CHAPTER 21

Magnetic resonance imaging

The magnetic field produced by nuclear particles can be used as a diagnostic tool

Introduction

Magnetic resonance imaging (MRI) is a relatively new diagnostic tool that can provide doctors with high-quality images of many body systems. It can provide high-resolution details of anatomical structures. Images of certain tissues or diseases may be enhanced.

MRI is structurally and functionally complicated. This chapter discusses the basic functional principles of MRI.

First, the patient who is to have the scan is placed inside a big open tube. Inside the tube a very strong magnetic field is produced. The magnetic field aligns the nuclei of the atoms of interest in the body. Once these nuclei are aligned, pulses of radio waves are applied to the body. The aligned nuclei are able to absorb these radio waves. Once the external radio waves are switched off, the absorbed radio energy is re-emitted from the nuclei. The returning radio waves are detected and analysed to produce images of the body parts. The result is that the body is turned into a radio wave emitting source. With the different body parts and different diseased or healthy tissues emitting radio waves differently, the pattern of the radio wave emission provides information about the structure of the body parts.

NOTE: Unlike CT, where the image formation process relies on the attenuation of external energy (X-rays), the signals for MRI images are generated within the body (although induced first by the external radio waves). This can be compared to radioisotope scans, where the image formation also relies on rays emitted from within the body, although the difference is the use of gamma rays emitted by the injected radioisotopes in nuclear scans.

An MRI machine

The rest of this chapter elaborates on the points mentioned above, with emphasis on:

1. Why nuclei align when they are subjected to a strong magnetic field.
2. Why aligned nuclei absorb radio waves, and the rules governing the re-emission of the radio waves.
3. How the re-emitted radio waves are analysed to form images of body parts.

Nuclear spin

21.1

- ***Identify that the nuclei of certain atoms and molecules behave as small magnets***
- ***Identify that protons and neutrons in the nucleus have properties of spin and describe how net spin is obtained***
- ***Explain that the behaviour of nuclei with a net spin, particularly hydrogen, is related to the magnetic field they produce***

To fully explain the spin of the nucleus, quantum physics is required, which is beyond the scope of this course. To simplify the concept of nuclear spin, the nucleus can be visualised to spin on its axis. A spinning nucleus carries an angular momentum that is related to the spin number (I). The spin number is a quantum mechanic number and is basically determined by the number of protons and neutrons inside the nucleus. There are three groups of value for I: 0, integral values and half-integral values (e.g. $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ and so on). The spin number of a nucleus will be 0 if both its atomic number and atomic mass number are even numbers. When the atomic number is odd and the atomic mass number is even, then the spin number will be an integer. When the atomic mass number is odd, then the spin number is always multiple of $\frac{1}{2}$. The spin number for some of the common elements is listed in Table 21.1.

Table 21.1

Element	Proton number	Neutron number	Spin number (I)
Hydrogen-1	1	0	$\frac{1}{2}$
Hydrogen-2	1	1	1
Helium-4	2	2	0
Oxygen-16	8	8	0
Sodium-23	11	12	$\frac{3}{2}$
Phosphorus-31	15	16	$\frac{1}{2}$

NOTE: Students are not required to know the method for calculating the spin number.

Magnetic field associated with the nuclear spin

Recall that moving charged particles will create a magnetic field. Since a nucleus contains positive charges (due to its protons), if it spins, there will be an associated magnetic field. Taking the elements listed in Table 21.1 for example, all *except* helium-4 and oxygen-16 will produce their own magnetic field due to their non-zero spin number and hence angular momentum.

The spinning nucleus produces a magnetic field with its net axis parallel to the spinning axis and direction determined by the right-hand grip rule. A small magnet provides a useful analogy. As shown in Figure 21.1 (a), when the nucleus is spinning in a clockwise direction, the fingers curl in the clockwise direction and the thumb points upwards. This is to say that the magnetic field produced by this spinning nucleus has a net axis that is directing upwards, similar to a bar magnet with its north pole pointing upwards. The opposite is true if the nucleus is spinning in the anti-clockwise direction, as shown in Figure 21.1 (b).

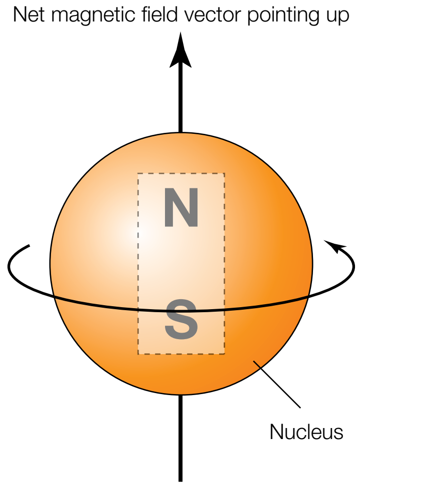


Figure 21.1 (a) Spinning of a nucleus in a clockwise direction produces a magnetic field that resembles a bar magnet that has its north pole pointing upwards

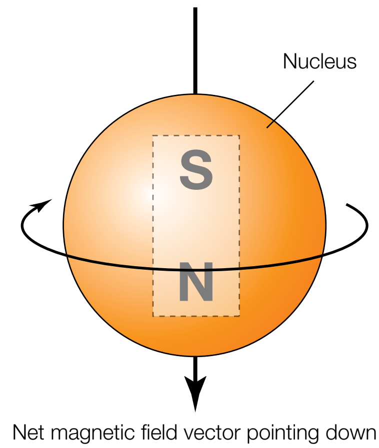


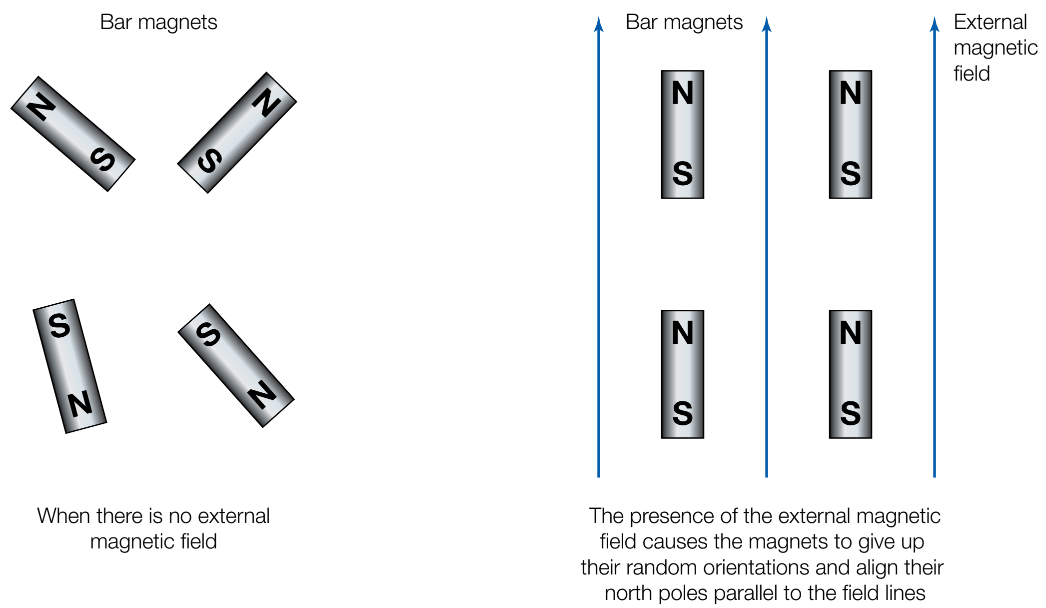
Figure 21.1 (b) Spinning of a nucleus in an anti-clockwise direction produces a magnetic field that resembles a bar magnet that has its north pole pointing downwards

21.2 The nucleus in a magnetic field

- ***Explain that the behaviour of nuclei with a net spin, particularly hydrogen, is related to the magnetic field they produce***
- ***Describe the changes that occur in the orientation of the magnetic axis of nuclei before and after the application of a strong magnetic field***

Consider what would happen when bar magnets with random orientations are placed inside a strong uniform magnetic field. As shown in Figure 21.2, these magnets will

Figure 21.2 Aligning of the bar magnets inside an external magnetic field



align with the magnetic field such that the north poles are pointing in the direction of the field.

Randomly orientated nuclei that have associated magnetic fields due to their spin will also align when they are subjected to a strong external magnetic field; however, there is a slight difference. As shown in Figure 21.3, nuclei can align with either the net magnetic field axis ('the north pole') pointing in the direction of the external magnetic field, known as **parallel alignment**, or in the opposite direction to the magnetic field, known as **anti-parallel alignment**.

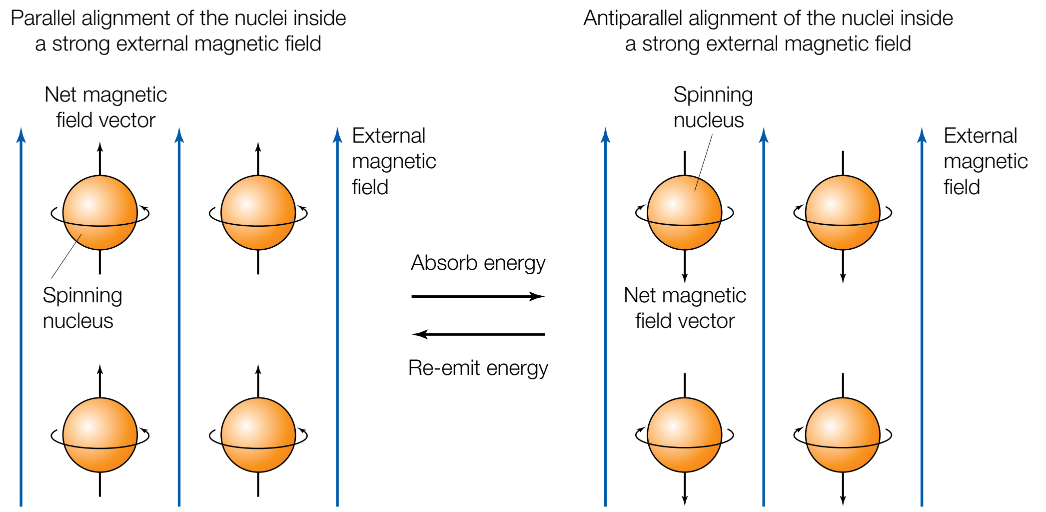


Figure 21.3 Alignment of nuclei inside an external magnetic field

Parallel alignments have a slightly lower energy level than anti-parallel alignments and such energy differences are proportional to the strength of the applied magnetic field. Also, under normal circumstances, there are always more parallel alignments compared to anti-parallel alignments, and once again the difference is proportional to the strength of the magnetic field. When applying a magnetic field strength of 1.5 T, there is approximately one extra parallel alignment for every 100 million nuclei aligned. This has two consequences. First is the formation of the net magnetic field. Before the alignment of the nuclei, the magnetic fields they produce are all randomly orientated, therefore no net magnetic field will be expressed. However, the extra parallel alignments when a strong magnetic field is applied will result in a net magnetic field in the parallel direction. The result of this is known as **net magnetisation (M)**. Second, parallel alignments can absorb energy (externally applied in the form of pulses of radio waves) and move into anti-parallel alignments. This energy can be re-emitted once the anti-parallels return to the original parallel alignments. This conversion between parallel and anti-parallel alignments forms the basis of MRI.

All nuclei that have a net spin will align within an external magnetic field in the ways described above. Nevertheless, hydrogen atoms are the chosen targets in MRIs. Hydrogen atoms respond well to the external magnetic field and are abundant in the body, as they are found in water and fat molecules.

NOTE: Nuclei that have 0 net spin therefore will not respond to the external magnetic field.

21.3 Precession

- ***Define precessing and relate the frequency of the precessing to the composition of the nuclei and the strength of the applied external magnetic field***

Representing the aligning of the nuclei by using bar magnets as an analogy is adequate but incomplete. This is because even though the net magnetic field axis of the spinning nuclei aligns with the external magnetic in either a parallel or anti-parallel fashion, the spinning motion of the nuclei means that their rotational axis will not be parallel to the magnetic field, but rather revolves around it. This is known as **precession**.

Definition

Precession is the movement where the rotational axis of a spinning object revolves around another central axis.

Hence the nuclei, when trying to align within the external magnetic field, will do so by either precessing parallel to the magnetic field lines, shown in Figure 21.4 (a) or precessing in an anti-parallel fashion as shown in 21.4 (b).

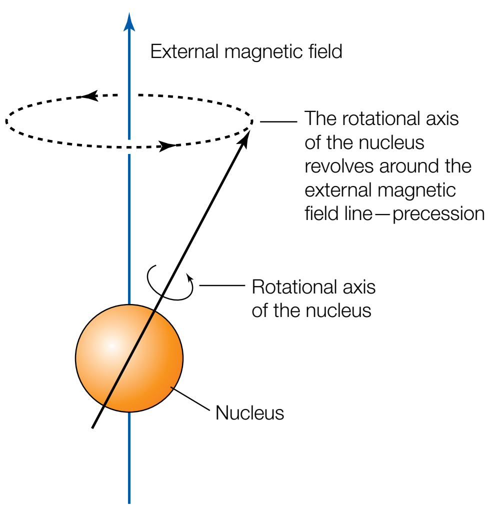


Figure 21.4 (a) Precession of the nuclei parallel to the magnetic field

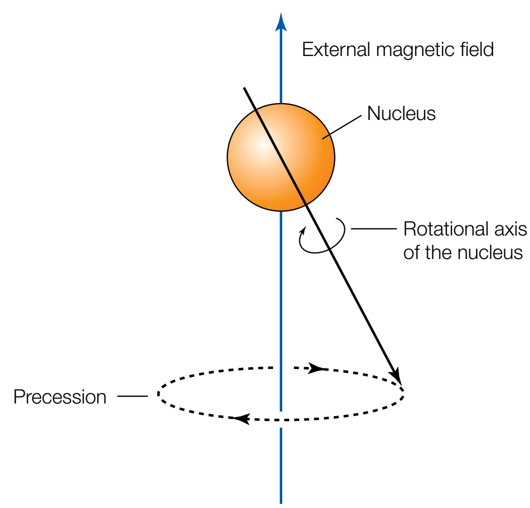


Figure 21.4 (b) Precession of the nuclei anti-parallel to the magnetic field

21.4 Larmor frequency

- ***Define precessing and relate the frequency of the precessing to the composition of the nuclei and the strength of the applied external magnetic field***
- ***Discuss the effect of subjecting precessing nuclei to pulses of radio waves***

An important property that is associated with the precession of the nuclei is the **Larmor frequency**.

Definition

Larmor frequency is the frequency at which the nucleus precesses around the external magnetic field lines. In other words, it is the number of revolutions the rotational axis of the spinning nucleus will complete in one second.

The Larmor frequency is not a constant but is dependent on two factors: the nature of elements, and the strength of the external magnetic field. This can be described by the equation $\omega = \frac{\gamma}{2\pi} B$, where ω is the Larmor frequency, γ is the gyromagnetic ratio (a constant for each element) and B is the strength of the magnetic field. Hence it is obvious that the Larmor frequency is different for different elements and can be changed by changing the external magnetic field strength. Table 21.2 lists a few Larmor frequencies at a magnetic field strength of 1.5 T.

The importance of the Larmor frequency for MRI is that the nucleus of the element will only absorb the pulses of radio waves and change their alignment from parallel to anti-parallel if the radio wave frequency corresponds to the Larmor frequency of the element. If the two frequencies do not match, then the nucleus will not resonate and will not absorb the pulses of radio waves.

The fact that hydrogen atoms have their unique Larmor frequency means that they can be selectively targeted in MRI by choosing the specific frequency radio waves. The Larmor frequency of the hydrogen atoms may also be augmented slightly by changing the strength of the magnetic field (recall $\omega = \frac{\gamma}{2\pi} B$) and this forms an important part of image formation as described below.

Table 21.2 The Larmor frequency of various elements

Element	Larmor frequency at 1.5 Tesla (MHz)
Hydrogen-1	63.86
Hydrogen-2	9.803
Sodium-23	16.90
Phosphorus-31	25.88

21.5 Image formation: locating the signals

After the body has been subjected to a strong magnetic field (the **main magnetic field**) and pulses of radio waves, all hydrogen nuclei that have absorbed the radio waves will start to re-emit the radio waves, which now carry the anatomical information for image reconstruction. One crucial step in image reconstruction is to distinguish the radio waves coming from different locations of the body, for instance, distinguishing those emitted by the brain from those emitted by the liver, those from the left-hand side of the organ from those from the right, as well as those from the front of the body from those of the back. To achieve this, three **gradient magnetic fields** are used. One in the longitudinal axis of the body, the *z*-axis, enables slice selection; one in the *x*-axis and the other in the *y*-axis together describe the planes

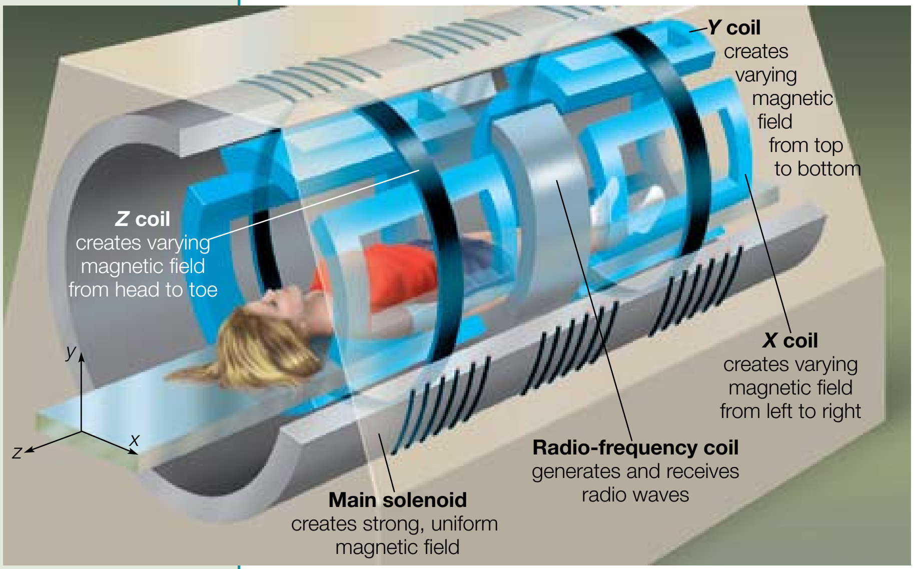


Figure 21.5 MRI apparatus: the main solenoid and the gradient coils: the main solenoid produces the strong magnetic field used to align the nuclei of the atoms while the gradient coils augment this main magnetic field, which is essential for locating the returning radio signals

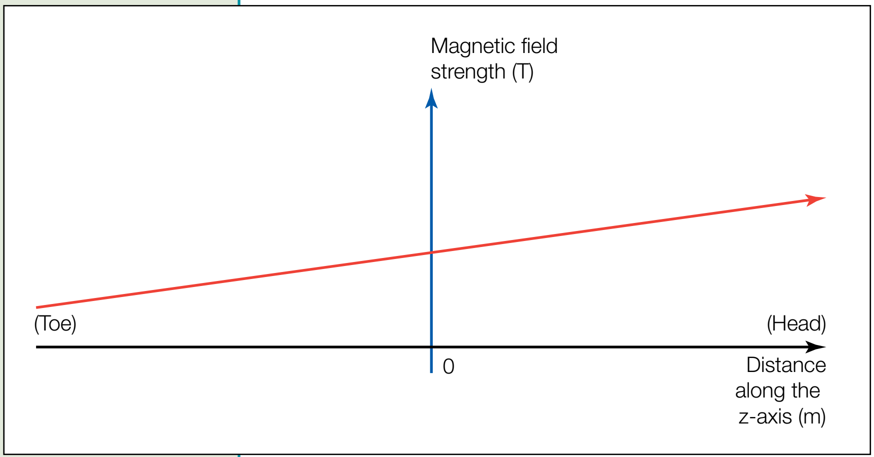
that are perpendicular to the *z*-axis (see Fig. 21.5). These gradient magnetic fields are produced by **gradient coils** as describe below and are added to the strong main magnetic field produced by the main solenoid used to align the nuclei of the atoms. The basic principle of using gradient magnetic fields is that the magnetic field strength at any unique *x*, *y* and *z* coordinate is slightly different from the others, such that the tissues at this location will resonate to specific frequency radio waves hence later re-emitting radio waves with an unique frequency which can then be analysed to provide information of the tissues' location.

Slice selection

By convention, MRI images are represented by slices, and commonly, horizontal slices. To select slices along the *z*-axis, a longitudinal gradient coil is used. This is shown in Figure 21.5.

This gradient coil produces a gradient magnetic field along the z-axis, and is added to the main magnetic field, which is used to align the nucleus of the atoms. Such a gradient field is set up to augment the main magnetic field by about 1% in magnitude so that the field strength towards the head increases uniformly, shown in the graph in Figure 21.6. This results in distinct Larmor frequencies for the hydrogen atoms within different slices along the *z*-axis of the body. (Recall that the Larmor frequency is proportional to the strength of the magnetic field.) A radio oscillator is employed to selectively produce radio waves at a specific frequency to target the hydrogen nuclei within a particular slice along the *z*-axis. Later, these radio waves are re-emitted and received by the receiving coil and the anatomical information carried by these radio waves is made slice-specific.

Figure 21.6 Magnetic field strength



ANALOGY: This slice selection method is similar to tagging labels. The anatomical information within different slices are tagged with different labels (the specific Larmor frequencies) so that they can be differentiated when they are received.

Locating signals within a slice

A similar idea is used to locate the signals coming from within one slice. The *x* coil produces a gradient magnetic field in the *x*-axis that differentiates the left from the right, whereas the y coil produces a gradient field along the y-axis which differentiates the top from the bottom. However, rather than modifying the Larmor frequency, the x gradient field encodes the position by causing the nuclei of the hydrogen atoms to precess at slightly different frequencies depending on the positions of the atoms within the slice. This is known as **frequency encoding**. The y gradient field on the other hand modulates the phase of the precession of the nuclei depending on the positions. The phase difference in this context refers to nuclei precessing at the same frequency but one nucleus may be precessing ahead of the other one depending on its position. This is known as **phase encoding**.

A typical slice has 256 frequency encoding values and 256 phase encoding values, which together divide the slice into 256 × 256 voxels. Tissues within each voxel have different frequency and phase encoding values, allowing their position to be located within the slice.

21.6 Image formation: tissue differentiation and contrasts

- ***Explain that the amplitude of the signal given out when precessing nuclei relax is related to the number of nuclei present***
- ***Explain that large differences would occur in the relaxation time between tissue containing hydrogen bound water molecules and tissues containing other molecules***

The second step to image formation is to reconstruct the actual outline of the organs. Since only hydrogen nuclei are targeted, the image reconstruction is essentially a mapping out of the hydrogen nuclei. Consequently, the shape of the organ or tissue depends on the distribution of the hydrogen nuclei. The brightness of the image on the other hand is related to the intensity of radio waves received and is determined by:

1. The number of hydrogen atoms in a particular organ.
2. The way the pulses of radio waves are sent and detected. This is related to the relaxation of the hydrogen nuclei within the organ and is discussed in detail later.
3. The level of pre-saturation.
4. The use of a contrast agent.

NOTE: Tissues that emit more radio waves will appear bright on the screen whereas tissues that emit less will appear dark.

The re-emitted radio waves are weak. For the reconstruction of MRI images, the process of sending and receiving the pulses of radio waves has to be repeated many times so that the returning radio wave signals can be superimposed on each other to make the overall signal sufficiently strong. Although the repetition of the signal transmission provides a means of creating image contrast (see the next section), there are a few downsides to that. First, MRI scans generally take more time to complete compared to other imaging methods, such as CT scans. Second, the patient undergoing an MRI scan needs to hold still and constantly hold their breath to ensure that the hydrogen nuclei are not moved for each of the subsequent re-emissions of the radio waves, which would result in blurry images. Thus MRI scans are not suitable for uncooperative patients (e.g. people who are demented) and young children. MRIs are not the best for scanning organs that are constantly moving, for instance, the chest wall and the heart.

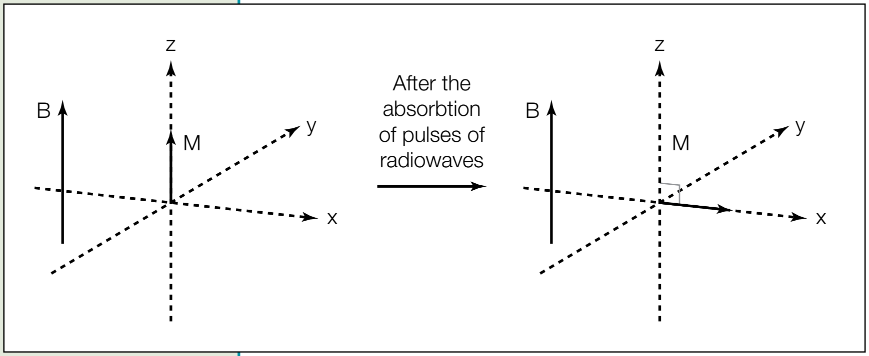
Image intensity and the hydrogen density

Since hydrogen nuclei are the source of radio wave signals, organs or tissues that have more hydrogen atoms per unit volume will appear brighter. Water-containing tissues, such as cysts or fatty tissues, are all rich in hydrogen and therefore show up well on MRI images. Bones on the other hand are not rich in hydrogen atoms and therefore do not show up well using MRI (unless contrast is used).

Image contrast and relaxation

To summarise, when the nuclei are subjected to a strong magnetic field, some precess parallel to the field whereas others precess anti-parallel. Normally, there are more parallel than anti-parallel alignments or precessions such that a net magnetic vector aligning parallel to the external magnetic field results. This is known as **net magnetisation (M)**. When the nuclei are subjected to pulses of radio waves, the parallel alignments will absorb the energy and move into the higher energy anti-parallel alignments. At the same time, the anti-parallel alignments will simultaneously re-emit their energy to return to the parallel alignments—nevertheless, overall, in responding to the pulses of radio waves, there are more nuclei changing from parallel to anti-parallel compared to the reverse. The overall result is that the M vector gradually rotates away from its parallel position to the external field lines and eventually reaches the position that is 90° to the field lines. This rotation of the M vector into the horizontal plane (the plane described by the *x* and *y* axes) is known as **transverse magnetisation**; this is shown in Figure 21.7. While the M vector is in the transverse plane, the precession of the nuclei are all in phase due to the action of the external magnetic field. This induces EMF in the receiving coil to form the MR signals.

Figure 21.7 The rotation of net magnetisation (M) from parallel (0°) to the external magnetic field to 90° to the field lines when the precessing nuclei are subjected to pulses of radio waves at their Larmor frequency



When the radio waves are switched off, all nuclei return to their original alignments and re-emit the radio waves as they do so. This is known as relaxation, which has two aspects: T1 and T2 relaxation. The new concept introduced in this section is that T1 and T2 relaxation is based on the changes in the M vector.

T1 relaxation

T1 relaxation is related to the returning of the M vector to the starting parallel position. T1 relaxation time (or just T1) is defined as the time taken for the M vector to return to 63% of its original value and is an exponential function as shown in Figure 21.8 opposite. At a microscopic level, the energy dissipation is via the excited (spinning) hydrogen nuclei transferring their energy to the surround lattice, therefore T1 relaxation is also known as **spin-lattice relaxation**.

Different tissues will have different T1 relaxation profiles or times. Large molecules and bound water molecules such as in the fat, liver and spleen have a short T1, while free water has a long T1. See Figure 21.8.

T2 relaxation

T2 relaxation is related to that fact that while the M vector is in the transverse plane, the hydrogen nuclei all precess in a coherent way (in phase) as a result of the external magnetic field. As the M vector returns to the original position, the precessing nuclei lose coherence, which is accompanied by a reduction in the induced MR signals. This is known as T2 relaxation. T2 relaxation time (or just T2) is defined as the time for the nuclei to decay to 37% of their initial precession coherence. Once again, T2 relaxation follows an exponential function, as shown in Figure 21.9. Microscopically, during T2 relaxation, the precessing nuclei transfer their energy to other precessing nuclei rather than the lattice, hence T2 relaxation is also known as **spin-spin relaxation**.

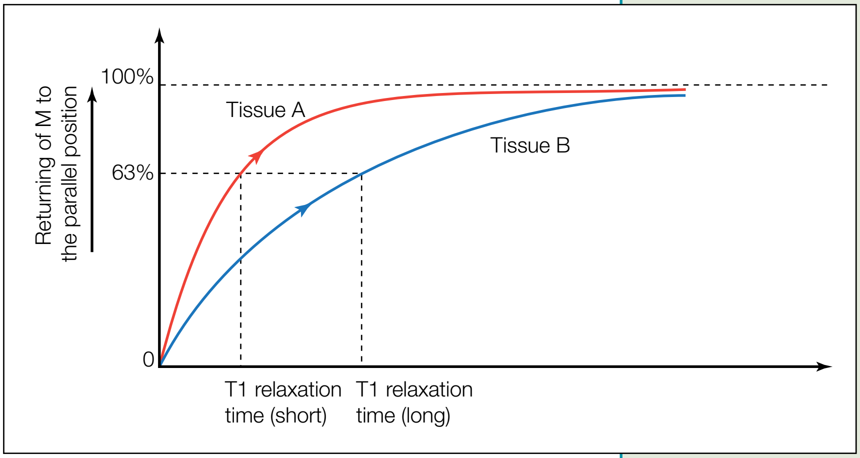


Figure 21.8 The profile for T1 relaxation of two different tissue types

There are also different T2 profiles. Large molecules found in tendons and muscles have a short T2 while free water has a long T2 (see Figure 21.9 below).

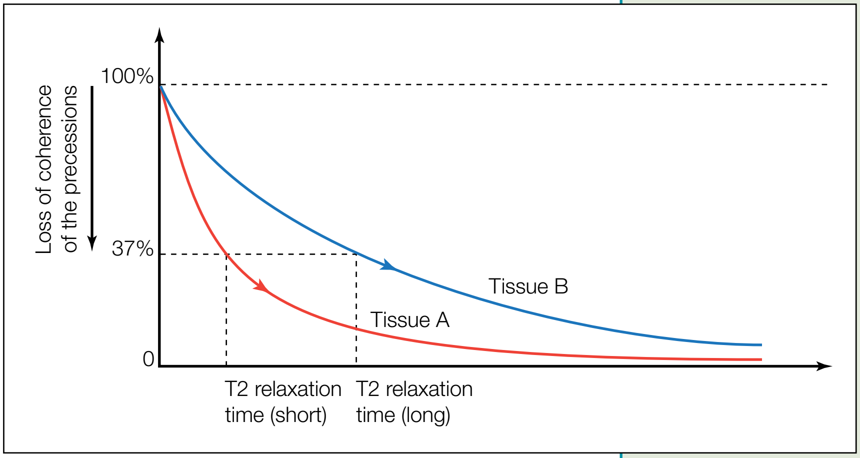
Obviously, the two forms of the relaxation processes have to occur simultaneously, with an increase in T1 relaxation being accompanied by an increase in T2 relaxation. This is because as more nuclei are returning to their original alignments, the loss of coherence of the nuclear precession will also increase.

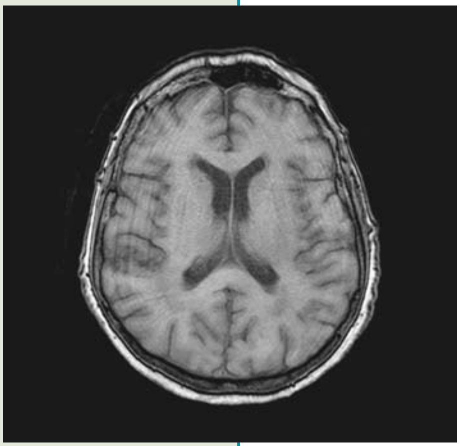
T1 and T2 weighted images

By sending and receiving pulses of radio waves at various rates, MRI can enhance tissue contrast to produce either T1 weighted images (enhancing tissues with a short T1) or T2 weighted images (enhancing tissues with a long T2). Two parameters need to be introduced. **Repetition time (TR)** is the elapsed time between successive pulses of input radio waves. **Echo delay time (TE)** is the time delay between the sending of the radio waves and measurement of the first returning radio signal.

To produce a T1 weighted image, that is, to emphasise tissues that have a short T1, a short TR is used. A short TR will enable tissues with a short T1 to maximise the absorption of radio waves. This is because as soon as the M vector returns to the original position (very quickly), there will be radio waves available for absorption. Tissues that have a long T1 will take a longer time to recover before they can absorb radio waves again, and therefore will 'miss out' on the opportunity to absorb the many pulses of radio waves. Consequently when tissues re-emit the radio waves, the tissues with a short T1 will emit more than those with a long T1 (because they have absorbed more), and hence will appear brighter.

Figure 21.9 The profile for T2 relaxation of two different tissue types



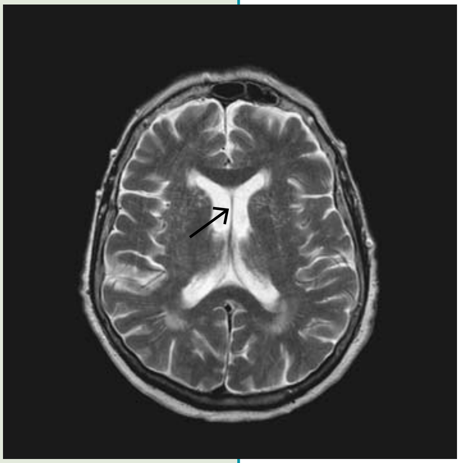


A cross-sectional image of the brain—T1 weighted

In T1 weighted images, a short repetition time is used. Tissues with a short T1 will appear bright.

On the other hand, in order to produce a T2 weighted image, that is, to enhance tissues that have a long T2, a long TE is needed. A long TE means the signals from T2 relaxation are measured long after the sending of the initial radio wave pulses. This will result in only tissues with a long T2 contributing to the returning signals because of the precession of the nuclei are still in phase, whereas tissues with a short T2 will have their T2 signal diminished to a very low level by this time. This allows the tissues with a long T2 to appear brighter and tissues with a short T2 to be suppressed.

In T2 weighted images, a long echo delay time is used. Tissues with a long T2 will appear bright.



A cross-sectional image of the brain—T2 weighted. Note that the cerebral spinal fluid (water) appears bright (see arrow).

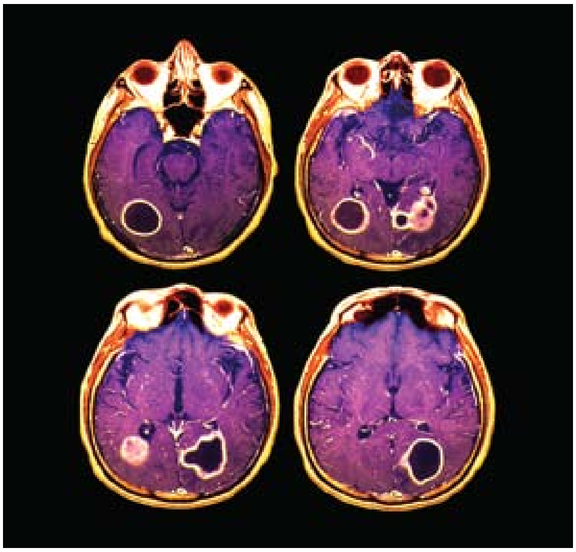
Also, in T1 weighted images, the T2 effect needs to be suppressed. Hence in T1 weighted images, a short TE is used in order to suppress the T2 weighting. Similarly, a long TR is chosen to decrease the T1 weighting in T2 weighted images. Also by choosing a balanced TR and TE, images that are neither T1 nor T2 weighted can be produced, and these may occasionally be clinically useful.

NOTE: It is futile to have both T1 and T2 weighted effects simultaneously because this means the contrast is lost, that is, all tissues will light up at the same time.

Image contrast by pre-saturation and contrast agents

These two concepts are complex and will only be discussed briefly.

Pre-saturation refers to continuously sending pulses of radio waves targeting the tissue (say tissue A) that needs to be suppressed. These radio waves will rotate and maintain the M vector in the transverse plane. At the same time, the induced voltages or MR signals due to the coherent precession of the nuclei of tissue A are destroyed by the use of a spoiler coil so that they do not contribute to the image formation. The radio frequency oscillator then produces another set of radio waves targeting other tissues of interest (say tissues B and C). These tissues will absorb the energy, but the tissue that is to be suppressed (tissue A) will not because its M vector is maintained in the transverse plane and therefore



Coloured MRI scans of an axial (horizontal) section through the brain of a 38-year-old patient with cerebral abscesses (dark circles surrounded by white rings): the abscesses have been highlighted by the injection of a gadolinium fails to relax. Consequently, upon relaxation, tissues B and C will re-emit the radio wave they have absorbed and light up on the scan images; whereas tissue A will be suppressed (appear dark) because it has not absorbed any radio wave energy. Examples of these include fat saturation, where fat tissues are selectively suppressed, and magnetisation transfer suppression, where free water is suppressed.

Contrast agents work by affecting the relaxation time of the target tissues and most commonly their T1 relaxation time. **Gadolinium**, a common contrast agent, works by shortening the T1 relaxation time of the target tissues, such as cancerous tissues. This results in enhancement of such tissues on the scanning images if T1 weighting is employed.

Hardware used in magnetic resonance imaging

- ***Gather and process secondary information to identify the function of the electromagnet, radio frequency oscillator, radio receiver and computer in the MRI equipment***

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H12.3A, B, D
H12.4F

Magnets

In first generation MRIs, magnetic fields were either provided by large permanent magnets or electromagnets. These magnets were bulky and could only produce magnetic fields up to 0.5 Tesla. These 'low' magnetic field strengths meant that the image quality was poor. Further contributing to the problem was that electromagnets lost large amounts of heat energy during their operation. Modern MRIs use very strong magnetic fields, ranging from 1 Teslas to 2.5 Teslas. These strong magnetic fields may be provided by a superconducting coil magnet. Such a magnet has zero resistance when cooled below its critical temperature, so that only a very small amount of energy is lost as heat.

NOTE: Recall that heat loss = I^2R.

Furthermore, when using superconductor coil magnets, once the voltage is switched on, the current will continue to flow to produce the required magnetic field even after the voltage is turned off. This 'perpetuating' current makes such magnets very efficient to use. (Refer to Chapter 13 for further information on superconductors.)

The main advantage superconductor magnets have over normal solenoid magnets is their ability to produce very powerful magnetic fields and at the same time minimise the amount of energy lost as heat. This is because superconducting magnets have no resistance to the flow of electricity, hence all electrical energy input can be converted into magnetic fields. If resistance is present, an attempt to increase the magnetic field strength by increasing the current will see the electrical energy diverted into heat rather than converted into magnetic fields. Also directly related to their high energy efficiency, superconducting coil magnets are smaller.

One disadvantage of using superconducting magnets is that they need to be cooled by, for instance, liquid helium. This makes them more expensive and more technically demanding.

The main magnetic field used to align the nuclei must be very strong in order to be effective. This strong magnetic field means that the main solenoid (the superconducting magnet) can potentially attract metal objects placed inside the scanning room or from within patient's body! Therefore, it is absolutely critical to have no unsecured metal, such as scissors, inside the scan room as they may fly towards the main solenoid and cause damage. Patients who have metal wares inside their body, for instance, metal clips to a cerebral aneurysm (an abnormally dilated brain vessel) cannot have MRI scans as these clips maybe moved by the strong magnetic field, causing an intracranial haemorrhage (bleeding inside the brain). This can be fatal!

Radio frequency oscillator

The radio frequency oscillator produces radio waves with the required frequencies. As mentioned, only radio waves that have frequencies equal to the Larmor or resonant frequency of the target nuclei will be absorbed. Since there is a range of Larmor frequencies for the hydrogen nuclei, due to the way they are bonded in compounds, as well as the influence of the gradient magnetic fields used for locating signals, the radio frequency oscillator needs to be able to produce a range of frequencies precisely. In summary, the role of the radio frequency oscillator is to produce the right frequency radio waves to match the required Larmor or resonant frequencies.

Radio receiver

The radio receiver is a set of coils that detect the returning radio waves and digitise them for later processing. The coil may be the same coil that is used to produce the radio waves initially. The size of the receiving coil (radio receiver) may vary, with the smaller coil more sensitive than the larger one. An rf (radio frequency) shield is used to shield the returning radio waves from the background radio waves from local radio and TV stations.

Computer

A powerful computer system is required to analyse the returning radio waves because of the complex nature of these waves. The returning radio waves are analysed for intensity as well as *x*, *y* and *z* coordinates in order to determine their origins, as well as tissue specificity. They are then processed to form the actual images. The computer also controls the repetition time and echo delay time in order to produce T1 or T2 weighted images. Furthermore, the computer controls pre-saturation and many other forms of radio wave transmission and radio wave manipulation in order to improve tissue contrast.

Medical uses of MRI

FIRST-HAND AND SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H12.3A, B, D
H12.4C
H13.1A, B, C, E

- ***Perform an investigation to observe images from magnetic resonance image (MRI) scans, including a comparison of healthy and damaged tissue***
- ***Identify data sources, gather, process and present information using available evidence to explain why MRI scans can be used to:***
  - ***detect cancerous tissues***
  - ***identify areas of high blood flow***
  - ***distinguish between grey and white matter in the brain***

MRI has extensive uses in clinical medicine. MRI has a higher resolution than ultrasound and CT scans and avoids the use of harmful ionising radiation. MRI can be used to resolve and visualise most tissues in the body, whether healthy or diseased. Some examples are described below.

Brain and spinal cord

MRI is the imaging method of choice for studying central nervous system (the brain and the spinal cord) anatomy and diseases. In addition to the high resolutions MRI can provide, which enable small anatomical structures such as the pituitary gland and the pineal gland to be resolved, MRI is also able to differentiate the grey matter from the white matter in the brain.

The brain consists of a cortex, also known as the grey matter, on the external side and the white matter deeper inside. The spinal cord consists of central grey matter and surrounding white matter. The grey matter is composed of neuron (nerve) cell bodies while the white matter is composed of neuron axons. Importantly, neuron cell bodies have a different hydrogen atom density compared to the neuron axons, and also the hydrogen atoms are bonded differently, and thus have different T1 and T2 relaxation times. Consequently, the grey matter and white matter show distinctive contrast on MRI images and can be easily distinguished. This can be contrasted to CT images of the brain and spinal cord, where the grey matter and the white matter cannot be clearly differentiated due to their similar attenuation (absorption) of X-rays.

The high resolution and the ability to clearly distinguish the grey matter from the white matter is clinically important for diagnosing diseases like brain or spinal abscess, brain or spinal tumour and brain infarction (stroke). Multiple sclerosis, a demyelination disease that affects the white matter of the brain, changes the hydrogen composition of the white matter so that plaque formed in the white matter as a result of the disease can be readily visualised. This plaque does not show up well on CT images due to its similar X-ray attenuation compared to the rest of the brain tissues. MRI is also excellent in detecting vertebral disc herniation—a cause of acute back pain.

TR

Risk assessment matrix

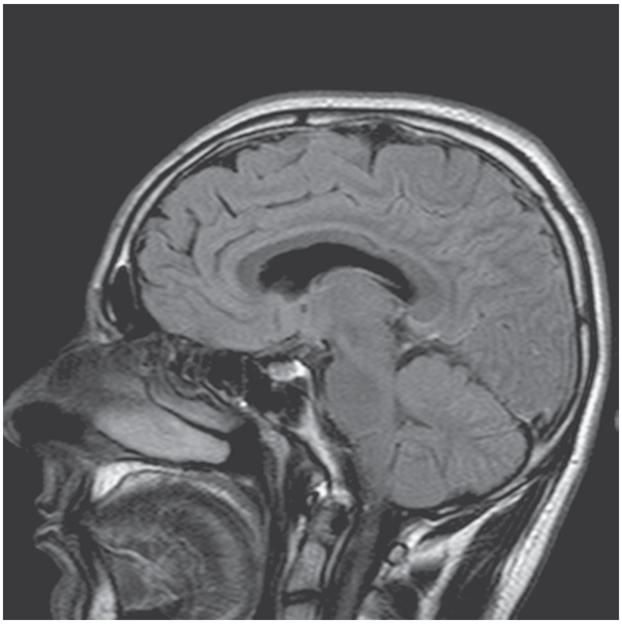


Figure 21.10 (a) MRI of the brain: healthy

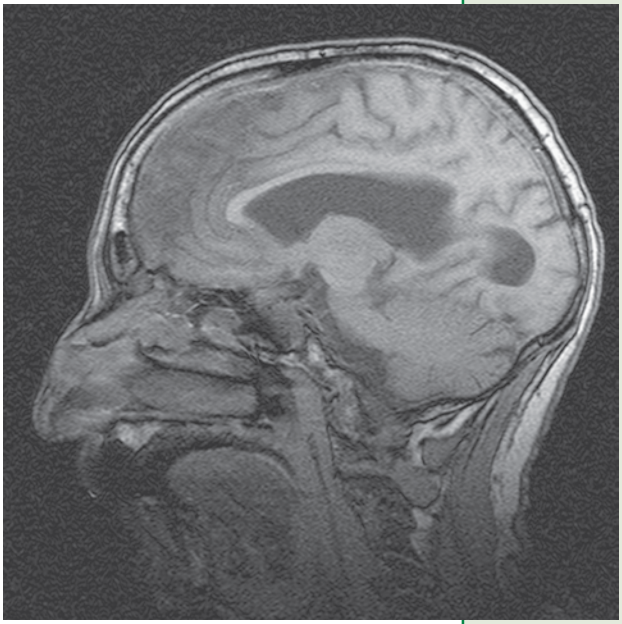


Figure 21.10 (b) MRI of the brain showing a loss of differentiation between the grey matter and the white matter; this may be due to a lack of blood supply to the brain—a stroke

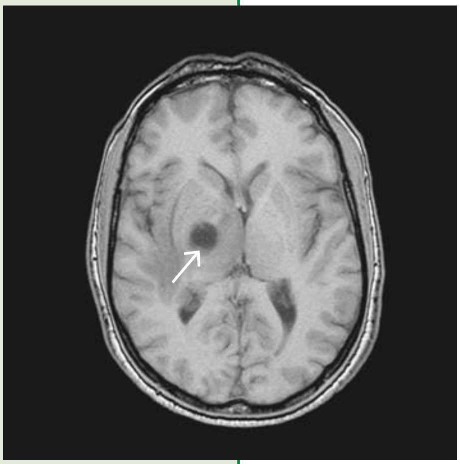


Figure 21.11 (a)
A brain tumour

Figure 21.11 (b)
A tumour that has spread to the spine (sacrum) (see arrow)

Detecting cancerous tissues

MRI is also used to detect cancerous tissues, for example lung, brain, thyroid and kidney cancers. Cancer cells may contain hydrogen atoms that have different T1 and T2 relaxation times, and hence may form a contrast with the surrounding tissues, see Figure 21.11 (a) and (b). Furthermore, cancerous tissues usually contain cells that are either damaged or malfunctioning, and therefore leakier. They often have a higher level of water or hydrogen content—this makes the cancerous tissues show up well on MRI images. Cancerous tissues, due to their high metabolic rate, will take up more contrasting material when administered and this further enhances their visualisation. For instance, a lymph node that takes up gadolinium will appear bright on a T1 weighted image due to the shortening of its T1 by gadolinium. Such a lymph node is usually malignant, as a normal lymph node only takes up gadolinium minimally.

Nevertheless, for economical and practical reasons, most malignancies are detected by CT scans rather than MRIs. (MRIs are expensive and are not always available). Occasional supplementary PET scans may help to assess the spread of the cancer.

Blood flow: Magnetic resonance angiogram

MRI can be used to selectively reconstruct blood vessels and therefore is excellent for studying the vascular (blood vessel) anatomy, particular in the brain. This is also known as **magnetic resonance angiogram (MRA)**. There are two ways blood vessels can be selectively studied using magnetic resonance. One method is known as time-of-flight MRA. In this modality, both the stationary tissue and blood are pre-saturated with radio waves.

NOTE: Recall that to achieve saturation is to continuously bombard the tissue with radio waves so that its M vector cannot relax and the nuclei can no longer absorb more energy.

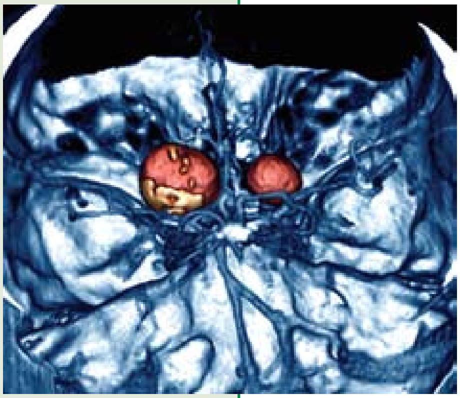
However, because blood flows away, blood which was pre-saturated is now elsewhere. The fresh blood that flows in is unsaturated and therefore is able to absorb radio waves and later re-emit them for the reconstruction of the blood vessel anatomy.

NOTE: The surrounding tissue will not re-emit any radio waves because it has not absorbed any.

The second method is known as phase contrast MRA. In this, the background tissue signals are subtracted from the flow-enhanced signals (due to the movement induced phase shift in the precession of the hydrogen nuclei), and the difference is used for the blood vessel reconstruction. A minimum of two image signals is required. Phase contrast MRA produces better quality images compared to time-of-flight MRA due to a better background tissue suppression; however, it has a more prolonged scanning time.

MRA is used to study the blood vessels that supply the brain: the carotid arteries and circle of Willis. The blood vessels can be easily

Figure 21.12
MRA of the circle of Willis showing Berry aneurysm



visualised, and problems such as thrombus (clots), leakage, aneurysm (abnormal dilation of the blood vessel which can break and bleed, see Figure 21.12), stenosis (narrowing) and many more can be diagnosed. MRA is the key investigation for stroke patients. MRA is better than CT angiogram because a contrast agent (which can damage the kidneys) is not needed. In addition, it is able to provide a better resolution and contrast so that smaller vessels and smaller problems can be identified.

Figure 21.13 MRI of the knee, with two different views

Soft tissues

MRI is excellent for the study of soft tissues. Tissues like muscles, tendons, ligaments and cartilages all have excellent MRI signals that can be analysed to give high-resolution images. MRI is commonly used to study the musculoskeletal system to diagnose degenerative joint diseases, such as osteoarthritis, torn tendons, torn muscles or other mechanical injuries. Injured tissues enhance particularly well with T2 weighting. The principle behind this is that injured soft tissues accumulate water, and free water has a long T2 relaxation time and shows up brightly on T2 weighted images.

Functional MRI

By manipulating the ways radio waves are transmitted and received, MRI can be used to study the perfusion (degree of blood flow) of various organs, and hence the functional aspects of the organs.

NOTE: Remember MRI is unsuitable for scanning any body parts that are constantly moving.

Observing MRI images

You are required to observe MRI images and make comparisons between the healthy and the diseased organs or tissues. This section provides some selections of MRI images, including a comparison between the healthy and diseased appearances of the same organs. You may wish to obtain more images of interest through further research. Some suggested sources include the internet, medical textbooks and journals. The book 'MRI-basic principles and applications' by Mark A. Brown and Richard C. Semelka published by John Wiley & Sons in 2003 contains a variety of MRI images. It may be used as a handy reference should a more in-depth understanding of MRI be sought.

After observing the MRI images:

- Which features of these images can help to identify them as MRI images. Make a list to describe how MRI images are different from CT images.
- One thing MRI images have in common with CT images is the ability to represent organs using slices oriented in different planes. How many different types of slices are there and what are they?
- Observe the T1 and T2 weighted images of the same organ, list the differences. Remember, water appears bright on T2 weighted images and dark on T1 weighted images.

A comparison between the imaging techniques

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H11.3A, C
H12.3A, B, C, D
H12.4A, C, F
H13.1A, B
H14,1A, B, E, G, H

■ *Identify data sources, gather and process information to compare the advantages and disadvantages of X-rays, CAT scans, PET scans and MRI scans*

The advantages and disadvantages of ultrasound, plain X-rays, CT scans, endoscopies and nuclear scans have been discussed individually in the previous chapters. The main advantages and disadvantages of MRI are summarised below.

Advantages

- MRI provides high-resolution images of body organs. MRIs can visualise almost all body organs well, except those which are constantly in motion, such as the heart and chest wall. With the application of various forms of signal sequencing (e.g. T1, T2 weighting, pre-saturation and so on), excellent contrast between tissues, both healthy and diseased, can be achieved. Under many circumstances, MRI is the best image modality to achieve diagnosis.
- MRI avoids the use of harmful ionising radiation.
- Compared to endoscopies, MRI is non-invasive.

Disadvantages

- MRI is very costly. MRI machines are expensive and the cost of maintenance (including the cost of the coolants for the superconductor magnets) is also high.
- The main solenoid used by MRI takes a tunnel shape. Some patients when lying inside this tunnel can develop severe anxiety attacks and claustrophobia. These patients are unable to undergo MRI scans.
- MRI examinations are lengthy. They require patients to be still, which may pose difficulties when scanning children or uncooperative patients.

Table 21.3 compares all image methods in terms of their cost, resolution, length of the examination, comfort and safety as well as their uses for each of the body systems.

Table 21.3 A summary of all scanning methods studied in this module

	Ultrasound	Plain X-ray	CT scan	Endoscope	Nuclear medicine	MRI
Cost[a]	One of the cheapest image methods: about \$50 to \$100	One of the cheaper image methods: about \$20 to \$50	Moderately expensive: cost is around \$200	The doctors' fee is about \$200[b]	A standard radioisotope scan is around \$100; a PET scan is over \$500	Expensive: cost ranging from \$400 to \$600
Resolution	Low 1–5 mm	High 0.5 mm	Moderate 1 mm	Very high 0.1 mm	Low 5–10 mm	High 0.5 mm
Length of the examination[c]	Varies: usually about 30 minutes	About 1 minute	About 5 minutes	Varies: usually about 30 minutes	Varies: radioisotope scans usually take about 5 to 10 minutes, PETs can take up to 30 minutes	15 to 30 minutes

	Ultrasound	Plain X-ray	CT scan	Endoscope	Nuclear medicine	MRI
Comfort and safety	Non-invasive and the patient is usually quite comfortable. Because no ionising radiation is used, it is 100% safe.	Comfortable. Minimal harm to the patient due to the low dose of X-rays used. Not recommended in pregnancy.	Comfortable. More harm than plain X-ray films due to the higher dose of X-rays used. Not recommended in pregnancy.	The procedure is invasive and has associated risks. Examination is generally uncomfortable and needs to be performed under anaesthetic.	Comfortable. Gamma radiation may cause harm. Not recommended in pregnancy.	Most patients find it comfortable apart from the noises of the machine. Some patients can be claustrophobic and can develop panic attacks while having the scan.
Central nervous sytem	The brain and the spinal cord cannot be visualised well because of their bony coverage.	The brain and the spinal cord cannot be visualised.	Can be used to diagnose most pathologies, including stroke, tumour, infection, abscess and bleeding.	Not available.	For studying the function of the brain and diagnosing functional brain diseases, for example, epilepsy.	**Can diagnose most pathologies and is more accurate than CT. MRA can be used to study the blood vessels supplying the brain and the spinal cord.
Cardio-vascular system	**Duplex ultrasound is the diagnostic tool of choice for studying cardiac and vascular conditions. Duplex scan can exam both the anatomy and the blood flow.	Contrast can be injected to outline blood vessels. Used for studying coronary vessels (blood vessels that supply the heart)—coronary angiography.	Good for studying the anatomy of the heart and the course of a blood vessel. Contrast may improve the image quality.	Not available.	Tc-99m labelled albumin can be used to trace the blood flow. Tc-99m labelled MIBI can be used to assess the cardiac function.	MRA is good for studying the anatomy of blood vessels. Functional MRI is occasionally used to study the perfusion of organs.
Respiratory system	Airway and lungs are difficult to visualise due to their rib coverage.	**Screening investigation for lung conditions. Although not all that accurate, it provides clues based on which other scans may be ordered.	**Pathologies detected on a plain X-ray film can be further evaluated using a CT scan. Reliable and accurate.	Bronchoscope can be used to detect airway lesions, such as a tumour.	Ventilation and perfusion scan is useful for diagnosing pulmonary embolism.	Rarely used (due to movement).
Digestive system	Good for detecting gallstones. Can visualise liver, pancreas and spleen.	Only with the use of contrast, the gastrointestinal tract may be visualised. Limited values.	**The scanning modality of choice for detecting intra-abdominal pathologies. Can visualise well all intra-abdominal organs and the gastrointestinal tract (although not too accurate for small luminal conditions). Image quality can be further improved by the use of contrast agents.	Gastroscope and colonoscope are usefully for detecting luminal pathologies of the gastrointestinal tract. Laparoscope is the most accurate diagnostic tool for intra-abdominal conditions, however it is invasive. Laparoscope is an essential component of key-hole surgery.	Occasionally used for functional bowel diseases, such as gastroparesis (ineffective contraction of the gastrointestinal tract leading to a delayed transit time). PET can be used to detect the intra-abdominal spread of a cancer.	Occasionally used for detecting intra-abdominal malignancies.

continues

	Ultrasound	Plain X-ray	CT scan	Endoscope	Nuclear medicine	MRI
Musculo-skeletal system	Useful for accessing soft tissue injuries. Low resolution and operative dependency limit its use.	**The investigation of choice for bone conditions, mainly fractures. Often the first line investigation for musculoskeletal pain.	Can visualise bones and soft tissues well. Useful for assessing complex injuries such as very comminuted fractures (small fragments). 3D CT can further aid the diagnosis.	Arthroscope can be used to diagnose and treat joint conditions, for example, diagnosing osteoarthritis or repairing torn ligaments.	Bone scan can detect conditions that are unable to be seen on a plain X-ray film or a CT image. Occult fracture and osteomyelitis are some examples.	**MRI has a similar role compared to CT but has a higher resolution therefore is more accurate and reliable. MRI can visualise tendons, ligaments and cartilages better than CT.

a. Cost can vary quite substantially. Different doctors or radiographers may charge different rates. Also examination of certain body systems may be more expensive than others. Hence only a rough estimation is provided here.
b. Most endoscopic examinations need to be performed in the operating theatre with the presence of an anaesthetist, therefore these costs need to be added. In addition, if endoscopic procedures are performed, further costs will incur.
c. Not including set-up time and positioning of the patient.
d. Patient usually needs to be injected first and then return a few hours later for the actual scan. This waiting is not included as a part of the examination time.
** Most useful or most commonly used imaging method for this body system.

The impact of medical applications of physics on society

SECONDARY SOURCE INVESTIGATION

PFAs

H4, H5

PHYSICS SKILLS

H12.3A, B, C, D, E
H12.4A, B, C, F
H14.1A, B, D, E, G, H
H14.3C, D

■ *Gather, analyse information and use available evidence to assess the impact of medical applications of physics on society*

There is no doubt that an increase in the knowledge of and the ability to manipulate physics has led to the development of many advanced imaging methods. Ultrasound, plain X-rays, CTs, endoscopies, nuclear medicine scans and MRIs all have important roles in studying the anatomy of the body and establishing diagnosis of conditions. The impacts of these imaging methods on society are multi-dimensional, both positive and negative.

Healthier society

The advance in imaging techniques allows early diagnosis hence better management of certain diseases, leading to a healthier society. For instance, ultrasound has been widely used in antenatal clinics for detecting foetal abnormalities before birth. This allows minor abnormalities or deformities to be corrected via intrauterine interventions. In the case of major abnormalities or deformities, other options maybe discussed with the parents. Chest X-rays have been widely adopted to screen for lung diseases, such as tuberculosis (TB), in immigrants arriving to Australia. This helps to reduce the incidence of TB in our country. CT scans and PET scans have been used to detect and evaluate the spread of cancer, helping doctors to work out the best treatment for the patient, whether for surgical resection or radiotherapy or chemotherapy.

The invention of laparoscopes has led to the development of key-hole surgeries. Key-hole removal of the gall bladder leaves behind smaller wounds (key-hole size), allowing a quicker recovery time as well as a lower infection and complication rate. Arthroscopic surgeries of the joints, whether to repair a torn ligament or tendon can minimise post-operative pain and rehabilitation and therefore enable patients to return to their full function earlier.

SR

'Assess'

Increase in medical knowledge

As described in Chapter 20, PET scans allow the study of regional functions of the brain. This allows doctors to predict the outcomes of certain debilitating diseases of the brain, such as multiple sclerosis (where there is a scarring of the brain with unknown aetiology) or stroke.

Economics

Associated with the advance in medical imaging methods is the increase in cost. Some of the medical imaging devices are very expensive. An MRI or a PET machine costs millions of dollars to install and maintain. It poses a heavy burden on the government and healthcare funding to provide these scans in all hospitals.

Ethics

With the widespread use of imaging methods comes some unresolved ethical issues. For example, if a foetus was diagnosed to have a major genetic defect or a major abnormality on ultrasound, what to do next? Is it ethical to perform an abortion and what is the latest time to perform it? Is it ethical to perform intra-uterine operations? Is it ethical to have the birth of the foetus?

Certain imaging devices are expensive and may only be available to those who are rich (in the private hospitals). By using better scanning techniques, the rich can have diseases detected, and thus treated, early. Not all human beings are being treated equally.

The use of ionising radiation, such as in nuclear medicine, X-rays or CT, in women who are pregnant but do not know this at the time of the test—causing later foetal deformity—is both an ethical and a legal concern.

CHAPTER REVISION QUESTIONS

1. Although the element carbon-12 forms the basic building block for most body tissues, it does not contribute to the image formation in MRI. Explain the reason for this.
2. Nuclei with a net spin, when subjected to a strong external magnetic field, will align either parallel or anti-parallel to the magnetic field lines.
   (a) Are there more parallel or anti-parallel alignments?
   (b) Identify which type of alignment has a higher energy level.
   (c) Describe what can be done to change the low energy alignments to the high energy alignments.
   (d) Explain the significance of the change in alignments of the nuclei in the context of MRI.
3. (a) Define precession.
   (b) Explain why precession is an important part of MR image formation.
4. Describe how MRI is able to locate signals coming from different positions along the longitudinal axis of the body. In your answer, discuss the significance of the Larmor frequency for signal location along the longitudinal axis of the body.
5. The returning radio waves from the nuclei as they return to their original alignments are used for MR image reconstruction. Describe the factors that determine the brightness and contrast of the images formed.

6. (a) Define T1 relaxation and T1 relaxation time.
   (b) Define T2 relaxation and T2 relaxation time.
7. Describe how MRI produces T1 weighted images. What tissues show up brightly on T1 weighted images?
8. Describe how MRI produces T2 weighted images. What tissues show up brightly on T2 weighted images?
9. (a) Identify the main hardware components of an MRI machine.
   (b) Describe the advantages of superconducting magnets over normal solenoid magnets.
   (c) Describe one safety precaution needed when operating a MRI machine.
10. June is a 57-year-old woman who presented to her GP with neurological symptoms. Her GP referred her to a neurologist, who then ordered an MRI scan of her brain and spinal cord.
   (a) Explain why the neurologist chose MRI over CT.
   (b) Identify one disadvantage of MRI, assuming June is not claustrophobic.
   (c) If June has a metal pacemaker for her heart condition, can she still have the scan? Why?
   (d) If MRI is negative for any medical conditions, describe what other options there are for the neurologist.
11. Ken is a 19-year-old boy who twisted his right knee during a soccer match. He heard a pop and this was followed by knee swelling and excruciating pain. He limped into an orthopaedic surgeon's consulting room. The surgeon suspected that Ken might have torn one of the ligaments in the knee and ordered an MRI scan of the knee.
   (a) Would plain X-ray films have any value in this clinical scenario?
   (b) Could ultrasound be used for diagnosing ligament tears in the knee joint? Explain.
12. Define MRA and name two clinical scenarios for which MRA may be useful.
13. Assess the impact of medical physics on society.

SR

Answers to chapter revision questions