Lecture Four

MRI DESIGN: Gradient Functions

Gradients are coils of wire that, when a current is passed through them, alter the magnetic field strength of the magnet in a controlled and predictable way. They add to or subtract from the existing field in a linear fashion so that the magnetic field strength at any point along the gradient is known (Figure 27.1).

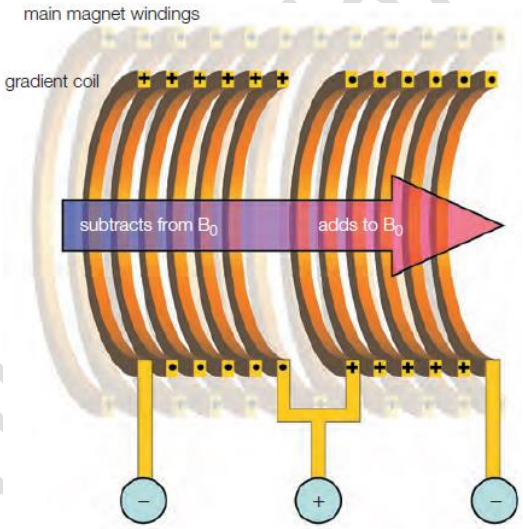


Figure 27.1 A gradient coil.

When a gradient is applied the following occur.

At **magnetic isocentre** (the centre of all three gradients), the field strength remains unchanged even when the gradient is switched on. At a certain distance away from isocentre, the field strength either increases or decreases. The magnitude of the change depends on the distance from isocentre and the strength of the gradient (Figure 27.2).

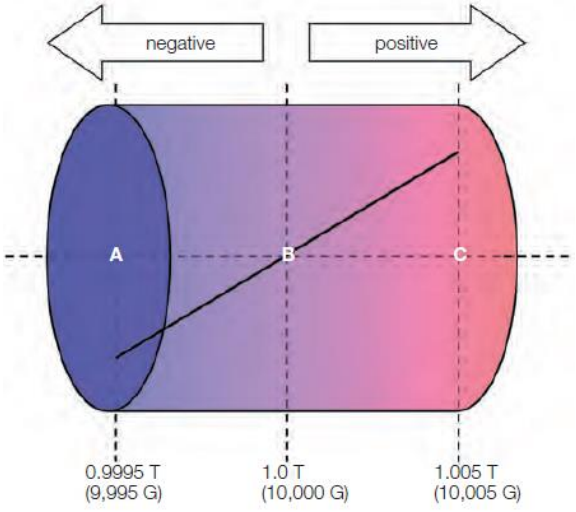


Figure 27.2 Gradients and changing field strength.

The slope of the gradient signifies the rate of change of the magnetic field strength along its length. The strength or *amplitude* of the gradient is determined by *how much current* is applied to the gradient coil. Larger currents create steeper gradients, so that the change in field strength over distance is greater. The reverse is true of smaller currents.

The polarity of the gradient determines which end of the gradient produces a higher field strength than isocentre (positive) and which a lower field strength than isocentre (negative). The *polarity* of the gradient is determined by the *direction of the current* flowing through the coil. As coils are circular, current either flows clockwise or anticlockwise.

The *maximum amplitude* of the gradient determines the maximum achievable *resolution*. Therefore, if at least one (and sometimes all three) gradients are steep, small voxels are achieved.

The *maximum speeds* at which gradients can be switched on and off are called the **rise time** and **slew rate**. Both of these factors determine the maximum scan speeds of a system. Therefore, in fast sequencing the gradients have high slew rates.

How gradients work

The precessional frequency of the magnetic moments of nuclei is proportional to the magnetic field strength experienced by them (as stated by the Larmor equation). The frequency of the signal received from the patient can be changed according to its position along the gradient. The precessional phase is also affected, as faster magnetic moments gain phase compared with their slower neighbours. Imposing a gradient magnetic field, therefore:

• changes the field strength in a linear fashion across a distance in the patient;

• changes the precessional **frequency** of magnetic moments of nuclei in a linear fashion across a distance in the patient (Table 27.1);

Table 27.1 Frequency changes along a linear gradient.

Position along gradient	Field strength (gauss)	Larmor frequency (MHz)
isocentre	10000	42.5700
1 cm negative from isocentre	9999	42.5657
2 cm negative from isocentre	9998	42.5614
1 cm positive from isocentre	10001	42.5742
2 cm positive from isocentre	10002	42.5785
10 cm negative from isocentre	9990	42.5274

• changes the precessional **phase** of magnetic moments of nuclei in a linear fashion across a distance in the patient (Figure 27.3). These characteristics can be used to **encode** the MR signal in three dimensions. In order to do this, there must be three orthogonal sets of gradients situated within the bore of the magnet. They are named according to the axis along which they work:

• The *Z gradient* alters the magnetic field strength along the *Z axis.*

• The *Y gradient* alters the magnetic field strength along the *Y axis.*

• The *X gradient* alters the magnetic field strength along the *X axis.*

• The **magnetic isocentre** is the centre of all three gradients.

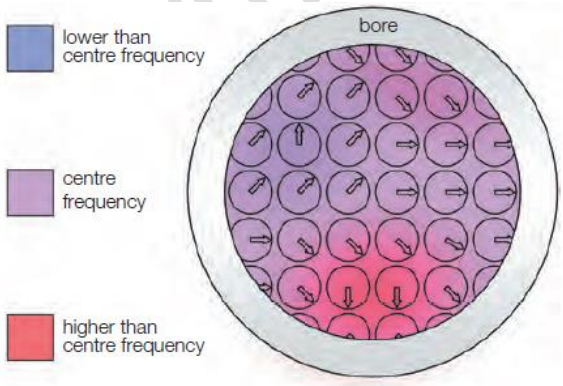


Figure 27.3 How gradients change frequency and phase.

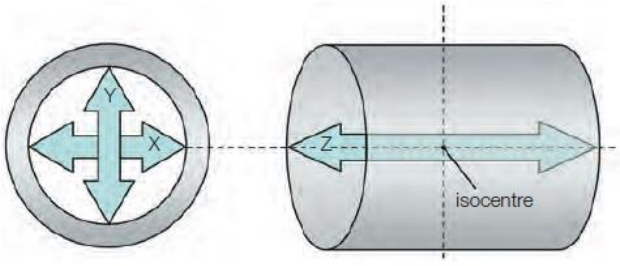


Figure 27.4 Gradient axes.

The field strength here does not change even when a gradient is applied (Figure 27.4). There are only three gradients, but they are used to perform many important functions during a pulse sequence. For example, in gradient echo sequences, a gradient is used to refocus spins and produce a gradient echo. One of these functions is **spatial encoding**; that is, spatially locating a signal in three dimensions. In order to do this, three separate functions are necessary. Usually each gradient performs one of the following tasks. The gradient used for each task depends on the plane of the scan and on which gradient the operator selects to perform frequency or phase encoding.

• **Slice selection** – locating a slice in the scan plane selected.

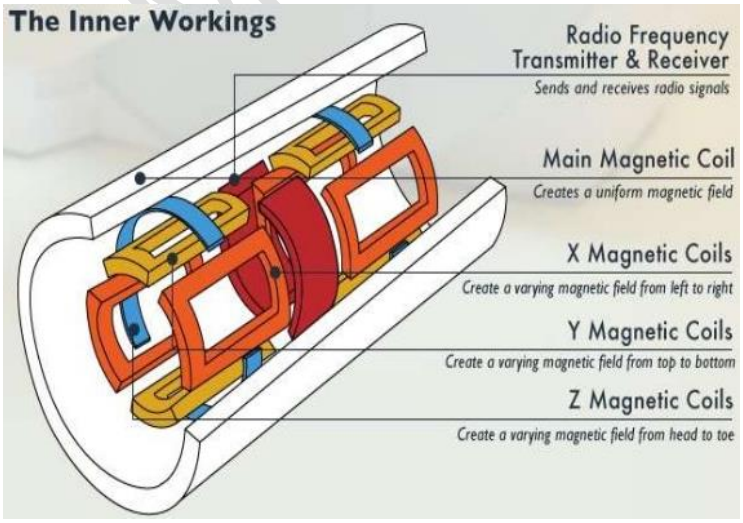
• Spatially locating signal along the short axis of the image. This is called **phase encoding**.

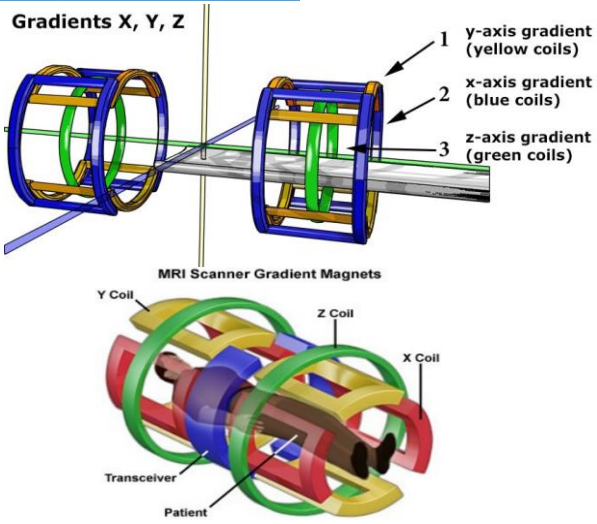
• Spatially locating signal along the long axis of the image. This is called **frequency encoding** (Table 27.2).

Table 27.2 Gradient axes in orthogonal imaging.

	Slice selection	Phase encoding	Frequency encoding
Sagittal	X	Y	Z
Axial (body)	Z	Y	X
Axial (head)	Z	X	Y
Coronal	Y	X	Z

(Where X is across the bore of the magnet from right to left)





KEY POINTS

✓ When a moving current is passed through a conductor, a magnetic field is induced around it.

✓ Gradient coils are conductors that cause a linear change in magnetic field strength along their axes when a current is passed through them.

✓ The amount of current passing through the coil determines the amplitude, strength or slope of the gradient.

✓ The direction of the current passing through the coil determines its polarity.

✓ When a gradient is switched on it causes a linear change in magnetic field strength and therefore precessional frequency and phase of the magnetic moments of spins that lie along it.

MRI DESIGN: Slice Selection

Mechanism

As a gradient alters the magnetic field strength of the magnet linearly, the magnetic moments of spins within a specific slice location along the gradient have a unique precessional frequency when the gradient is on. Transmitting RF at that unique precessional frequency therefore selectively excites a slice.

Example: a 1T field strength magnet with a gradient imposed that has changed the field strength between slices A and B causing a change in precessional frequency between slices A and B of 2.6 MHz (Figure 28.1).

• The precessional frequency of magnetic moments between slices A and B has changed by 2.6 MHz.

• To excite nuclei in slice A, an RF pulse of 41.20 MHz must be applied.

• Slice B and all other slices are not excited because their precessional frequencies are different due to the influence of the gradient.

• To excite slice B, another RF pulse with a frequency of 43.80 MHz must be applied. Nuclei in slice A do not resonate after the application of this pulse because they are spinning at a different frequency.

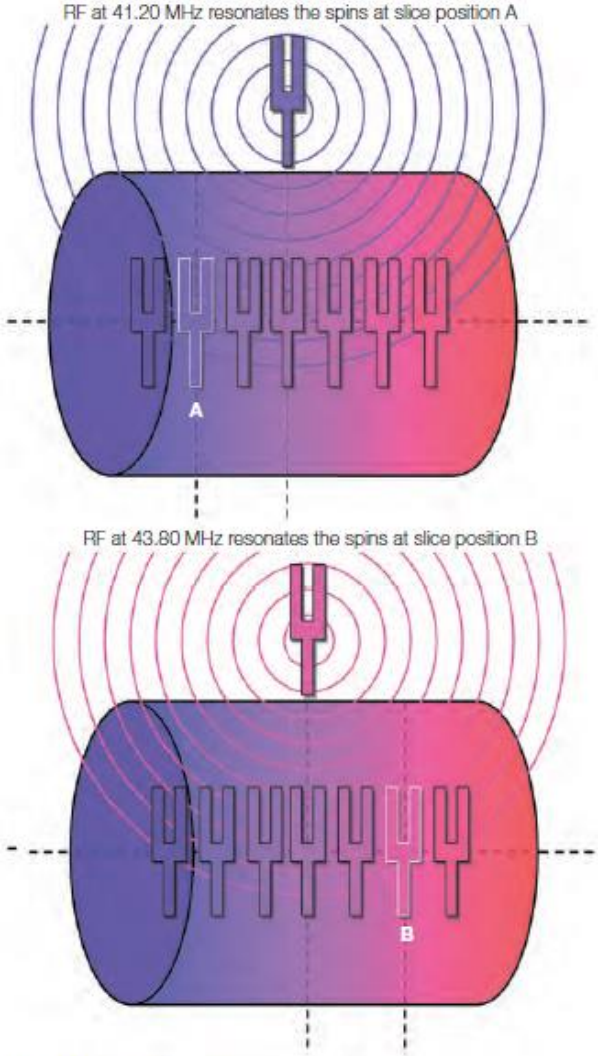


Figure 28.1 Slice selection.

The scan plane selected determines which gradient performs slice selection. In a superconducting system the following usually apply (in an open magnet system, the Z and Y axes are transposed and some manufacturers transpose X and Y):

• The Z gradient selects axial slices, so that nuclei in the patient's head spin at a different frequency to those in the feet.

• The Y gradient selects coronal slices, so that nuclei at the back of the patient spin at a different frequency to those at the front.

• The X gradient selects sagittal slices, so that nuclei on the righthand side of the patient spin at a different frequency to those on the left (Figure 28.2).

• A combination of any two gradients selects oblique slices.

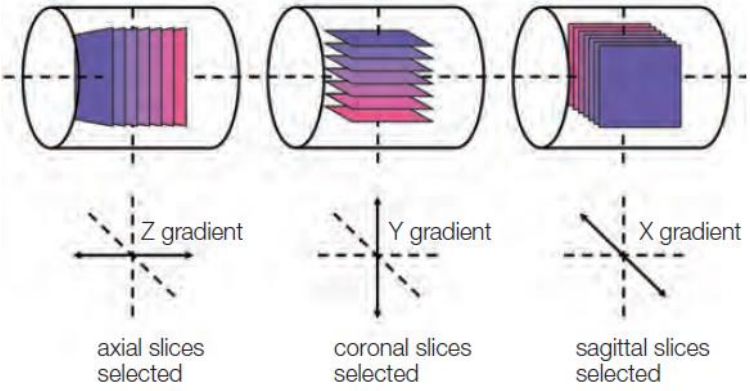


Figure 28.2 Using X, Y and Z gradients to select slices.

Slice thickness

In order to attain slice thickness, a range of frequencies must be transmitted to produce resonance across the whole slice (and therefore to excite the whole slice). This range of frequencies is called a bandwidth and because RF is being transmitted at this instant, it is specifically called the **transmit bandwidth**.

The slice thickness is determined by the slope of the slice select gradient and the transmit bandwidth. It affects inplane spatial resolution and SNR.

• Thin slices require a steep slope or a narrow transmit bandwidth, and improve spatial resolution.

• Thick slices require a shallow slope or a broad transmit bandwidth, and decrease spatial resolution (Figure 28.3).

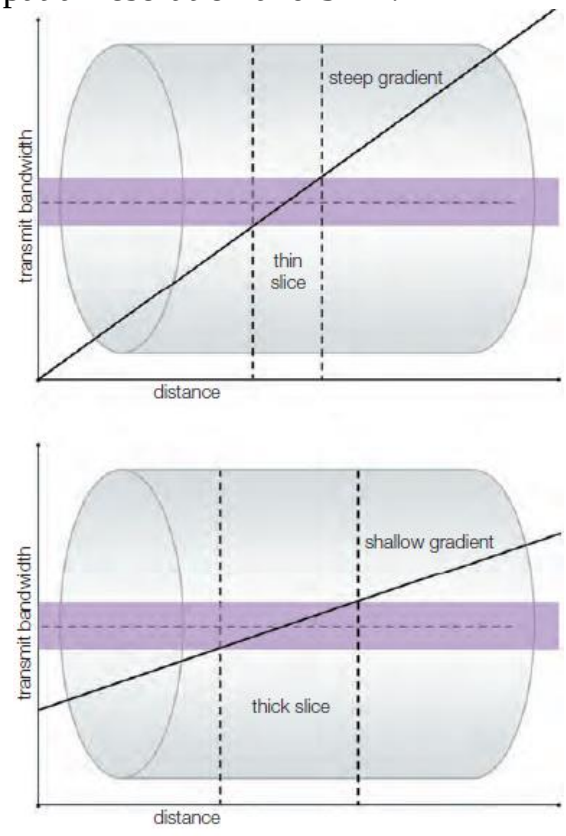
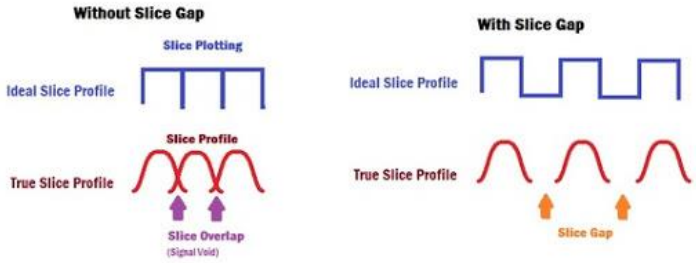


Figure 28.3 Transmit bandwidth, gradient slope and slice thickness

A slice is therefore excited by transmitting RF with a centre frequency corresponding to the middle of the slice, and a bandwidth and gradient slope according to the thickness of the slice required. The slice gap or skip is the space between slices. Too small a gap in relation to the slice thickness can lead to an artefact called **cross-talk**. This is caused because RF excitation pulses are Gaussian in shape (not exactly square). They have small 'tails' that overlap when RF pulses are too close together. This causes part of a slice to receive too much RF, resulting in cross-talk artefact.



The slice select gradient is always switched on during the delivery of the RF excitation pulse in the pulse sequence. It is switched on in the positive direction. The slice select gradient is also applied during the 180° pulse in spin echo sequences so that the RF rephasing pulse can be delivered specifically to the selected slice (Figure 28.4). Although not always shown, in all pulse sequences compensatory gradients are applied around each application of the slice select gradient. This is to compensate for the change of phase that the gradient imposes. This change of phase is not wanted in the slice selection process and is eliminated by these compensatory gradients.

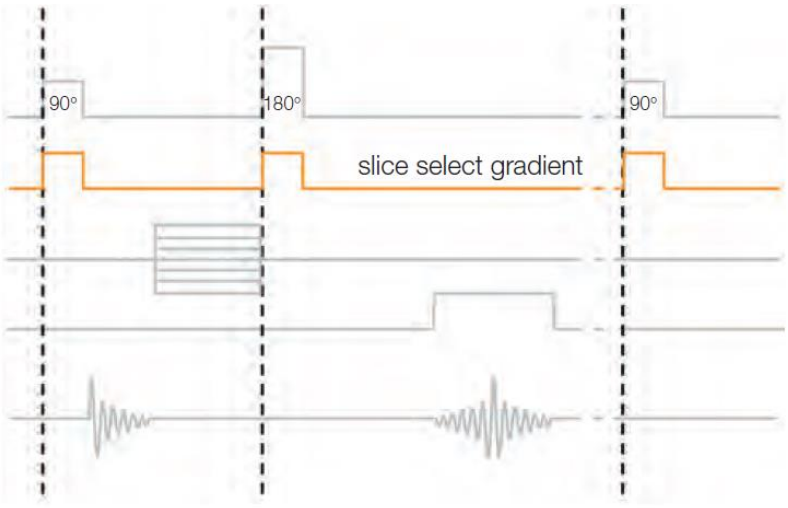


Figure 28.4 Timing of slice selection in a spin-echo pulse sequence.

KEY POINTS

✓ Slices are selected by applying a gradient at the same time as the RF excitation and rephasing pulse.

✓ The slice select gradient changes the magnetic field strength and therefore the precessional frequency of the magnetic moments of spins that lie along it.

✓ An RF pulse at the specific frequency of magnetic moments of spins in a particular slice on the gradient causes resonance of the slice.

✓ RF is transmitted width a bandwidth or range of frequencies on either side of the centre frequency of the slice.

✓ Slice thickness is altered by changing either the slope of the slice select gradient or the transmit bandwidth.

✓ Thin slices require either a steep slice select gradient slope or a narrow transmit bandwidth.

✓ Thick slices require either a shallow slice select gradient slope or a broad transmit bandwidth.

MRI DESIGN: Contrast Agents

In order to increase contrast between pathology and normal tissue, enhancement agents may be introduced that selectively affect the T1 and T2 relaxation times in tissues. Both T1 recovery and T2 decay are influenced by the magnetic field experienced locally within the nucleus. The local magnetic field responsible for these processes is caused by:

• the main magnetic field;

• fluctuations as a result of the magnetic moments of nuclear spins in neighbouring molecules.

These molecules rotate or tumble, and the rate of rotation of the molecules is a characteristic property of the solution. It is dependent on:

• magnetic field strength;

• viscosity of the solution;

• temperature of the solution.

Molecules that tumble with a frequency at or near the Larmor frequency have more efficient T1 recovery times than other molecules (Figure 50.1).

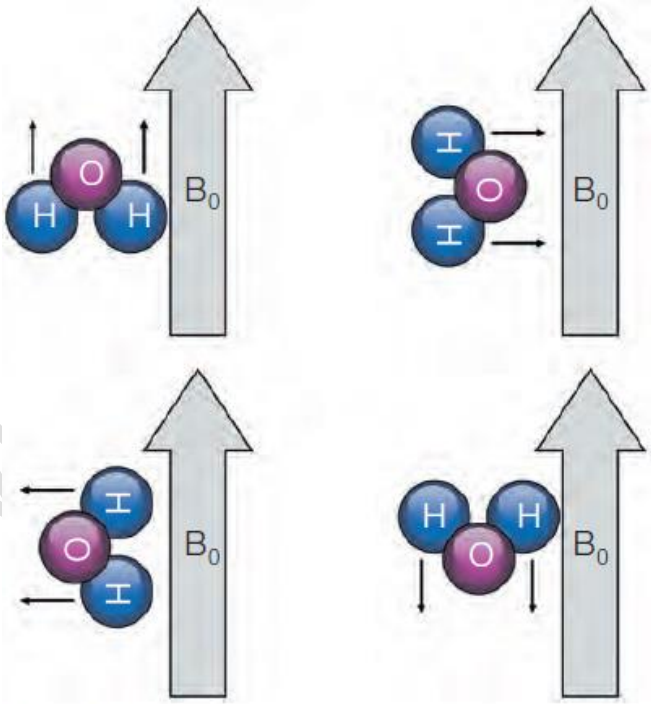


Figure 50.1 Tumbling of water molecules.

The phenomenon by which excited protons are affected by nearby excited protons and electrons is called dipole-dipole interaction. If a tumbling molecule with a large magnetic moment such as gadolinium is placed in the presence of water protons, local magnetic field fluctuations occur near the Larmor frequency. T1 relaxation times of nearby protons are therefore reduced and so they appear bright on a T1 weighted image. This effect on a substance whereby relaxation rates are altered is known as relaxivity.

Gadolinium

Gadolinium (Gd) is a paramagnetic agent. It is a trivalent lanthanide element that has seven unpaired electrons and an ability to allow rapid exchange of bulk water to minimize the space between itself and water within the body. It has a large magnetic moment and, when it is placed in the presence of tumbling water protons, fluctuations in the local magnetic field are created near the Larmor frequency. The T1 relaxation times of nearby water protons are therefore reduced, resulting in an increased signal intensity on T1 weighted images. For this reason, gadolinium is known as a T1 enhancement agent.

Chelation

Gadolinium is a rare earth metal that cannot be excreted by the body and would cause long-term side effects as it binds to membranes. By binding the gadolinium ion to a chelate such as diethylene triaminepentaacetic acid (DTPA, a ligand), the chelate compound Gd-DTPA is formed, which can be safely excreted.

Administration

The effective dosage of Gd-DTPA is 0.1 millimoles per kilogram of body weight (mmol/kg) – approximately 0.2 ml/kg or 0.1 ml/lb – with a maximum dose of 20 ml.

Clinical applications

Gadolinium has proven invaluable in imaging the central nervous system because of its ability to pass through breakdowns in the blood–brain barrier (BBB). Clinical indications for gadolinium include:

• tumours (Figure 50.3); • infection; • arthrography (Figure 50.2);

• post-operation lumbar disc; • breast disease; • vessel patency and morphology.

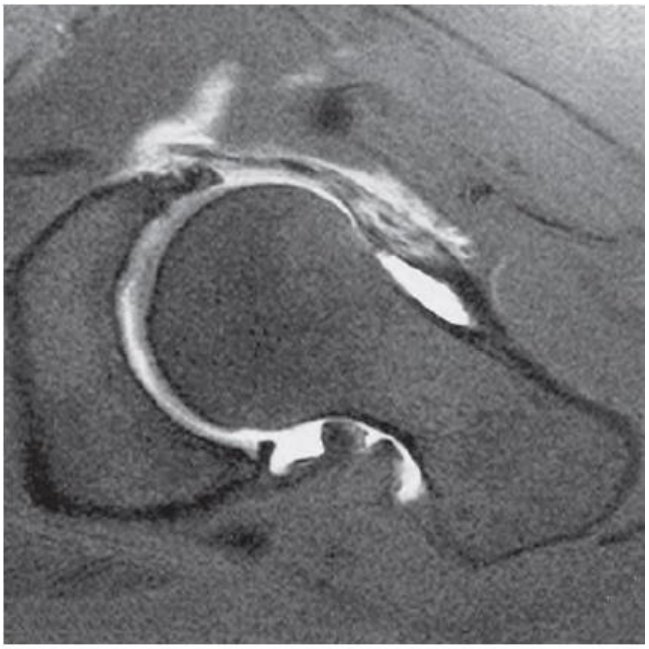


Figure 50.2 Axial arthrogram of the hip using gadolinium.

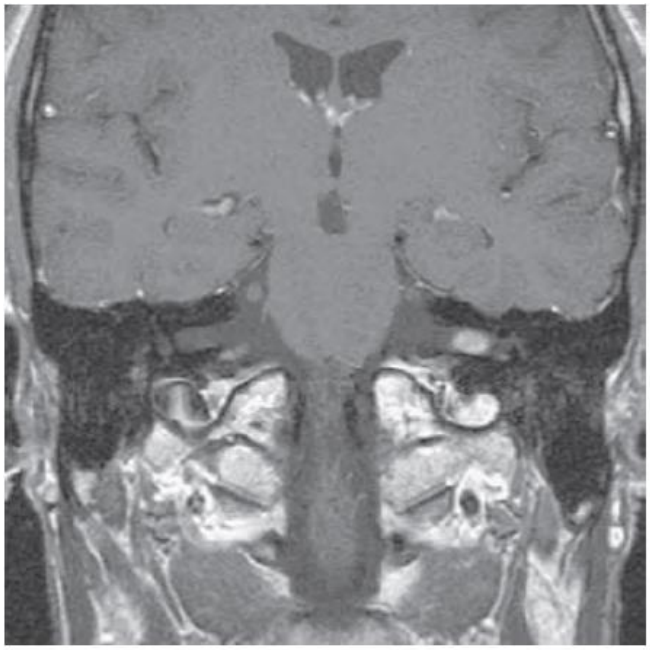


Figure 50.3 Coronal T1 weighted image of a small left acoustic neuroma after administration of gadolinium.

Iron oxide

Iron oxides shorten relaxation times of nearby hydrogen atoms and therefore reduce the signal intensity in normal tissues. This results in a signal loss on proton density weighted or heavily T2 weighted images. Super-paramagnetic iron oxides are known as T2 enhancement agents. Iron oxide is taken up by the reticuloendothelial system and excreted by the liver, so that normal liver is dark and liver lesions are bright on T2 weighted images.

Administration

The recommended dose of iron oxide is 0.56 mg of iron per kg of body weight. This should be diluted in 100 ml of 50% dextrose and given intravenously over 30 mins. The diluted drug is administered through a 5-micron filter at a rate of 2–4 mmol/min. This agent should be used within 8 hours following dilution.

Clinical applications

Iron oxide is mainly used in liver and biliary imaging (Figure 50.4).

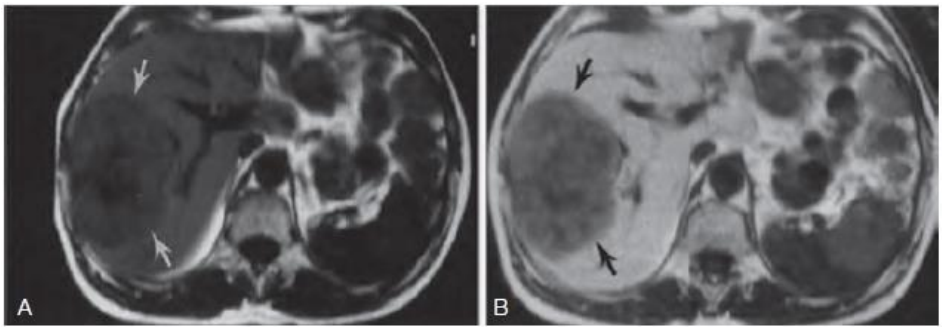


Figure 50.4 Axial T1 weighted image of the liver without (left) and with (right) manganese contrast.The enhanced image shows enhancement of normal liver so that the liver pathology is darker.

Other contrast agents

Gastrointestinal contrast agents are sometimes used for bowel enhancement. These include barium, ferromagnetic agents and fatty substances. However, due to constant peristalsis, these agents enhance bowel motion artefacts more often than enhancing pathological lesions. The use of anti-spasmodic agents helps to retard peristalsis to decrease these artefacts. Other agents include helium, which is inhaled and assists in the evaluation of lung perfusion.

Key points.

- The purpose of contrast agents is to ensure that pathology has a different contrast to surrounding normal anatomy.
- Contrast agents are either T1 or T2 enhancement agents.
- The effect of altering the relaxivity rates of tissues by administering a contrast agent is called relaxivity.