed to teslas).

## NET MAGNETIC VECTOR (NMV)

Magnetic moments of hydrogen spins are constantly changing their orientation because, due to Zeeman interaction, they are always moving between high- and low-energy states. Spins gain and lose energy, and their magnetic moments therefore constantly alter their alignment relative to $B_0$. In thermal equilibrium, at any moment in time, there are a greater proportion of spins with their magnetic moments aligned in the same direction as $B_0$ than against it. As there is a larger number aligned parallel, there is always a small excess in this direction that produces a net magnetic moment (Figure 1.5). This is called the NMV and reflects the relative balance between spin-up and spin-down nuclei. It is the sum of all magnetic moments of excess spin-up nuclei and is measurable (in the order of microteslas) [3]. It aligns in the same direction as the main magnetic field in the longitudinal plane or *z*-axis.

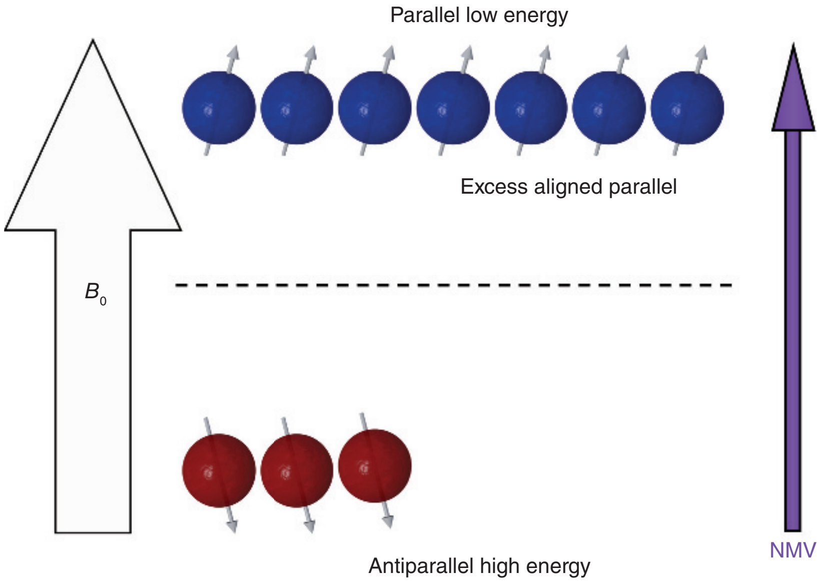


**Figure 1.5** The net magnetic vector.

The number of spins that constitute this small excess depends on the number of molecules per gram of tissue and the strength of $B_0$. According to Avogadro's law, there are about $6 \times 10^{23}$ molecules per gram of tissue, and the number of excess spins is in the order of $6 \times 10^{17}$ per gram of tissue [4]. In thermal equilibrium, the strength of the external field also determines the relative quantities of spin-up to spin-down nuclei because this also affects the difference in energy levels between the two energy states (see Equation (1.2)). As the magnitude of the external magnetic field increases, more magnetic moments line up in the parallel direction because the amount of energy spins must possess to align their magnetic moments in opposition to the stronger field (and line up in the antiparallel direction) increases. As the field strength increases, fewer spins possess enough energy to align their magnetic moments in opposition to the larger $B_0$ field. As a result, the low-energy population increases in size, the high-energy population decreases in size, and therefore the number of excess number of spins also increases. At 1.5 T, the number in excess is about 4.5 for every million protons; at 3 T, this increases to about 10 per million [5]. Consequently, the NMV also increases in size and is one of the reasons why the signal-to-noise ratio (SNR) increases at higher field strengths (see Chapter 7).

**Equation 1.2**

| | | |
|---|---|---|
| $N^+ / N^- = e^{-\Delta E / kT}$ | $N^+$ and $N^-$ are the number of spins in the high- and low-energy populations, respectively.<br>$\Delta E$ is the energy difference between the high- and low-energy populations in Joules (J)<br>$k$ is Boltzmann's constant ($1.381 \times 10^{-23}$ J/K)<br>$T$ is the temperature of the tissue in Kelvin (K) | This equation enables prediction of the number of spins in the high- and low-energy populations and how this is dependent on temperature. In MRI, thermal equilibrium is presumed in that there are no significant changes in body temperature in the scan room |

**Table 1.3** Things to remember – alignment.

| |
|---|
| When placed in an external magnetic field, the magnetic moments of hydrogen align in a spin-up, low-energy or spin-down, high-energy orientation |
| At thermal equilibrium, there are more spin-up, low-energy than spin-down, high-energy spins so the net magnetic vector (NMV) of the patient is orientated in the same direction as $B_0$ |
| The difference in energy between these populations is mainly determined by the strength of $B_0$ |
| As $B_0$ increases the energy difference between the two populations also increases as the number of spin-up, low-energy spins increases relative to the number of spin-down, high-energy spins |
| The signal-to-noise ratio (SNR) increases at higher values of $B_0$ (see Chapter 7) |

# PRECESSION AND PRECESSIONAL (LARMOR) FREQUENCY

Each hydrogen nucleus spins on its axis as in Figure 1.6. The influence of $B_0$ produces an additional spin or wobble of the magnetic moments of hydrogen around $B_0$. This secondary spin is called **precession** and causes the magnetic moments to circle around $B_0$. The course they take is called the **precessional path**, and the speed at which they precess around $B_0$ is called the **precessional frequency**. The precessional frequency is often called the **Larmor frequency** because it is determined by the **Larmor equation** (Equation (1.3)). The unit of precessional frequency is hertz (Hz) where 1 Hz is one cycle or rotation per second (s), and 1 megahertz (MHz) is one million cycles or rotations per second. The magnetic moments of all spin-up and spin-down nuclei precess around $B_0$ on a precessional path at a Larmor frequency determined by $B_0$ (Figure 1.7).

| Equation 1.3 | | |
|---|---|---|
| $\omega_0 = \gamma B_0/2\pi$ simplified to $\omega_0 = \gamma B_0$ | $\omega_0$ is the precessional or Larmor frequency (MHz)<br>$\gamma$ is the gyromagnetic ratio (MHz/T)<br>$B_0$ is the strength of the external magnetic field (T) | This is the Larmor equation. The $2\pi$ function enables the conversion of $\omega_0$ from angular to cyclical frequency. As $\gamma$ is a constant, for a given MR-active nucleus $\omega_0$ is proportional to $B_0$ |

The **gyromagnetic ratio** expresses the relationship between angular momentum and the magnetic moment of each MR-active nucleus. It is constant and is expressed as the precessional frequency of the magnetic moment of a specific MR-active nucleus at 1 T. The unit of the gyromagnetic ratio is therefore MHz/T. The gyromagnetic ratio of hydrogen is 42.58 MHz/T. Other MR-active nuclei have different gyromagnetic ratios, so their magnetic moments have different precessional frequencies at the same field strength (Table 1.4).

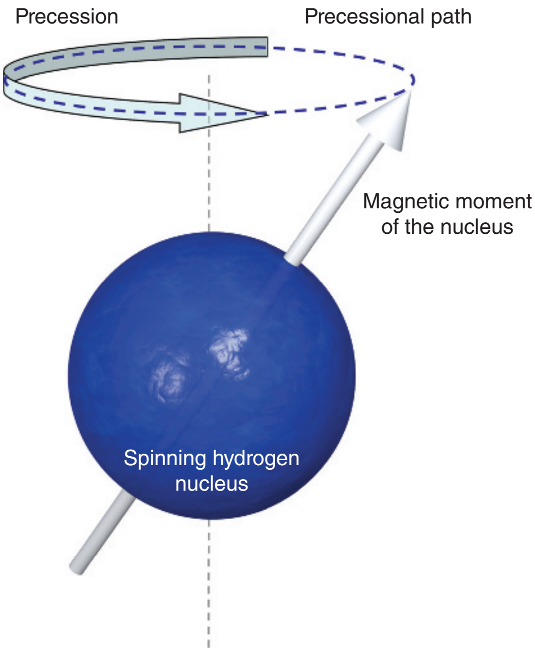


**Figure 1.6** Precession.

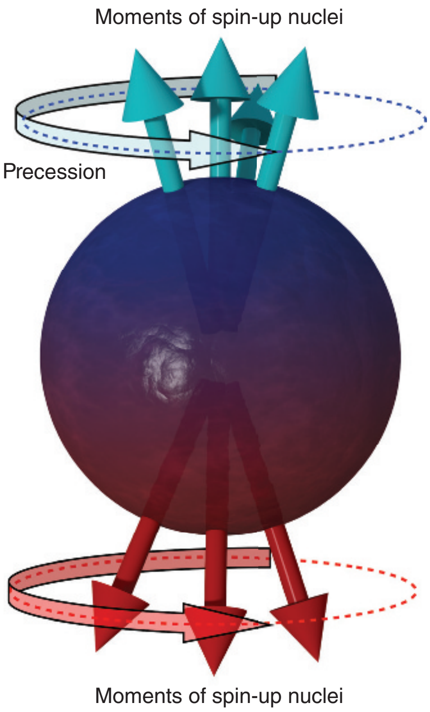


**Figure 1.7** Precession of the spin-up and spin-down populations.

**Table 1.4** Magnetic characteristics of common elements.

| Element | Nuclear spin | Gyromagnetic ratio (MHz/T) | Larmor frequency at 1.5 T (MHz) |
|---|---|---|---|
| $^{1}H$ (hydrogen) | 1/2 | 42.5774 | 63.8646 |
| $^{13}C$ (carbon) | 1/2 | 10.7084 | 16.0621 |
| $^{15}N$ (nitrogen) | 1/2 | 4.3173 | 6.4759 |
| $^{17}O$ (oxygen) | 5/2 | 5.7743 | 8.6614 |

In addition, magnetic moments of MR-active nuclei have different precessional frequencies at different field strengths. For hydrogen, for example:

- At 1.5 T, the precessional frequency is 63.87 MHz (42.58 MHz × 1.5 T).
- At 1.0 T, the precessional frequency is 42.57 MHz (42.58 MHz × 1.0 T).
- At 0.5 T, the precessional frequency is 21.29 MHz (42.58 MHz × 0.5 T).

These frequencies fall into the **radiofrequency (RF)** band of the electromagnetic spectrum (Figure 1.8).

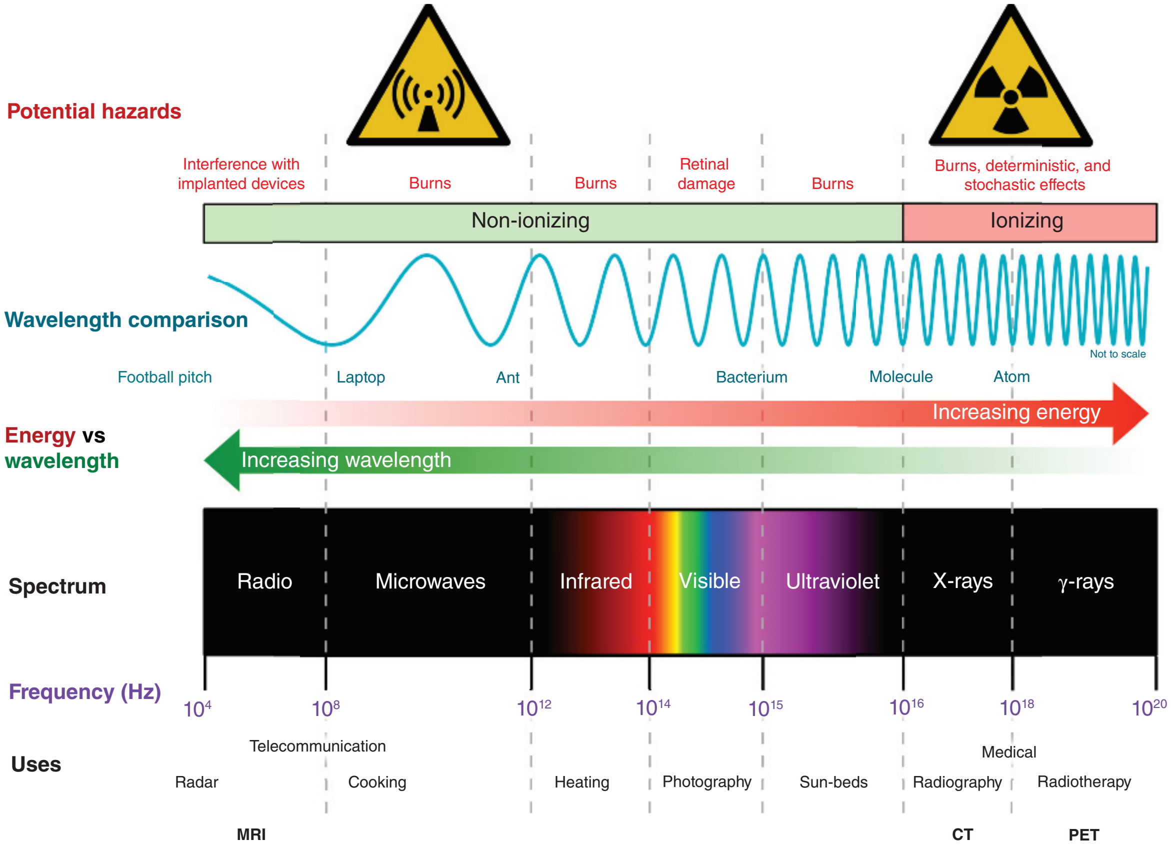


**Figure 1.8** The electromagnetic spectrum.

## Learning tip:
## What does the Larmor equation tell us?

All MR-active nuclei have their own unique gyromagnetic constant or ratio so that when they are exposed to the same field strength, their magnetic moments precess at different frequencies, i.e. magnetic moments of hydrogen precess at a different frequency to magnetic moments of either fluorine or carbon, which are also MR-active nuclei. This allows specific imaging of hydrogen. Other MR-active nuclei are ignored because the precessional or Larmor frequency of their magnetic moments is different to that of hydrogen (we explore how this is done later). In addition, as the gyromagnetic ratio is a constant of proportionality, $B_0$ is proportional to the Larmor frequency. Therefore, if $B_0$ increases, the Larmor frequency increases proportionally and vice versa.

# PRECESSIONAL PHASE

**Phase** refers to the position of magnetic moments on their precessional path at any moment in time. The unit of phase is a **radian**. A magnetic moment travels through 360 rad or 360° during one rotation. In this context, **frequency** is the rate of change phase of magnetic moments, i.e. it is a measure of how quickly the phase position of a magnetic moment changes over time. In MRI, the relative phase positions of all magnetic moments of hydrogen are important.

- **Out of phase** or **incoherent** means that magnetic moments of hydrogen are at *different* places on the precessional path at a moment in time.
- **In phase** or **coherent** means that magnetic moments of hydrogen are at the *same* place on the precessional path at a moment in time.

When the only influence is $B_0$, the magnetic moments of the nuclei are out of phase with each other, and therefore the NMV does not precess.

**Table 1.5** Things to remember – precession.

| |
|---|
| Magnetic moments of all the spins precess around $B_0$ at the Larmor frequency that is proportional to $B_0$ for a given MR-active nucleus. Frequency therefore refers to how fast magnetic moments of spins are precessing and is measured in MHz in MRI |
| For field strengths used in clinical imaging, the Larmor frequency of hydrogen is in the radio-frequency (RF) band of the electromagnetic spectrum |
| Phase refers to the position of a magnetic moment of a spin on its precessional path at any moment in time |
| At equilibrium, the magnetic moments of the spins are out of phase with each other |

# RESONANCE

Resonance is a phenomenon that occurs when an object is exposed to an oscillating perturbation that has a frequency close to its own natural frequency of oscillation. When a nucleus is exposed to an external force that has an oscillation similar to the natural frequency of its magnetic moment (its Larmor frequency), the nucleus gains energy from the external source. If energy is delivered at a different frequency to that of the Larmor frequency, resonance does not occur, and the nucleus does not gain energy. As magnetic moments of hydrogen nuclei precess in the RF band of the electromagnetic spectrum, for resonance of hydrogen to occur, an RF pulse of energy is applied at the Larmor frequency of hydrogen. Other MR-active nuclei, whose magnetic moments are aligned with $B_0$, do not resonate, because the precessional frequencies of these magnetic moments are different to that of hydrogen. This is because their gyromagnetic ratios are different.

Resonance is achieved by transmitting an RF pulse called an **RF excitation pulse**. This is produced by a transmit coil (see Chapter 9). As with any type of electromagnetic radiation, it consists of an electric and magnetic field that propagate in waves at 90° to each other. These waves have a frequency that resides in the RF band of the electromagnetic spectrum. The RF excitation pulse is derived from the magnetic component only (the electric field produces heat), and unlike the $B_0$ field, which is stationary, the RF excitation pulse produces an oscillating magnetic field, termed $B_1$. The $B_1$ field is applied at 90° to $B_0$ at a narrow range or bandwidth of frequencies centered around a central frequency (termed the transmit bandwidth; see Chapters 5 and 6). The magnetic field associated with the RF excitation pulse $B_1$ is very weak compared with that of the main external field $B_0$ [6].

## The results of resonance – classical theory

From the classical theory perspective, application of the $B_1$field in a plane at 90° to $B_0$, termed the **transverse plane** or ***x–y*-axis**, causes magnetic moments of the spins to precess around this axis rather than about the longitudinal plane or *z*-axis. As we have just learned, the Larmor equation determines that precessional frequency is proportional to the field strength. As the $B_1$ magnetic field associated with the RF excitation pulse is weak, the magnetic moments of spins precess at a much lower frequency than they do when they are aligned in the longitudinal plane and experience the much larger $B_0$ field. The transition results in a spiral motion downward of the NMV from the longitudinal to the transverse plane. This spiral motion is called **nutation** and is caused by two precessional motions that happen simultaneously; precession around $B_0$ and a much slower precession around $B_1$ [7].

Another consequence of the RF excitation pulse is that the magnetic moments of the spin-up and spin-down nuclei move into phase with each other. Magnetic moments that are in phase (or coherent) are in the same place on their precessional path at any given time. When resonance occurs, all magnetic moments move to the same position on the precessional path and are then in phase (Figure 1.9).

## The results of resonance – quantum theory

Application of an RF pulse that causes resonance is termed **excitation**, which means it is "energy-giving." The RF excitation pulse gives energy to hydrogen nuclei and causes a net increase in the number of high-energy, spin-down nuclei (Figure 1.10). This is because the spin-up, low-energy hydrogen nuclei absorb energy from the RF excitation pulse and move into the high-energy population. At the same time, the spin-down, high-energy nuclei are stimulated to release energy and return to the low-energy state. However, because there are more low-energy spins, the net effect is of energy absorption [8].

## Learning tip:
## $B_0$ vs $B_1$

The RF excitation pulse is characterized by its amplitude ($B_1$) and its frequency. For resonance to occur, the frequency of the RF excitation pulse must equal the Larmor frequency of magnetic moments of the hydrogen nuclei. If this match occurs, $B_1$ causes magnetic moments of the hydrogen nuclei to precess in the transverse plane. How fast they precess in the transverse plane is derived from the Larmor equation, which states that precessional frequency is proportional to the field strength (see Equation (1.3)). As $B_1$ is much smaller than $B_0$, magnetic moments of the hydrogen nuclei precess at a much lower frequency than they do before resonance when affected only by $B_0$. Before resonance, not only do they precess faster but their magnetic moments are out of phase, and they therefore have no net transverse component. However, when the $B_1$ field is applied in the transverse plane, magnetic moments align with this field and, in doing so, gain phase coherence. This causes an increase in transverse magnetization. The combination of development of phase coherence and nutation results in coherent magnetization that precesses in the transverse plane. During the RF excitation pulse, the transverse magnetization precesses at a frequency dependent on the amplitude of the $B_1$ field [4].

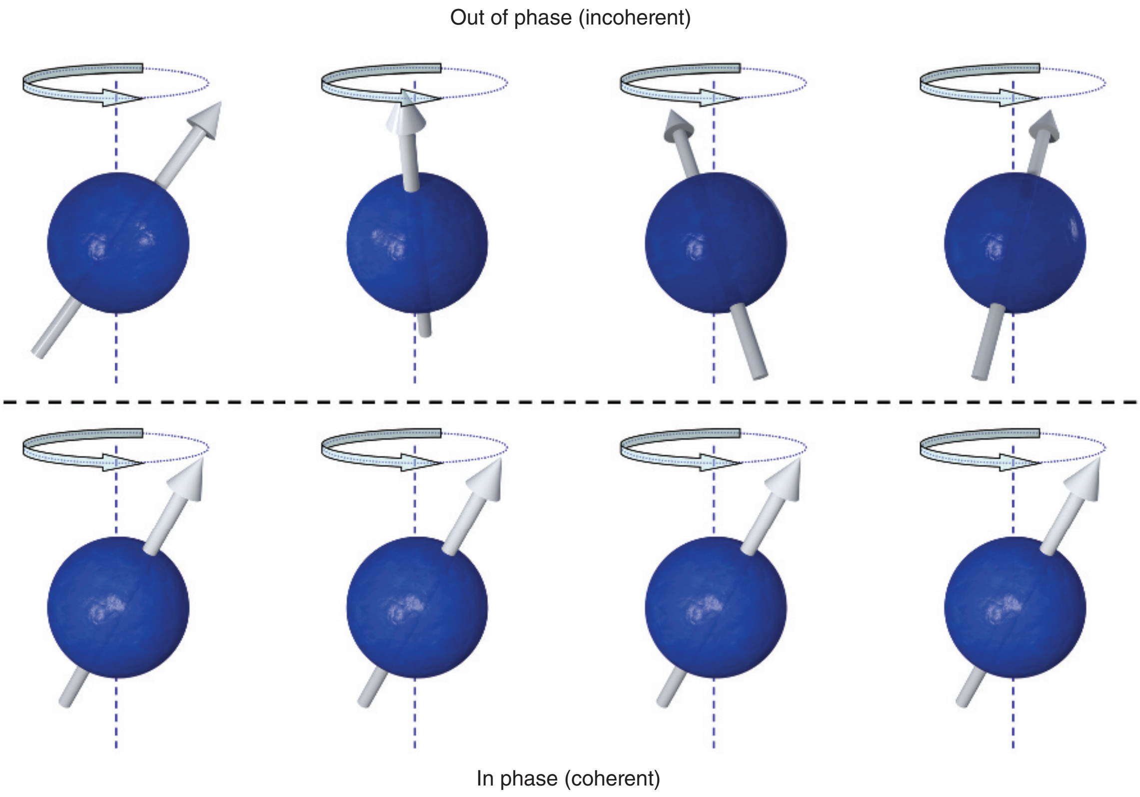


**Figure 1.9** In phase (coherent) and out of phase (incoherent).

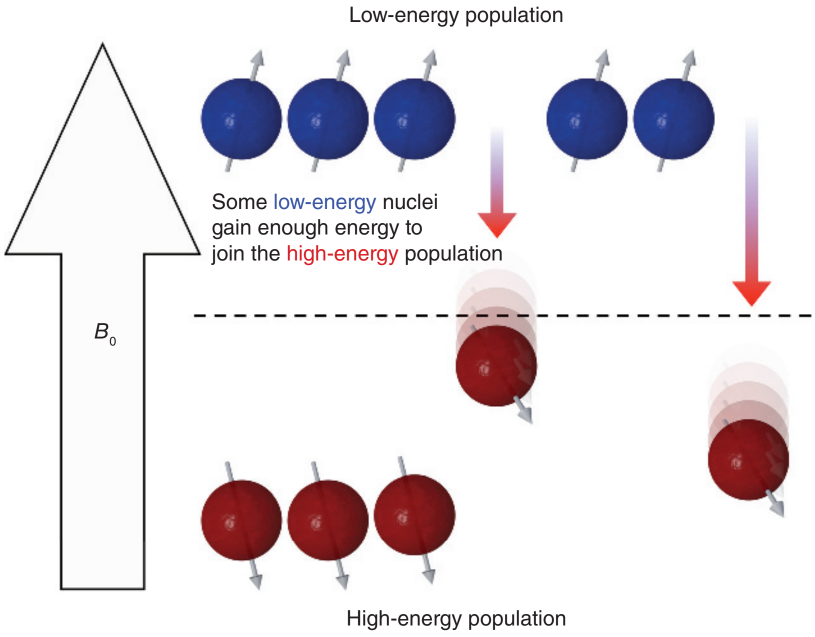


**Figure 1.10** Energy transfer during excitation.

If just the right amount of energy is absorbed, the NMV lies in the transverse plane at 90° to $B_0$. When it does, it has moved through a **flip** or **tip angle** of 90° (Figure 1.10). 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-energy and low-energy populations and thus the strength of $B_0$ (Equation (1.4)). As the field strength increases, the energy difference between the two populations increases so that more energy (higher frequencies) is required to produce resonance.

**Equation 1.4**

| | | |
|---|---|---|
| $E=h\omega_0$ | $E$ is the energy of a photon (Joules, J)<br>$h$ is Planck's constant ($6.626 \times 10^{34}$ J/s)<br>$\omega_0$ 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 particles that possess energy and at the same time behave like waves that have frequency (wave-particle duality) |
| $\Delta E = h\omega_0 = h\gamma B_0$ | $\Delta E$ is the energy difference between the spin-up and spin-down populations<br>$h$ is Planck's constant ($6.626 \times 10^{34}$ J/s)<br>$\omega_0$ is the precessional or Larmor frequency (MHz)<br>$\gamma$ 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 $B_0$ |

## Learning tip: The flip angle

The magnitude of the flip angle depends on the amplitude and duration of the RF excitation pulse. Usually, the flip angle is 90°, i.e. the NMV is given enough energy by the RF excitation pulse to move through 90° relative to $B_0$. However, as the NMV is a vector, even if flip angles other than 90° are used, there is always a component of magnetization in a plane perpendicular to $B_0$. With a flip angle of 90°, the nuclei are given sufficient energy so that the longitudinal NMV is completely transferred into a transverse NMV. When flip angles less than or more than 90° are used, only a portion of the NMV is transferred to the transverse plane. The flip angle depends on the strength of the $B_1$ field and for how long it is applied (Equation (1.5)).

It can be seen from Equation (1.5) that a flip angle of 180° is caused when the RF excitation pulse is twice the magnitude of that used to produce a 90° flip angle [8]. In quantum mechanics, a 180° RF pulse produces an inversion of the spin populations, i.e. all the low-energy spins have enough energy to locate in the high-energy population and all the high-energy spins have been stimulated to give up their energy and locate in the low-energy population. This is called ***saturation*** and is caused when the spins are unable to absorb more energy or to be stimulated and release more energy. The amount of RF needed to produce a 90° flip angle is half of this value and relates to equalizing the high- and low-energy spins [6].

Equation 1.5

$\theta = \omega_1 \tau$
Therefore from the Larmor equation
$\theta = \gamma B_1 \tau$
$90° = \pi/2 = \gamma B_1 \tau$
$180° = \pi = \gamma B_1 \tau$

$\theta$ is the flip angle (°)
$\omega_1$ is the precessional frequency of $B_1$ (μT)
$B_1$ is the magnetic field associated with the RF excitation pulse (mT)
$\tau$ is the duration of the RF excitation pulse (ms)

This equation shows that the flip angle is determined by the strength of the $B_1$ field and the duration of the pulse. In trigonometry, a factor of $2\pi$ represents 360° A flip angle of 90° can therefore be written as $\pi/2$; a flip angle of 180° is $\pi$. Replacing $\theta$ with these values shows that an RF pulse producing a flip angle of 90° has either half the power or half the duration of an 180° RF pulse [9]

## Analogy: The watch analogy

The terms frequency and phase are used many times in this book, and it is important we understand the difference between them and how they relate to each other. The easiest analogy is the hour hand on an analog watch. Frequency is the time it takes the hour hand to make one revolution of the watch face, i.e. 12 h. The unit of frequency is Hz, where 1 Hz is one cycle or rotation per second. Using the watch analogy, the frequency of the hour hand is 1/4320 s=0.000 023 1 Hz as it moves around the watch face once every 12 h.

The phase of the hour hand, measured in degrees or radians, is the time on the watch, e.g. 1 o'clock, 2 o'clock, which corresponds to its position around the watch face when you look to see what time it is (Figure 1.11). The phase of the hour hand depends on its frequency (speed). If the frequency is correct, then the hour hand always tells the correct time. If the watch goes fast or slow, i.e. the frequency either increases or decreases, then the watch tells an incorrect time.

Imagine a room full of people, with watches that tell perfect time, who are asked to synchronize their watches at 12 noon. One hour later, all their watches say 1 o'clock because they have kept perfect time. They are in phase or coherent because they all tell the same time, and their hour hands are all at the same place on the watch face at the same time. However, if after synchronization the watches on the left-hand side of the room go fast for 1 h, and the watches on the right-hand side of the room go slow for 1 h, then at 1 o'clock they tell different times. The watches on the left-hand side of the room tell a time greater than 1 o'clock, e.g. 1.15 p.m., and those on the right-hand side of the room tell a time less than 1 o'clock, e.g. 12.45 p.m. Therefore, the watches are out of phase or incoherent because they tell different times, and their hour hands are not at the same place on the watch face at the same time.

The phase difference between them depends on their relative frequencies between the time 12 noon and 1 o'clock. If the difference in frequencies is large, then the difference in phase is greater than if the frequency difference is small. Phase and frequency are therefore connected. In this context, the frequency of the hour hand is related to its change of phase over time. In other contexts, used later in this book, frequency is a change of phase over distance. The watch analogy is used many times in this book. Look out for the watch symbol in the margin.

### Learning tip:
### Stationary vs rotating frame of reference

The **stationary frame of reference** refers to the observer (i.e. you) viewing something moving. You and the room you are situated in are stationary, and what you are observing moves. You are an outsider looking in.

The **rotating frame of reference** refers to the observer viewing this from a different perspective. Imagine you are "the thing" that moves: what would the room look like? You are stationary, and the room would appear to move around you because you are now part of the rotating system.

A good example of this is to imagine what happens during an RF excitation pulse. If you were to observe this from the stationary frame of reference, then you would observe nutation of the NMV around $B_0$ and simultaneously around $B_1$. As $B_0$ is larger than $B_1$, the outside observer sees fast precession around $B_0$ and a much slower spiraling down onto the transverse plane around $B_1$. If, however, you were to observe this from inside the rotating frame of reference, then you would see something different. Imagine that you are riding along with the NMV inside the rotating system at the frequency associated with $B_0$. You would then only observe the slow precession of the NMV from the z-axis onto the x–y-axis caused by $B_1$ [4].

**Refer to animation 1.1 on the supporting companion website for this book: www.wiley.com/go/westbrook/mriinpractice**

## MR SIGNAL

Because of resonance, in-phase or coherent magnetization precesses in the transverse plane. This changing magnetic field generates an electric current. **Faraday's law** of induction explains this phenomenon. The change of magnetic flux through a closed circuit induces an **electromotive**

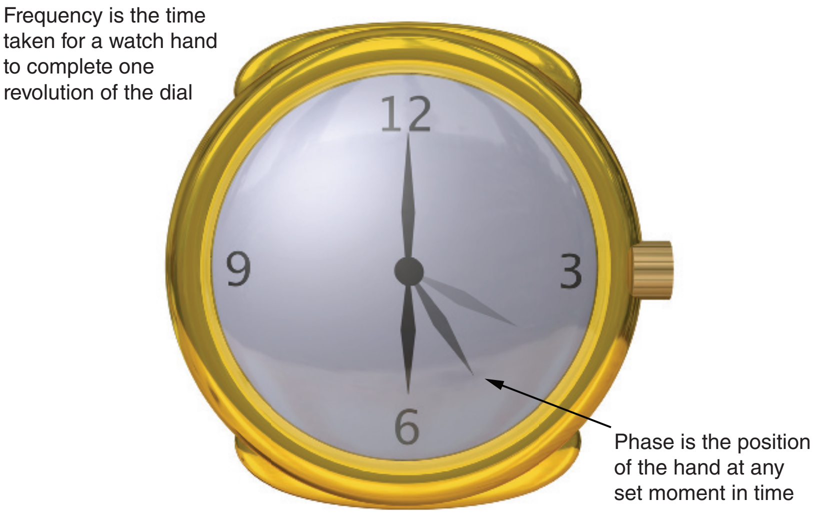


**Figure 1.11** Phase and frequency (the watch analogy).

**force (emf)** in the circuit. The emf is defined as the energy available from a unit of charge traveling once around a loop of wire. The emf drives a current in the circuit and is the result of a changing magnetic field inducing an electric field.

The laws of electromagnetic induction (Faraday) state that the induced emf:

- is proportional to the rate of change of magnetic field and the area of the circuit
- is proportional to the number of turns in a coil of wire (Equation (1.6))
- is in a direction so that it opposes the change in magnetic field that causes it **(Lenz's law)**.

According to Faraday's law, a changing magnetic field causes movement of charged particles, i.e. electrons. This flow of electrons is a current, and if a receiver coil or any conductive loop is placed in a moving magnetic field, i.e. the magnetization precessing in the transverse plane, a voltage generated by this current is induced in the receiver coil. This voltage is called **signal** and is produced when coherent (in phase) magnetization cuts across the coil. The frequency of signal depends on the frequency of rotation of the magnetic field – the magnitude of signal depends on the amount of coherent magnetization present in the transverse plane (Figure 1.12).

| Equation 1.6 | | |
|---|---|---|
| $\varepsilon = -N d\Phi / dt$ | $\varepsilon$ is the emf in volts (V)<br>N is the number of turns in a coil<br>$d\Phi$ is changing magnetic flux in a single loop (V/s)<br>dt is changing time (s) | This equation shows that the amount of induced current in a coil is related to the rate of change of magnetic flux (how fast the magnetic lines of flux are crossed) and the number of turns in a coil |

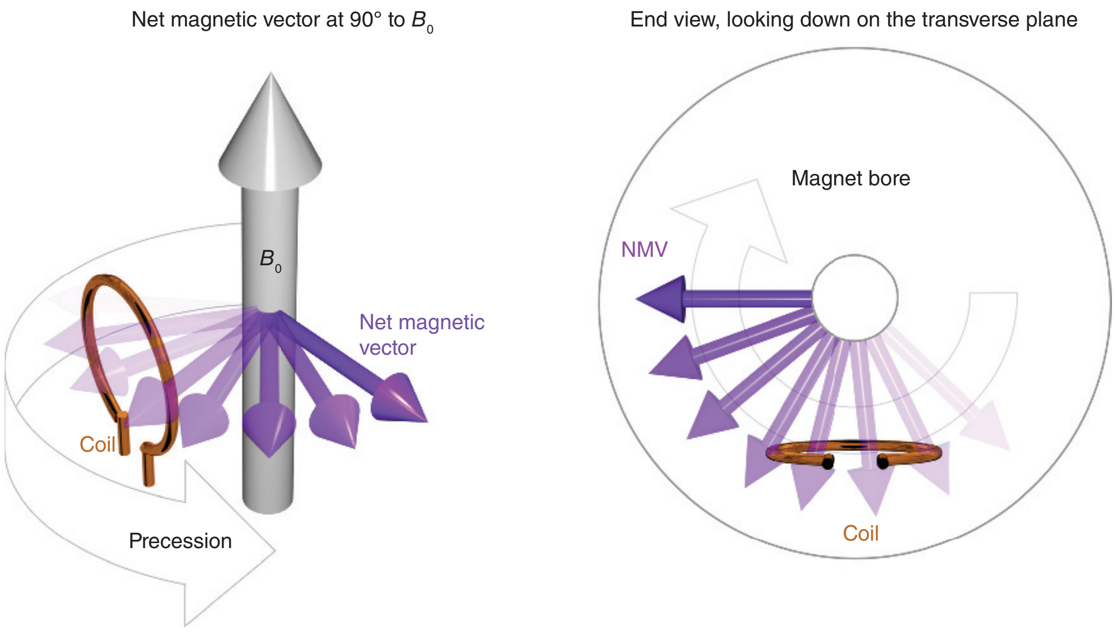


**Figure 1.12** Generation of the signal.

**Refer to animations 1.2 and 1.3 on the supporting companion website for this book: www.wiley.com/go/westbrook/mriinpractice**

# THE FREE INDUCTION DECAY (FID) SIGNAL

When the RF excitation pulse is switched off, the NMV is influenced only by $B_0$, and it tries to realign with it. To do so, the hydrogen nuclei lose energy given to them by the RF excitation pulse. The process by which hydrogen loses this energy is called **relaxation**. As relaxation occurs, the NMV returns to realign with $B_0$ because some of the high-energy nuclei return to the low-energy population and therefore align their magnetic moments in the spin-up direction. At the same time, but independently, the magnetic moments of hydrogen lose coherency due to dephasing. This occurs because of inhomogeneities in the $B_0$ field and due to interactions between spins in the patient's tissue (see Chapter 2). As the magnitude of transverse coherent magnetization decreases, so does the magnitude of the voltage induced in the receiver coil. The induction of decaying voltage is called the **free induction decay (FID)** signal. This is because spins *freely* precess influenced only by $B_0$, signal *decays* with time, and magnetic moments of the spins *induce* a current in the receiver coil.

The magnitude and timing of the RF pulses form part of **pulse sequences**, which are the basis of contrast generation in MRI (see Chapters 2–4).

## Learning tip:
## Vectors

The NMV is a vector quantity. It is created by two components at 90° to each other. These two components are magnetization in the longitudinal plane and magnetization in the transverse plane (Figure 1.13). Before resonance, there is full longitudinal magnetization parallel to $B_0$. After the application of the RF pulse and assuming a flip angle of 90°, the NMV is flipped fully into the transverse plane. There is now full transverse magnetization and zero longitudinal magnetization.

Once the RF excitation pulse is removed, the NMV recovers. As this occurs, the longitudinal component of magnetization grows again while the transverse component decreases (shown later in Figure 2.5). As the received signal amplitude is related to the magnitude of the coherent transverse component, signal in the coil decays as relaxation occurs.

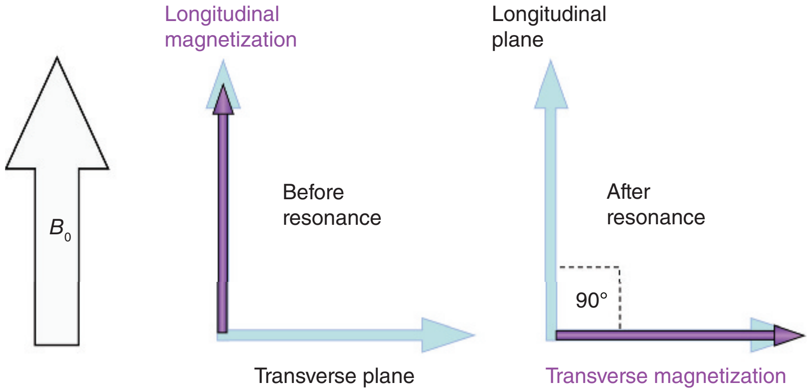


**Figure 1.13** Longitudinal and transverse magnetization.

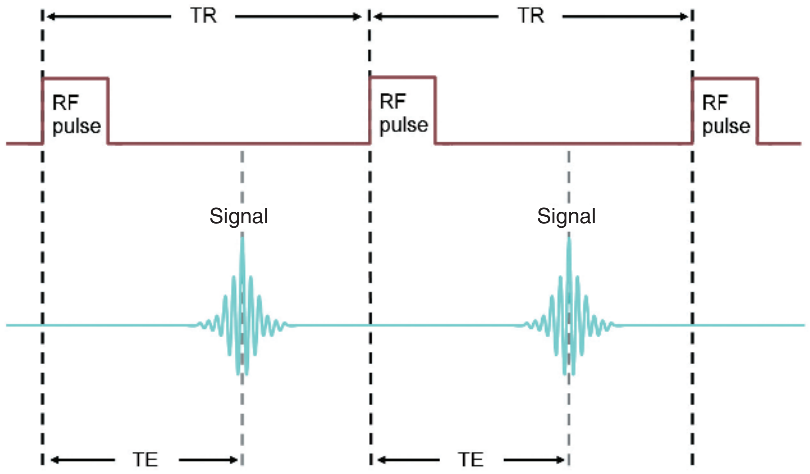


**Figure 1.14** A basic pulse sequence.

**Table 1.6** Things to remember – excitation and signal generation.

| |
|---|
| 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 |
| If a receiver coil (conductor) is placed in the transverse plane, the movement of the rotating coherent transverse magnetization causes a voltage in the coil |
| When the RF excitation pulse is removed, the magnetic moments of all spins dephase and produce a FID |

# PULSE TIMING PARAMETERS

A very simplified pulse sequence is a combination of RF pulses, signals, and intervening periods of relaxation (Figure 1.14). It is important to note that a pulse sequence as shown diagrammatically in Figure 1.14 merely shows in simple terms the separate timing parameters used in more complicated sequences, i.e. repetition time (TR) and echo time (TE).

A pulse sequence consists of several time periods. The main ones are outlined below.

- The **TR** is the time from the application of one RF excitation pulse to the application of the next RF excitation pulse for each slice and is measured in millisecond. The TR determines the amount of longitudinal relaxation that occurs between the end of one RF excitation pulse and application of the next. The TR thus determines the amount of T1 relaxation that has occurred when signal is read (see Chapter 2).
- The **TE** is the time from the application of the RF excitation pulse to the peak of signal induced in the receiver coil and is also measured in millisecond. The TE determines how much decay of transverse magnetization occurs. TE thus controls the amount of T2 relaxation that has occurred when signal is read (see Chapter 2).

In this chapter, we explored and describe the basic principles behind signal creation. The application of RF pulses and the receiving of signals at predefined times produce contrast in MRI images. In the next chapter, we look at these concepts in detail.

**For questions and answers on this topic, please visit the supporting companion website for this book: www.wiley.com/go/westbrook/mriinpractice**

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