# 1 Introduction to medical imaging

1.1 RADIOGRAPHY (X-RAY IMAGING)

1.1.1 Conventional radiography (X-rays, plain films)

X-rays are produced in an X-ray tube by focusing a beam of high-energy electrons onto a tungsten target. X-rays are a form of electromagnetic radiation, able to pass through the human body and produce an image of internal structures. The resulting image is called a radiograph, more commonly known as an 'X-ray' or 'plain film'. The common terms 'chest X-ray' and 'abdomen X-ray' are widely accepted and abbreviated to CXR and AXR.

As a beam of X-rays passes through the human body, some of the X-rays are absorbed or scattered producing reduction or attenuation of the beam. Tissues of high density and/or high atomic number cause more X-ray beam attenuation and are shown as lighter grey or white on a radiograph. Less dense tissues and structures cause less attenuation of the X-ray beam, and appear darker on radiographs than tissues of higher density. Five principal densities are recognized on plain radiographs (Fig. 1.1), listed here in order of increasing density:

1. Air/gas: black, e.g. lungs, bowel and stomach
2. Fat: dark grey, e.g. subcutaneous tissue layer, retroperitoneal fat
3. Soft tissues/water: light grey, e.g. solid organs, heart, blood vessels, muscle and fluid-filled organs such as bladder
4. Bone: off-white
5. Contrast material/metal: bright white.
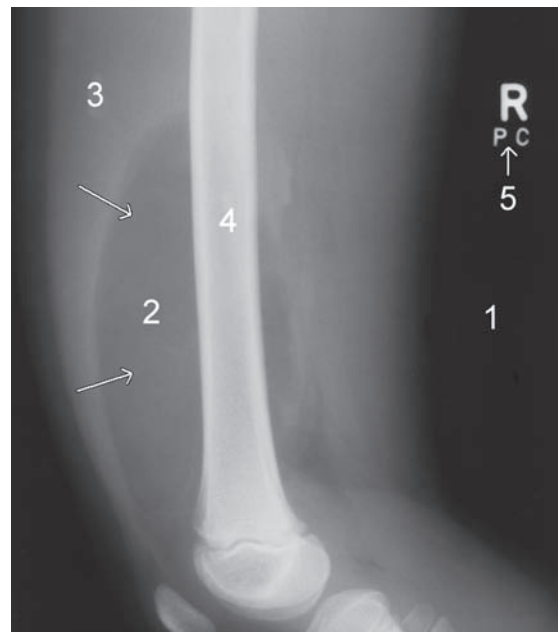
Figure 1.1 The five principal radiographic densities. This radiograph of a benign lipoma (arrows) in a child's thigh demonstrates the five basic radiographic densities: (1) air; (2) fat; (3) soft tissue; (4) bone; (5) metal.

1.1.2 Computed radiography, digital radiography and picture archiving and communication systems

In the past, X-ray films were processed in a darkroom or in freestanding daylight processors. In modern practice, radiographic images are produced digitally using one of two processes, computed radiography (CR) and digital radiography (DR). CR employs

cassettes that are inserted into a laser reader following X-ray exposure. An analogue-digital converter (ADC) produces a digital image. DR uses a detector screen containing silicon detectors that produce an electrical signal when exposed to X-rays. This signal is analysed to produce a digital image. Digital images obtained by CR and DR are sent to viewing workstations for interpretation. Images may also be recorded on X-ray film for portability and remote viewing. Digital radiography has many advantages over conventional radiography, including the ability to perform various manipulations on the images including:

- Magnification of areas of interest (Fig. 1.2)
- Alteration of density
- Measurements of distances and angles.

Many medical imaging departments now employ large computer storage facilities and networks known as picture archiving and communication systems (PACS). Images obtained by CR and DR are stored digitally, as are images from other modalities including computed tomography (CT), magnetic resonance imaging (MRI), ultrasound (US) and scintigraphy. PACS systems allow instant recall and display of a patient's imaging studies. Images can be displayed on monitors throughout the hospital in wards, meeting rooms and operating theatres as required.
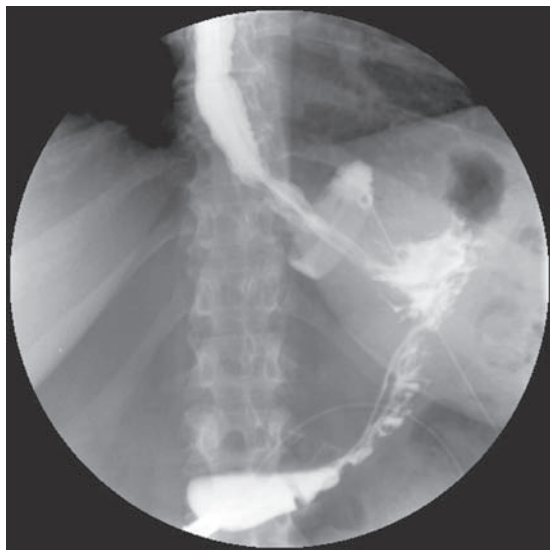
1.1.3 Fluoroscopy

Radiographic examination of the anatomy and motion of internal structures by a constant stream of X-rays is known as fluoroscopy. Uses of fluoroscopy include:

- Angiography and interventional radiology
- Contrast studies of the gastrointestinal tract (Fig. 1.3)
- Guidance of therapeutic joint injections and arthrograms
- Screening in theatre
  - General surgery, e.g. operative cholangiography
  - Urology, e.g. retrograde pyelography
  - Orthopaedic surgery, e.g. reduction and fixation of fractures, joint replacements.
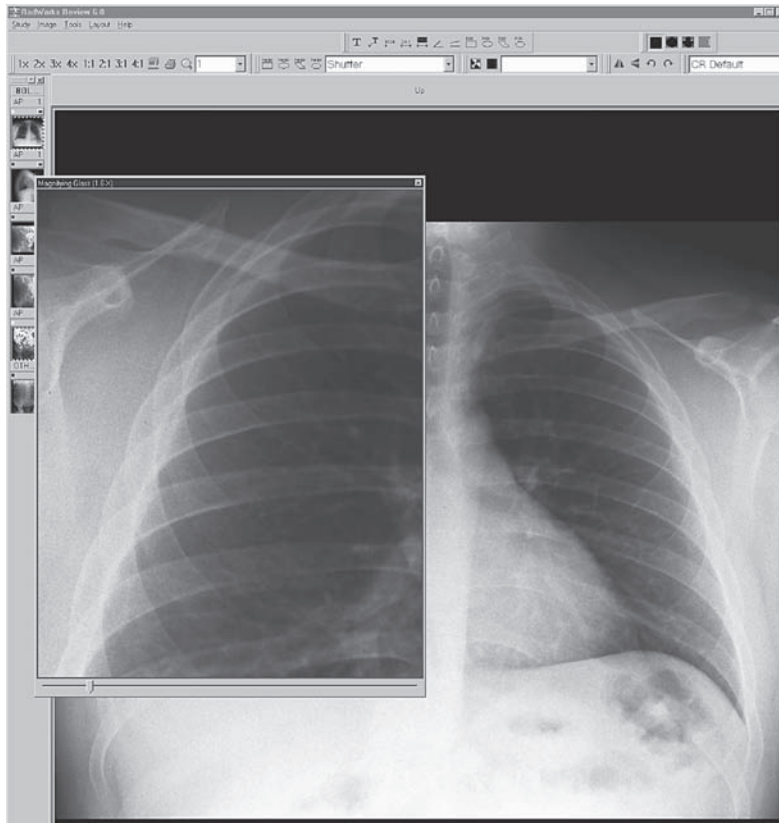
Figure 1.2 Computed radiography. With computed radiography images may be reviewed and reported on a computer workstation. This allows various manipulations of images as well as application of functions such as measurements of length and angle measurements. This example shows a 'magnifying glass' function, which provides a magnified view of a selected part of the image.

Figure 1.3 Fluoroscopy: Gastrografin swallow. Gastric band applied laparoscopically for weight loss. Gastrografin swallow shows normal appearances: normal orientation of the gastric band, gastrografin flows through the centre of the band and no obstruction or leakage.

Fluoroscopy units fall into two categories: image intensifier and flat panel detector (FPD). Image intensifier units have been in use since the 1950s. An image intensifier is a large vacuum tube that converts X-rays into light images that are viewed in real time via a closed circuit television chain and recorded as required. FDP fluoroscopy units are becoming increasingly common in angiography suites and cardiac catheterization laboratories ('cath labs'). The FDP consists of an array of millions of tiny detector elements (DELs). Most FDP units work by converting X-ray energy into light and then to an electric signal. FDP units have several technical advantages over image intensifier systems including smaller size, less imaging artefacts and reduced radiation exposure.

1.1.4 Digital subtraction angiography

The utility of fluoroscopy may be extended with digital subtraction techniques. Digital subtraction is a process whereby a computer removes unwanted information from a radiographic image. Digital subtraction is particularly useful for angiography, referred to as DSA. The principles of digital subtraction are illustrated in Fig. 1.4.

A relatively recent innovation is rotational 3D fluoroscopic imaging. For this technique, the fluoroscopy unit rotates through 180° while acquiring images, producing a cine display that resembles a 3D CT image. This image may be rotated and reorientated to produce a greater understanding of anatomy during complex diagnostic and interventional procedures.

1.2 CONTRAST MATERIALS

The ability of conventional radiography and fluoroscopy to display a range of organs and structures may be enhanced by the use of various contrast materials, also known as contrast media. The most common contrast materials are based on barium or iodine. Barium and iodine are high atomic number materials that strongly absorb X-rays and are therefore seen as dense white on radiography.

For demonstration of the gastrointestinal tract with fluoroscopy, contrast materials may be swallowed or injected via a nasogastric tube to outline the oesophagus, stomach and small bowel, or may be introduced via an enema tube to delineate the large bowel. Gastrointestinal contrast materials are usually based on barium, which is non-water soluble. Occasionally, a water-soluble contrast material based on iodine is used for imaging of the gastrointestinal tract, particularly where aspiration or perforation may be encountered (Fig. 1.3).

Iodinated (iodine containing) water-soluble contrast media may be injected into veins, arteries, and various body cavities and systems. Iodinated contrast materials are used in CT (see below), angiography (DSA) (Fig. 1.4) and arthrography (injection into joints).

1.3 CT

1.3.1 CT physics and terminology

CT is an imaging technique whereby cross-sectional images are obtained with the use of X-rays. In CT scanning, the patient is passed through a rotating gantry that has an X-ray tube on one side and a set of detectors on the other. Information from the detectors is analysed by computer and displayed as a grey-scale image. Owing to the use of computer analysis, a much greater array of densities can be

displayed than on conventional X-ray films. This allows accurate display of cross-sectional anatomy, differentiation of organs and pathology, and sensitivity to the presence of specific materials such as fat or calcium. As with plain radiography, high-density objects cause more attenuation of the X-ray beam and are therefore displayed as lighter grey than objects of lower density. White and light grey objects are therefore said to be of 'high attenuation'; dark grey and black objects are said to be of 'low attenuation'.

By altering the grey-scale settings, the image information can be manipulated to display the various tissues of the body. For example, in chest CT where a wide range of tissue densities is present, a good image of the mediastinal structures shows no lung details. By setting a 'lung window' the lung parenchyma is seen in detail (Fig. 1.5).

The relative density of an area of interest may be measured electronically. This density measurement is given as an attenuation value, expressed in Hounsfield units (HU) (named for Godfrey
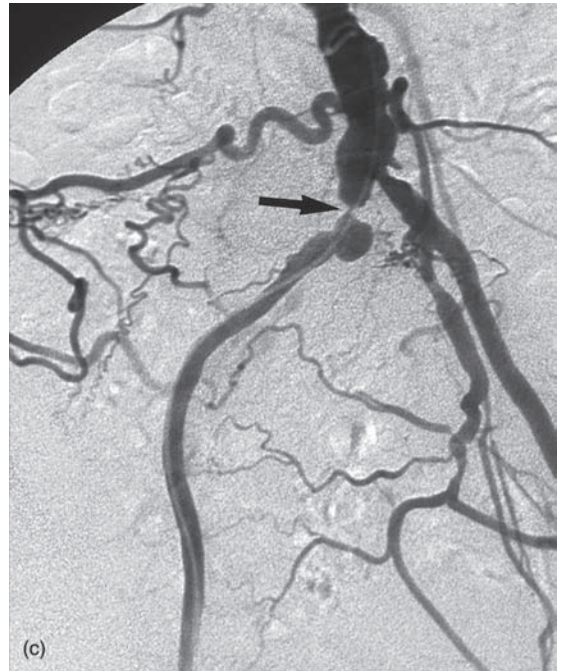
Figure 1.4 Digital subtraction angiography (DSA). (a) Mask image performed prior to injection of contrast material. (b) Contrast material injected producing opacification of the arteries. (c) Subtracted image. The computer subtracts the mask from the contrast image leaving an image of contrast-filled arteries unobscured by overlying structures. Note a stenosis of the right common iliac artery (arrow).
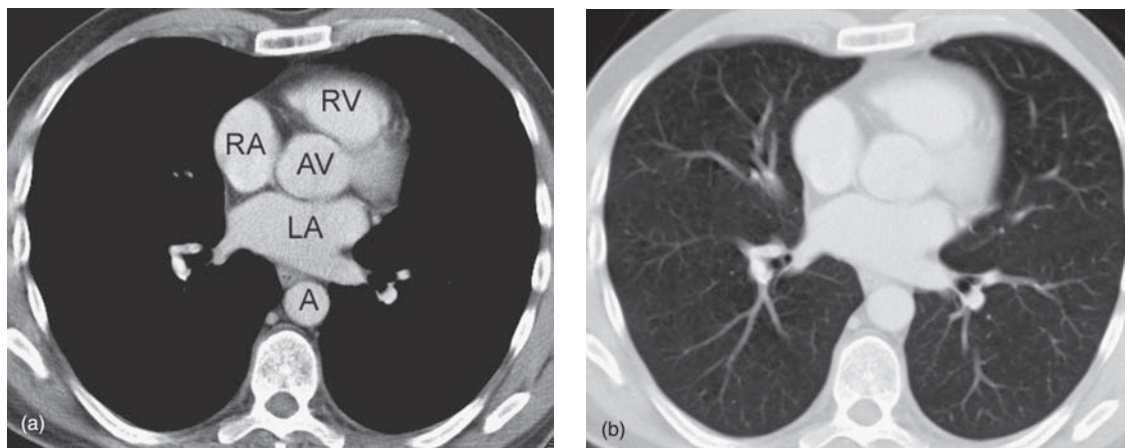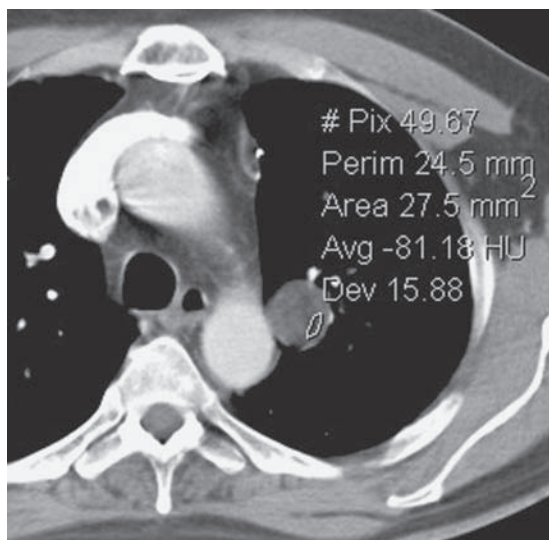
Figure 1.5 CT windows. (a) Mediastinal windows showing mediastinal anatomy: right atrium (RA), right ventricle (RV), aortic valve (AV), aorta (A), left atrium (LA). (b) Lung windows showing lung anatomy.

Hounsfield, the inventor of CT). In CT, water is assigned an attenuation value of 0 HU. Substances that are less dense than water, including fat and air, have negative values (Fig. 1.6); substances of greater density have positive values. Approximate attenuation values for common substances are as follows:

- Water: 0
- Muscle: 40
- Contrast-enhanced artery: 130
- Cortical bone: 500
- Fat: −120
- Air: −1000

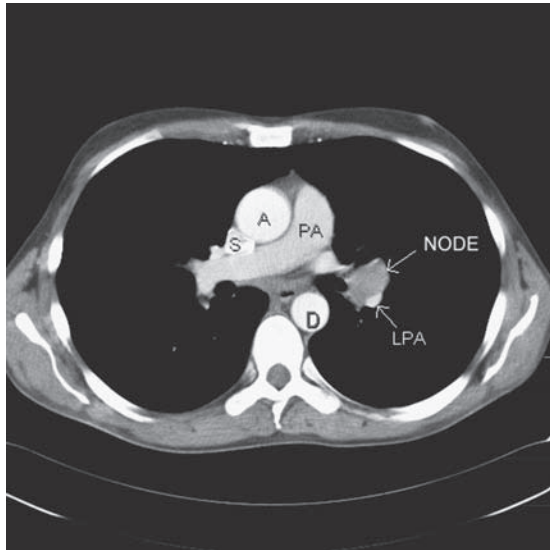## 1.3.2 Contrast materials in CT

Intravenous iodinated contrast material is used in CT for a number of reasons, as follows:
- Differentiation of normal blood vessels from abnormal masses, e.g. hilar vessels versus lymph nodes (Fig. 1.7)
- To make an abnormality more apparent, e.g. liver metastases
- To demonstrate the vascular nature of a mass and thus aid in characterization
- CT angiography (see below).

Oral contrast material is also used for abdomen CT:
- Differentiation of normal enhancing bowel loops from abnormal masses or fluid collections (Fig. 1.8)
- Diagnosis of perforation of the gastrointestinal tract
- Diagnosis of leaking surgical anastomoses
- CT enterography.

For detailed examination of the pelvis and distal large bowel, administration of rectal contrast material is occasionally used.

Figure 1.6 Hounsfield unit (HU) measurements. HU measurements in a lung nodule reveal negative values (−81) indicating fat. This is consistent with a benign pulmonary hamartoma, for which no further follow-up or treatment is required.

Figure 1.7 Intravenous contrast. An enlarged left hilar lymph node is differentiated from enhancing vascular structures: left pulmonary artery (LPA), main pulmonary artery (PA), ascending aorta (A), superior vena cava (S), descending aorta (D).

1.3.3 Multidetector row CT

Helical (spiral) CT scanners became available in the early 1990s. Helical scanners differ from conventional scanners in that the tube and detectors rotate as the patient passes through on the scanning table. Helical CT is so named because the continuous set of data that is obtained has a helical configuration.

Multidetector row CT (MDCT), also known as multislice CT (MSCT), was developed in the mid to late 1990s. MDCT builds on the concepts of helical CT in that a circular gantry holding the X-ray tube on one side and detectors on the other rotates continuously as the patient passes through. The difference with MDCT is that instead of a single row of detectors multiple detector rows are used. The original MDCT scanners used two or four rows of detectors, followed by 16 and 64 detector row scanners. At the time of writing, 256 and 320 row scanners are becoming widely available.

Multidetector row CT allows the acquisition of overlapping fine sections of data, which in turn allows the reconstruction of highly accurate and detailed 3D images as well as sections in any desired plane. The major advantages of MDCT over conventional CT scanning are:

Figure 1.8 Oral contrast. An abscess (A) is differentiated from contrast-filled small bowel (SB) and large bowel (LB).

- Increased speed of examination
- Rapid examination at optimal levels of intravenous contrast concentration
- Continuous volumetric nature of data allows accurate high-quality 3D and multiplanar reconstruction.

MDCT therefore provides many varied applications including:
- CT angiography: coronary, cerebral, carotid, pulmonary, renal, visceral, peripheral
- Cardiac CT, including CT coronary angiography and coronary artery calcium scoring
- CT colography (virtual colonoscopy)
- CT cholangiography
- CT enterography
- Brain perfusion scanning
- Planning of fracture repair in complex areas: acetabulum, foot and ankle, distal radius and carpus
- Display of complex anatomy for planning of cranial and facial reconstruction surgery (Fig. 1.9).

1.3.4 Limitations and disadvantages of CT
- Ionizing radiation (see below)
- Hazards of intravenous contrast material (see below)
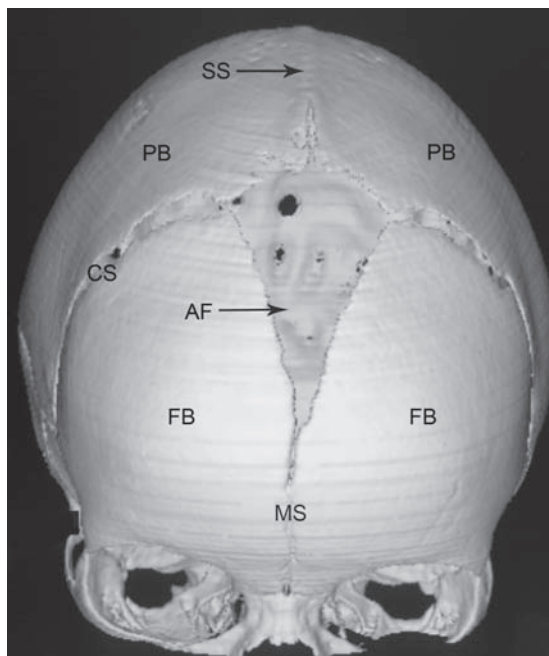
Figure 1.9 Three-dimensional (3D) reconstruction of an infant's skull showing a fused sagittal suture. Structures labelled as follows: frontal bones (FB), parietal bones (PB), coronal sutures (CS), metopic suture (MS), anterior fontanelle (AF) and fused sagittal suture (SS). Normal sutures are seen on 3D CT as lucent lines between skull bones. Note the lack of a normal lucent line at the position of the sagittal suture indicating fusion of the suture.

Solid organs, fluid-filled structures and tissue interfaces produce varying degrees of sound wave reflection and are said to be of different echogenicity. Tissues that are hyperechoic reflect more sound than tissues that are hypoechoic. In an US image, hyperechoic tissues are shown as white or light grey and hypoechoic tissues are seen as dark grey (Fig. 1.10). Pure fluid is anechoic (reflects virtually no sound) and is black on US images. Furthermore, because virtually all sound is transmitted through a fluid-containing area, tissues distally receive more sound waves and hence appear lighter. This effect is known as 'acoustic enhancement' and is seen in tissues distal to the gallbladder, the urinary bladder and simple cysts. The reverse effect, known as 'acoustic shadowing', occurs with gas-containing bowel, gallstones, renal stones and breast malignancy.

US scanning is applicable to:
- Solid organs, including liver, kidneys, spleen and pancreas
- Urinary tract
- Obstetrics and gynaecology
- Small organs including thyroid and testes
- Breast
- Musculoskeletal system.

- Lack of portability of equipment
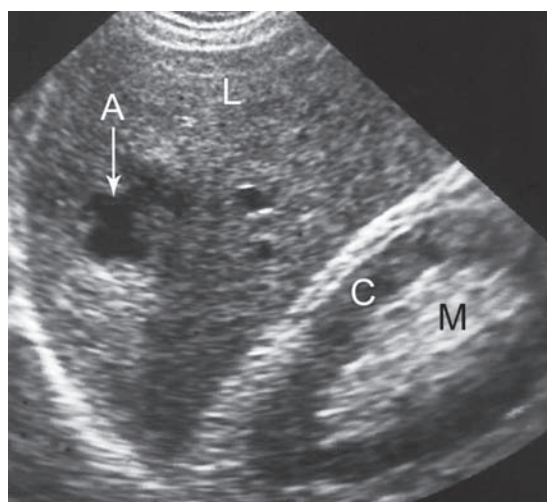- Relatively high cost.

1.4 US

1.4.1 US physics and terminology

US imaging uses ultra-high-frequency sound waves to produce cross-sectional images of the body. The basic component of the US probe is the piezoelectric crystal. Excitation of this crystal by electrical signals causes it to emit ultra-high-frequency sound waves; this is the piezoelectric effect. Sound waves are reflected back to the crystal by the various tissues of the body. These reflected sound waves (echoes) act on the piezoelectric crystal in the US probe to produce an electric signal, again by the piezoelectric effect. Analysis of this electric signal by a computer produces a cross-sectional image.

Figure 1.10 An abscess in the liver demonstrates tissues of varying echogenicity. Note the anechoic fluid in the abscess (A), moderately echogenic liver (L), hypoechoic renal cortex (C) and hyperechoic renal medulla (M).

An assortment of probes is available for imaging and biopsy guidance of various body cavities and organs including:

- Transvaginal US (TVUS): accurate assessment of gynaecological problems and of early pregnancy up to about 12 weeks' gestation
- Transrectal US (TRUS): guidance of prostate biopsy; staging of rectal cancer
- Endoscopic US (EUS): assessment of tumours of the upper gastrointestinal tract and pancreas
- Transoesophageal echocardiography (TOE): TOE removes the problem of overlying ribs and lung, which can obscure the heart and aorta when performing conventional echocardiography.
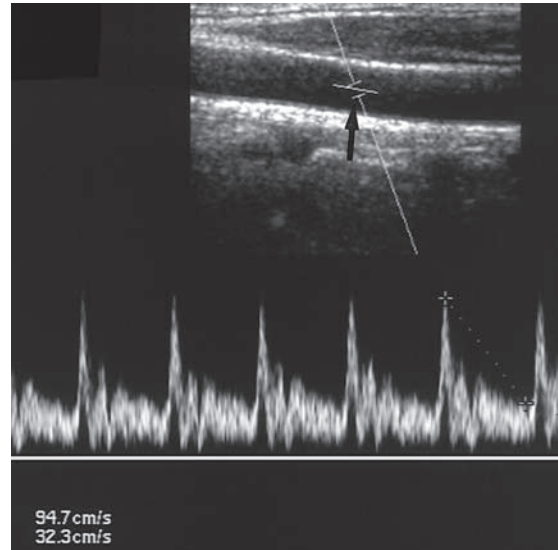
Advantages of US over other imaging modalities include:

- Lack of ionizing radiation, a particular advantage in pregnancy and paediatrics
- Relatively low cost
- Portability of equipment.

Figure 1.11 Duplex US. The Doppler sample gate is positioned in the artery (arrow) and the frequency shifts displayed as a graph. Peak systolic and end diastolic velocities are calculated and also displayed on the image in centimetres per second.

1.4.2 Doppler US

Anyone who has heard a police or ambulance siren speed past will be familiar with the influence of a moving object on sound waves, known as the Doppler effect. An object travelling towards the listener causes sound waves to be compressed giving a higher frequency; an object travelling away from the listener gives a lower frequency. The Doppler effect has been applied to US imaging. Flowing blood causes an alteration to the frequency of sound waves returning to the US probe. This frequency change or shift is calculated allowing quantitation of blood flow. The combination of conventional two-dimensional US imaging with Doppler US is known as Duplex US (Fig. 1.11).

Colour Doppler is an extension of these principles, with blood flowing towards the transducer coloured red, and blood flowing away from the transducer coloured blue. The colours are superimposed on the cross-sectional image allowing instant assessment of presence and direction of flow. Colour Doppler is used in many areas of US including echocardiography and vascular US. Colour Doppler is also used to confirm blood flow within organs (e.g. testis to exclude torsion) and to assess the vascularity of tumours.

1.4.3 Contrast-enhanced US

The accuracy of US in certain applications may be enhanced by the use of intravenously injected microbubble contrast agents. Microbubbles measure 3–5 μm diameter and consist of spheres of gas (e.g. perfluorocarbon) stabilized by a thin biocompatible shell. Microbubbles are caused to rapidly oscillate by the US beam and, in this way, microbubble contrast agents increase the echogenicity of blood for up to 5 minutes following intravenous injection. Beyond this time, the biocompatible shell is metabolized and the gas diffused into the blood. Microbubble contrast agents are very safe, with a reported incidence of anaphylactoid reaction of around 0.014 per cent. Contrast-enhanced US (CEUS) is increasingly accepted in clinical practice in the following applications:

- Echocardiography
  - Better visualization of blood may increase the accuracy of cardiac chamber measurement and calculation of ventricular function
  - Improved visualization of intracardiac shunts such as patent foramen ovale

- Assessment of liver masses
  - Dynamic blood flow characteristics of liver masses visualized with CEUS may assist in diagnosis, similar to dynamic contrast-enhanced CT and MRI.
  - CEUS may also be used for follow-up of hepatic neoplasms treated with percutaneous ablation or other non-surgical techniques.

1.4.4 Disadvantages and limitations of US

- US is highly operator dependent: unlike CT and MRI, which produce cross-sectional images in a reasonably programmed fashion, US relies on the operator to produce and interpret images at the time of examination.
- US cannot penetrate gas or bone.
- Bowel gas may obscure structures deep in the abdomen, such as the pancreas or renal arteries.

1.5 SCINTIGRAPHY (NUCLEAR MEDICINE)

1.5.1 Physics of scintigraphy and terminology

Scintigraphy refers to the use of gamma radiation to form images following the injection of various radiopharmaceuticals. The key word to understanding scintigraphy is 'radiopharmaceutical'. 'Radio' refers to the radionuclide, i.e. the emitter of gamma rays.

The most commonly used radionuclide in clinical practice is technetium, written in this text as ^{99m}Tc, where 99 is the atomic mass, and the 'm' stands for metastable. Metastable means that the technetium atom has two basic energy states: high and low. As the technetium transforms from the high-energy state to the low-energy state, it emits a quantum of energy in the form of a gamma ray, which has energy of 140 keV (Fig. 1.12).

Other commonly used radionuclides include gallium citrate (^{67}Ga), thallium (^{201}Tl), indium (^{111}In) and iodine (^{131}I).

The 'pharmaceutical' part of radiopharmaceutical refers to the compound to which the radionuclide is bound. This compound varies depending on the tissue to be examined.

For some applications, such as thyroid scanning, free technetium (referred to as pertechnetate) without a binding pharmaceutical is used.
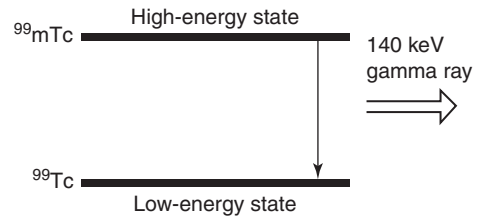
Figure 1.12 Gamma ray production. The metastable atom ^{99m}Tc passes from a high-energy to a low-energy state and releases gamma radiation with a peak energy of 140 keV.

The gamma rays emitted by the radionuclides are detected by a gamma camera that converts the absorbed energy of the radiation to an electric signal. This signal is analysed by a computer and displayed as an image (Fig. 1.13). The main advantages of scintigraphy are:

- High sensitivity
- Functional information is provided as well as anatomical information.

A summary of the more commonly used radionuclides and radiopharmaceuticals is provided in Table 1.1.

1.5.2 Single photon emission CT and single photon emission CT–CT

Single photon emission CT (SPECT) is a scintigraphic technique whereby the computer is programmed to analyse data coming from a single depth within the patient. SPECT allows greater sensitivity in the detection of subtle lesions overlain by other active structures (Fig. 1.14). The accuracy of SPECT may be further enhanced by fusion with CT. Scanners that combine SPECT with CT are now widely available. SPECT–CT fuses highly sensitive SPECT findings with anatomically accurate CT images, thus improving sensitivity and specificity.

The main applications of SPECT–CT include:

- ^{99m}Tc-MDP bone scanning
- ^{201}Tl cardiac scanning
- ^{99m}Tc-MIBG staging of neuroblastoma
- Cerebral perfusion studies.

1.5.3 Positron emission tomography and positron emission tomography–CT

Positron emission tomography (PET) is an established imaging technique, most commonly
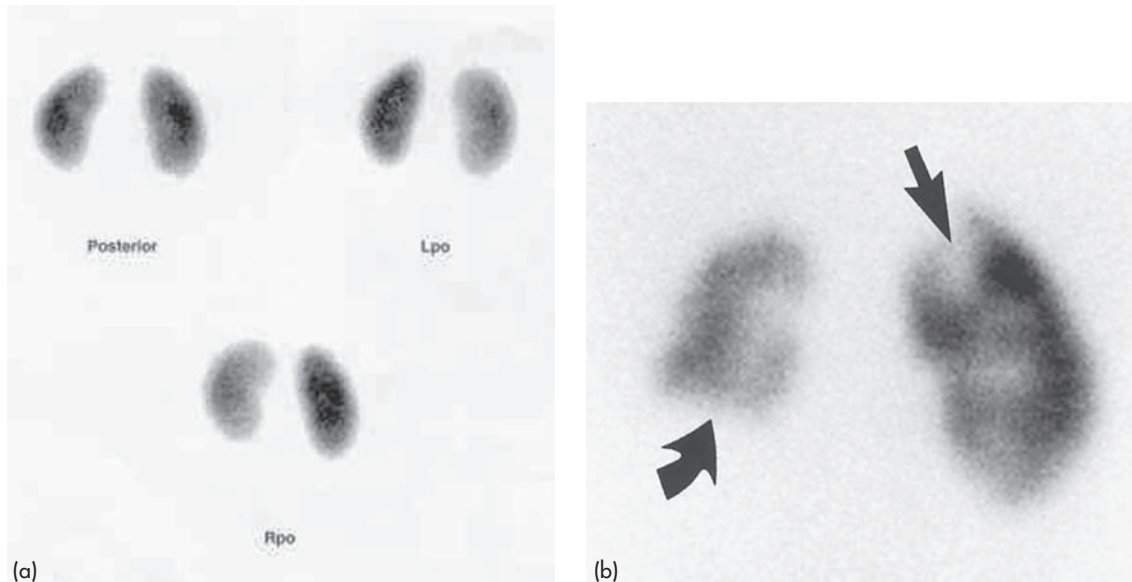
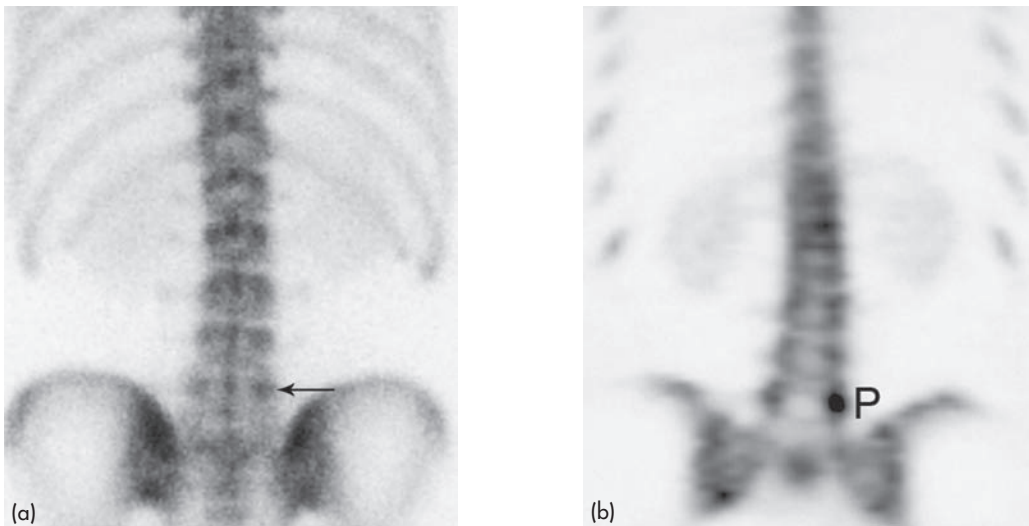**Figure 1.13** Scintigraphy (nuclear medicine): renal scan with ^{99m}Tc-DMSA (dimercaptosuccinic acid). (a) Normal DMSA scan shows normally shaped symmetrical kidneys. (b) DMSA scan in a child with recurrent urinary tract infection shows extensive right renal scarring, especially of the lower pole (curved arrow), with a smaller scar of the left upper pole (straight arrow).

Figure 1.14 Single photon emission CT (SPECT). (a) Scintigraphy in a man with lower back pain shows a subtle area of mildly increased activity (arrow). (b) SPECT scan in the coronal plane shows an obvious focus of increased activity in a pars interarticularis defect (P).

used in oncology. PET ulitizes radionuclides that decay by positron emission. Positron emission occurs when a proton-rich unstable isotope transforms protons from its nucleus into neutrons and positrons. PET is based on similar principles to other fields of scintigraphy whereby an isotope is attached to a biological compound to form a radiopharmaceutical, which is injected into the patient.

The most commonly used radiopharmaceutical

Table 1.1 Radionuclides and radiopharmaceuticals in clinical practice.

| Clinical application	Radiopharmaceutical
Bone scintigraphy	^{99m}Tc-methylene diphosphonate (MDP) ^{99m}Tc-hydroxymethylene diphosphonate (HDP)
Thyroid imaging	^{99m}Tc (pertechnetate)
Parathyroid imaging	^{99m}Tc-sestamibi
Renal scintigraphy	^{99m}Tc-mercaptoacetyltriglycerine (MAG3) ^{99m}Tc-diethyltriaminepentaacetic acid (DTPA)
Renal cortical scan	^{99m}Tc-dimercaptosuccinic acid (DMSA)
Staging/localization of neuroblastoma or phaeochromocytoma	^{123}I-metaiodobenzylguanidine (MIBG) ^{131}I-MIBG
Myocardial perfusion imaging	^{201}Thallium (^{201}Tl) ^{99m}Tc-sestamibi (MIBI) ^{99m}Tc-tetrofosmin
Cardiac gated blood pool scan	^{99m}Tc-labelled red blood cells
Ventilation/perfusion lung scan (VQ scan)	Ventilation: ^{99m}Tc-DTPA aerosol or similar Perfusion: ^{99m}Tc-macroaggregated albumen (MAA)
Hepatobiliary imaging	^{99m}Tc-iminodiacetic acid analogue, e.g. DISIDA or HIDA
Gastrointestinal motility study	^{99m}Tc-sulphur colloid in solid food ^{99m}Tc-DTPA in water
Gastrointestinal bleeding study	^{99m}Tc-labelled red blood cells
Meckel diverticulum scan	^{99m}Tc (pertechnetate)
Inflammatory bowel disease	^{99m}Tc-hexamethylpropyleneamineoxime (HMPAO) ^{99m}Tc -labelled sucralfate
Carcinoid/neuroendocrine tumour	^{111}In-pentetreotide (Octreoscan™)
Infection imaging	Gallium citrate (^{67}Ga) ^{99m}Tc-HMPAO-labelled white blood cells
Cerebral blood flow imaging (brain SPECT)	^{99m}Tc-HMPAO (Ceretec™)

in PET scanning is FDG (2-deoxyglucose labelled with the positron-emitter fluorine-18). FDG is an analogue of glucose and therefore accumulates in areas of high glucose metabolism. Positrons emitted from the fluorine-18 in FDG collide with negatively charged electrons. The mass of an electron and positron is converted into two 511 keV photons, i.e. high-energy gamma rays, which are emitted in opposite directions to each other. This event is known as annihilation (Fig. 1.15).

The PET camera consists of a ring of detectors that register the annihilations. An area of high concentration of FDG will have a large number of annihilations and will be shown on the resulting image as a 'hot spot'. Normal physiological uptake of FDG occurs in the brain (high level of glucose metabolism), myocardium, and in the renal collecting systems, ureters and bladder.

The current roles of PET imaging may be summarized as follows:
- Oncology
  - Tumour staging
  - Assessment of tumour response to therapy
  - Differentiate benign and malignant masses, e.g. solitary pulmonary nodule
  - Detect tumour recurrence

FDG
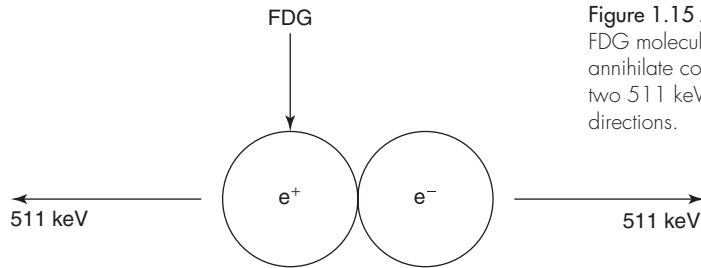
Figure 1.15 Annihilation. A positron (e⁺) emitted by an FDG molecule encounters an electron (e⁻). The two particles annihilate converting their mass into energy in the form of two 511 keV gamma rays, which are emitted in opposite directions.

- Cardiac: Non-invasive assessment of myocardial viability in patients with coronary artery disease
- Central nervous system
  - Characterization of dementia disorders
  - Localization of seizure focus in epilepsy.

As with other types of scintigraphy, a problem with PET is its non-specificity. Put another way, 'hot spots' on PET may have multiple causes, with false positive findings commonly encountered. The specificity of PET may be increased by the use of scanners that fuse PET with CT or MRI. PET–CT fusion imaging combines the functional and metabolic information of PET with the precise cross-sectional anatomy of CT (Fig. 1.16). Advantages of combining PET with CT include:

- Reduced incidence of false positive findings in primary tumour staging
- Increased accuracy of follow-up of malignancy during and following treatment.

PET–CT scanners are now widely available and have largely replaced stand alone PET scanners in modern practice. At the time of writing, PET–MR scanners are also becoming available in research and tertiary institutions.

1.5.4 Limitations and disadvantages of scintigraphy

- Use of ionizing radiation
- Cost of equipment
- Extra care required in handling radioactive materials
- The main disadvantage of scintigraphy is its nonspecificity; as described above, this may be reduced by combining scintigraphy with CT or MRI.

1.6 MRI

1.6.1 MRI physics and terminology

MRI uses the magnetic properties of spinning hydrogen atoms to produce images. The first step
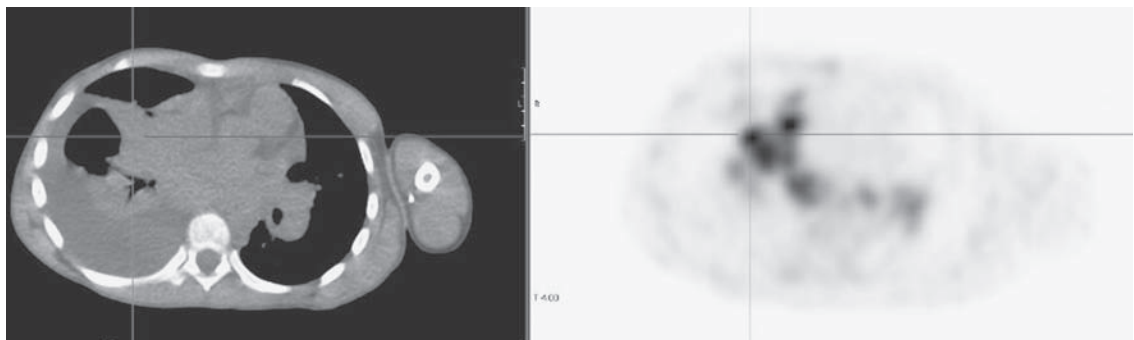
Figure 1.16 Positron emission tomography–CT (PET–CT): Hodgkin's lymphoma. CT image on the left shows neoplastic lymphadenopathy, collapsed lung and pleural effusion. Corresponding FDG-PET image on the right shows areas of increased activity corresponding to neoplastic lymphadenopathy. Collapsed lung and pleural effusion do not show increased activity, thus differentiating neoplastic from non-neoplastic tissue.

in MRI is the application of a strong, external magnetic field. For this purpose, the patient is placed within a large powerful magnet. Most current medical MRI machines have field strengths of 1.5 or 3.0 tesla (1.5T or 3T). The hydrogen atoms within the patient align in a direction either parallel or antiparallel to the strong external field. A greater proportion aligns in the parallel direction so that the net vector of their alignment, and therefore the net magnetic vector, will be in the direction of the external field. This is known as longitudinal magnetization.

A second magnetic field is applied at right angles to the original external field. This second magnetic field is known as the radiofrequency pulse (RF pulse), because it is applied at a frequency in the same part of the electromagnetic spectrum as radio waves. A magnetic coil, known as the RF coil, applies the RF pulse. The RF pulse causes the net magnetization vector of the hydrogen atoms to turn towards the transverse plane, i.e. a plane at right angles to the direction of the original, strong external field. The component of the net magnetization vector in the transverse plane induces an electrical current in the RF coil. This current is known as the MR signal and is the basis for formation of an image. Computer analysis of the complex MR signal from the RF receiver coils is used to produce an MR image.

Note that in viewing MRI images, white or light grey areas are referred to as 'high signal'; dark grey or black areas are referred to as 'low signal'. On certain sequences, flowing blood is seen as a black area referred to as a 'flow void'.

Each medical MRI machine consists of a number of magnetic coils:
- 1.5T or 3T superconducting magnet
- Gradient coils, contained in the bore of the superconducting magnet, used to produce variations to the magnetic field that allow image formation
  - Rapid switching of these gradients causes the loud noises associated with MRI scanning
- RF coils are applied to, or around, the area of interest and are used to transmit the RF pulse and to receive the RF signal
  - RF coils come in varying shapes and sizes depending on the part of the body to be examined

- Larger coils are required for imaging the chest and abdomen, whereas smaller extremity coils are used for small parts such as the wrist or ankle.

1.6.2 Tissue contrast and imaging sequences

Much of the complexity of MRI arises from the fact that the MR signal depends on many varied properties of the tissues and structures being examined, including:
- Number of hydrogen atoms present in tissue (proton density)
- Chemical environment of the hydrogen atoms, e.g. whether in free water or bound by fat
- Flow: blood vessels or CSF
- Magnetic susceptibility
- T1 relaxation time
- T2 relaxation time.

By altering the duration and amplitude of the RF pulse, as well as the timing and repetition of its application, various imaging sequences use these properties to produce image contrast. Terms used to describe the different types of MR imaging sequences include spin echo, inversion recovery and gradient-recalled echo (gradient echo).

1.6.2.1 Spin echo

Spin echo sequences include T1-weighted, T2-weighted and proton density. The following is a brief explanation of the terms 'T1' and 'T2'.

Following the application of a 90° RF pulse, the net magnetization vector lies in the transverse plane. Also, all of the hydrogen protons are 'in phase', i.e. spinning at the same rate. Upon cessation of the RF pulse, two things begin to happen:
- Net magnetization vector rotates back to the longitudinal direction: longitudinal or T1 relaxation
- Hydrogen atoms dephase (spin at slightly varying rates): transverse or T2 relaxation (decay).

The rates at which T1 and T2 relaxation occur are inherent properties of the various tissues. Sequences that primarily use differences in T1 relaxation rates produce T1-weighted images. Tissues with long T1 values are shown as low signal while those with

shorter T1 values are displayed as higher signal. Gadolinium produces T1 shortening; tissues or structures that enhance with gadolinium-based contrast materials show increased signal on T1-weighted images.

T2-weighted images reflect differences in T2 relaxation rates. Tissues whose protons dephase slowly have a long T2 and are displayed as high signal on T2-weighted images. Tissues with shorter T2 values are shown as lower signal (Fig. 1.17).

Proton density images are produced by sequences that accentuate neither T1 nor T2 differences. The signal strength of proton density images mostly reflects the density of hydrogen atoms (protons) in the different tissues. Proton density images are particularly useful in musculoskeletal imaging for the demonstration of small structures, as well as articular cartilage (Fig. 1.18).

1.6.2.2 Gradient-recalled echo (gradient echo)

Gradient-recalled echo (GRE) sequences are widely used in a variety of MRI applications. GRE sequences are extremely sensitive to the presence of substances that cause local alterations in magnetic properties. Examples of such substances include iron-containing haemosiderin and ferritin found in chronic blood. GRE sequences are used in neuroimaging to look for chronic blood in patients with suspected vascular tumours, previous trauma or angiopathy. An extension of GRE sequences in the brain known as susceptibility-weighted imaging (SWI) uses subtraction techniques to remove unwanted information and thereby increase sensitivity. GRE sequences also allow extremely rapid imaging and are used for imaging the heart and abdomen.

1.6.2.3 Inversion recovery

Inversion recovery sequences are used to suppress unwanted signals that may obscure pathology. The two most common inversion recovery sequences are used to suppress fat (STIR) and water (FLAIR). Fat suppression sequences such as STIR (short TI-inversion recovery) are used for demonstrating pathology in areas containing a lot of fat, such as
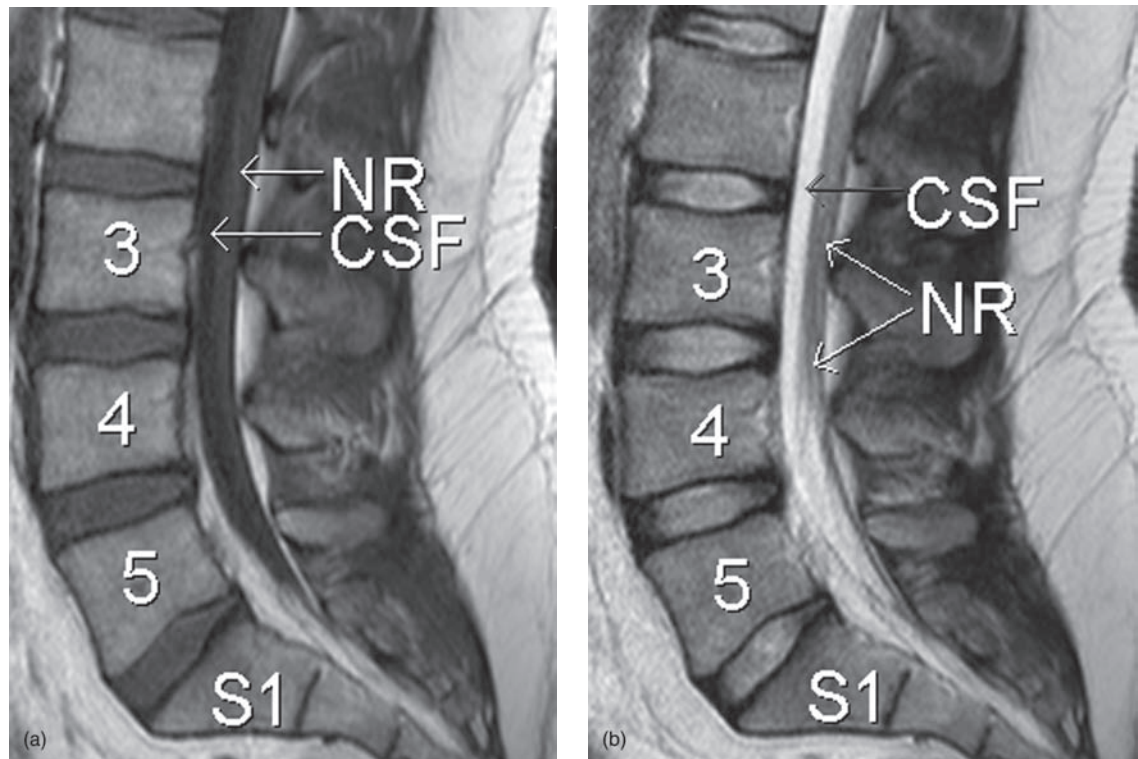
Figure 1.17 MRI of the lower lumbar spine and sacrum. (a) Sagittal T1-weighted image. Note: dark cerebral spinal fluid (CSF). (b) Sagittal T2-weighted image. Note: bright CSF; nerve roots (NR).
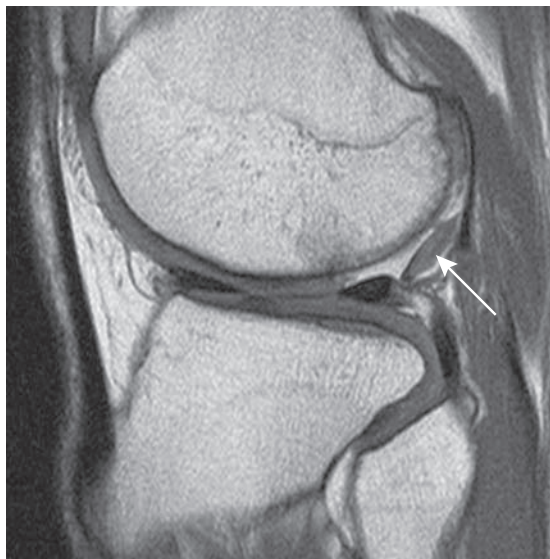
Figure 1.18 Proton density (PD) sequence. Sagittal PD MRI of the knee shows a cartilage fragment detached from the articular surface of the lateral femoral condyle (arrow).

Figure 1.19 Short tau inversion recovery (STIR) sequence. Sagittal STIR MRI of the lumbar spine shows a crush fracture of L2. Increased signal within L2 on STIR (arrows) indicates bone marrow oedema in a recent fracture.

the orbits and bone marrow. STIR sequences allow the delineation of bone marrow disorders such as oedema, bruising and infiltration (Fig. 1.19). FLAIR (fluid-attenuated inversion recovery) sequences suppress signals from CSF and are used to image the brain. FLAIR sequences are particularly useful for diagnosing white matter disorders such as multiple sclerosis.

1.6.3 Functional MRI sequences

1.6.3.1 Diffusion-weighted imaging

Diffusion-weighted imaging (DWI) is sensitive to the random Brownian motion (diffusion) of water molecules within tissue. The greater the amount of diffusion, the greater the signal loss on DWI. Areas of reduced water molecule diffusion show on DWI as relatively high signal.

Diffusion-weighted imaging is the most sensitive imaging test available for the diagnosis of acute cerebral infarction. With the onset of acute ischaemia and cell death there is increased intracellular water (cytotoxic oedema) with restricted diffusion of water molecules. An acute infarct therefore shows on DWI as an area of relatively high signal.

1.6.3.2 Perfusion-weighted imaging

In perfusion-weighted imaging (PWI) the brain is rapidly scanned following injection of a bolus of contrast material (gadolinium). The data obtained may be represented in a number of ways including maps of regional cerebral blood volume, cerebral blood flow, and mean transit time of the contrast bolus. PWI may be used in patients with cerebral infarct to map out areas of brain at risk of ischaemia that may be salvageable with thrombolysis.

1.6.3.3 Magnetic resonance spectroscopy

Magnetic resonance spectroscopy (MRS) uses different frequencies to identify certain molecules in a selected volume of tissue, known as a voxel. Following data analysis, a spectrographic graph of certain metabolites is drawn. Metabolites of interest include lipid, lactate, NAA (*N*-acetylaspartate), choline, creatinine, citrate and myoinositol. Uses of MRS include characterization of metabolic

brain disorders in children, imaging of dementias, differentiation of recurrent cerebral tumour from radiation necrosis, and diagnosis of prostatic carcinoma.

1.6.3.4 Blood oxygen level-dependent imaging

Blood oxygen level-dependent (BOLD) imaging is a non-invasive functional MRI (fMRI) technique used for localizing regional brain signal intensity changes in response to task performance. BOLD imaging depends on regional changes in concentration of deoxyhaemoglobin, and is therefore a tool to investigate regional cerebral physiology in response to a variety of stimuli. BOLD fMRI may be used prior to surgery for brain tumour or arteriovenous malformation (AVM), as a prognostic indicator of the degree of postsurgical deficit.

1.6.4 Magnetic resonance angiography and magnetic resonance venography

Flowing blood can be shown with different sequences as either signal void (black) or increased signal (white). Magnetic resonance angiography (MRA) refers to the use of these sequences to display arterial anatomy and pathology. Computer reconstruction techniques allow the display of blood vessels in 3D as well as rotation and viewing of these blood vessels from multiple angles. MRA is most commonly used to image the arteries of the brain, although is also finding wider application in the imaging of renal and peripheral arteries.

MRI of veins is known as magnetic resonance venography (MRV). MRV is most commonly used in neuroimaging to demonstrate the venous sinuses of the brain. For certain applications, the accuracy of MRA and MRV is increased by contrast enhancement with intravenous injection of Gd-DTPA.

1.6.5 Contrast material in MRI

Gadolinium (Gd) is a paramagnetic substance that causes T1 shortening and therefore increased signal on T1-weighted images. Unbound Gd is highly toxic and binding agents, such as diethylenetriamine pentaacetic acid (DTPA), are required for *in vivo* use. Gd-DTPA is non-toxic and used in a dose of 0.1 mmol per kilogram.

Indications for the use of Gd enhancement in MRI include:
- Brain
  - Inflammation: meningitis, encephalitis
  - Tumours: primary (Fig. 1.20), metastases
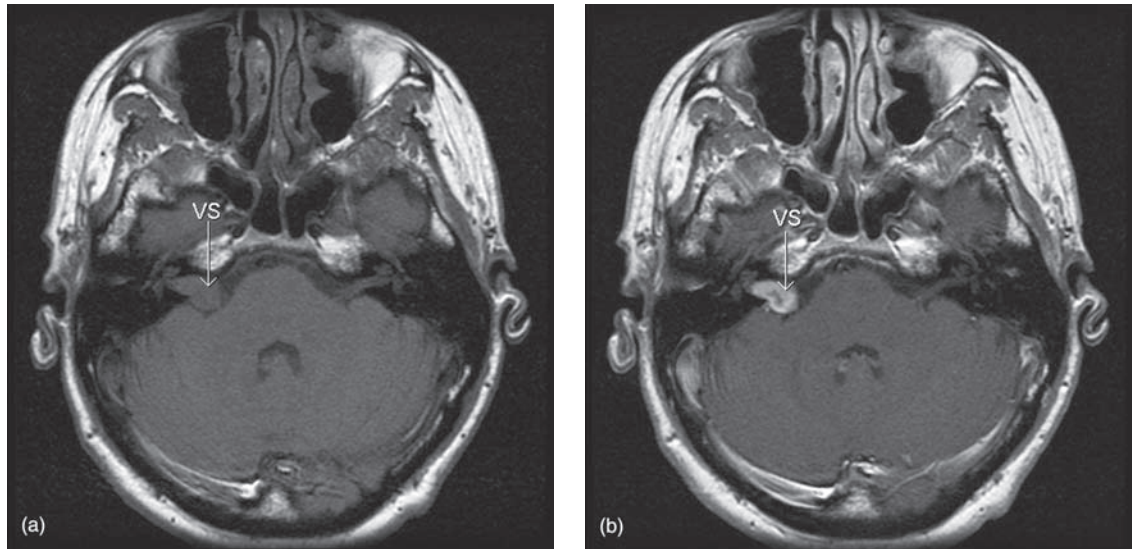
Figure 1.20 Intravenous contrast in MRI: vestibular schwannoma. (a) Transverse T1-weighted image of the posterior fossa shows a right-sided mass. (b) Following injection of gadolinium the mass shows intense enhancement, typical of vestibular schwannoma (VS). (See also Fig. 11.10.)

- Tumour residuum/recurrence following treatment
- Spine
  - Postoperative to differentiate fibrosis from recurrent disc protrusion
  - Infection: discitis, epidural abscess
  - Tumours: primary, metastases
- Musculoskeletal system
  - Soft tissue tumours
  - Intra-articular Gd-DTPA: MR arthrography
- Abdomen
  - Characterization of tumours of liver, kidney and pancreas.

1.6.6 Applications and advantages of MRI

Widely accepted applications of MRI include:
- Imaging modality of choice for most brain and spine disorders
- Musculoskeletal disorders, including internal derangements of joints and staging of musculoskeletal tumours
- Cardiac MR is an established technique in specific applications including assessment of congenital heart disease and aortic disorders
- MR of the abdomen is used in adults for visualization of the biliary system, and for characterization of hepatic, renal, adrenal and pancreatic tumours
- In children, MR of the abdomen is increasingly replacing CT for the diagnosis and staging of abdominal tumours
- MRA is widely used in the imaging of the cerebral circulation and in some centres is the initial angiographic method of choice for other areas including the renal and peripheral circulations.

Particular advantages of MRI in clinical practice include:
- Excellent soft tissue contrast and characterization
- Lack of artefact from adjacent bones, e.g. pituitary fossa
- Multiplanar capabilities
- Lack of ionizing radiation.

1.6.7 Disadvantages and limitations of MRI

- Time taken to complete examination

- Young children and infants usually require general anaesthesia
- Patients experiencing pain may require intravenous pain relief
- For examination of the abdomen, an antispasmodic, such as intravenous hyoscine, may be required to reduce movement of the bowel
- Safety issues related to ferromagnetic materials within the patient, e.g. surgical clips, or electrical devices such as pacemakers (see below)
- High auditory noise levels: earplugs should be provided to all patients undergoing MRI examinations
- Claustrophobia
  - Modern scanners have a wider bore and claustrophobia is less of a problem than in the past; intravenous conscious sedation may occasionally be required
- Problems with gadolinium: allergy (extremely rare) and nephrogenic systemic fibrosis (see below).

1.7 HAZARDS ASSOCIATED WITH MEDICAL IMAGING

Hazards associated with modern medical imaging are outlined below, and include:
- Exposure to ionizing radiation
- Anaphylactoid reactions to iodinated contrast media
- Contrast-induced nephropathy (CIN)
- MRI safety issues
- Nephrogenic systemic sclerosis (NSF) due to Gd-containing contrast media.

1.7.1 Exposure to ionizing radiation

1.7.1.1 Radiation effects and effective dose

Radiography, scintigraphy and CT use ionizing radiation. Numerous studies, including those on survivors of the atomic bomb attacks in Japan in 1945, have shown that ionizing radiation in large doses is harmful. The risks of harm from medical radiation are low, and are usually expressed as the increased risk of developing cancer as a result of exposure. Public awareness of the possible hazards of medical radiation is growing and it is important

for doctors who refer patients for X-rays, nuclear medicine scans or CT scans to have at least a basic understanding of radiation effects and the principles of radiation protection.

Radiation effects occur as a result of damage to cells, including cell death and genetic damage. Actively dividing cells, such as are found in the bone marrow, lymph glands and gonads are particularly sensitive to radiation effects. In general, two types of effects may result from radiation damage: stochastic and deterministic. Deterministic effects are due to cell death and include radiation burns, cataracts and decreased fertility. Severity of deterministic effects varies with dose and a dose threshold usually exists below which the effect will not occur. For stochastic effects, the probability of the effect, not its severity is regarded as a function of dose. Theoretically, there is no dose threshold below which a stochastic effect will not occur. The most commonly discussed stochastic effect is increased cancer risk due to radiation exposure.

Radiation dose from medical imaging techniques is usually expressed as effective dose. The concept of effective dose takes into account the susceptibilities of the various tissues and organs, as well as the type of radiation received. The SI unit of effective dose is joules per kilogram and is referred to as the sievert (Sv): $1 \text{ Sv} = 1.0 \text{ J kg}^{-1}$. The effective dose provides a means of calculating the overall risk of radiation effects, especially the risk of cancer.

At the time of writing, there is a debate in the medical literature and the public domain about the risks of radiation exposure due to medical imaging. Those who subscribe to the 'no threshold' theory maintain that there is an increased risk of fatal cancer from any medical imaging examination that uses ionizing radiation. Figures such as a 1 in 2000 lifetime attributable risk of fatal cancer from a single CT of the abdomen may be quoted. Opponents of this theory point to a lack of evidence. In any case, most providers and consumers of medical imaging would agree that it is desirable for referring doctors to have some knowledge of the levels of possible radiation exposure associated with common imaging tests. Furthermore, there is widespread acceptance within the medical imaging community that radiation exposure should be minimized.

To try to make sense of quoted effective doses, there is a tendency to list figures against the number of frontal CXRs that might produce the same dose. Another common factor used for comparison is the amount of background radiation that is received as a normal process. This varies depending on location, but is generally 2–3 mSv per year. Another comparison used is the amount of radiation exposure as a result of flying in an airliner, usually quoted as hours of flying at 12 000 metres. A 20-hour flight from Australia to London would result in an exposure of about 0.1 mSv, the equivalent of about five CXRs. Some typical effective doses (mSv) and relevant comparisons are listed in Table 1.2.

1.7.1.2 The ALARA principle

The basic rule of radiation protection is that all justifiable radiation exposure is kept as low as is reasonably achievable (ALARA principle). This can be achieved by keeping in mind the following points:
- Each radiation exposure is justified on a case-by-case basis.
- The minimum number of radiographs is taken and minimum fluoroscopic screening time used.
- Mobile equipment is only used when the patient is unable to come to the radiology department.
- US or MRI should be used where possible.
- Children are more sensitive to radiation than adults and are at greater risk of developing radiation-induced cancers many decades after the initial exposure.
- In paediatric radiology, extra measures may be taken to minimize radiation dose including gonad shields and adjustment of CT scanning parameters.

1.7.1.3 Pregnancy

Extra measures should also be taken for the care of women of reproductive age:
- Radiation exposure of abdomen and pelvis should be minimized.
- All females of reproductive age asked if they could be pregnant prior to radiation exposure.
- Multilingual signs posted in the medical imaging department asking patients to notify the radiographer of possible pregnancy.

As organogenesis is unlikely to be occurring in an embryo in the first 4 weeks following the last menstrual period, this is not considered a critical

Table 1.2 Effective doses of some common examinations.

Imaging test	Effective dose (mSv)	Equivalent number of CXRs	Equivalent time of background exposure	Equivalent hours of flying at 12 000 metres
CXR frontal	0.02	1	3 days	4
CXR lateral	0.04	2	6 days	8
Limb X-ray	0.02	1	3 days	4
Lumbar spine X-ray	1.5	75	6 months	300
AXR	0.7	35	3 months	150
CT head	2	100	8 months	400
CTPA	8	400	2 years	1200
CT abdomen	2–10	100–500	8 months–3 years	400–1800
DEXA bone densitometry	0.001	0.05	<1 day	<1
Mammogram	0.7	35	3 months	150

period for radiation exposure. Organogenesis commences soon after the time of the first missed period and continues for the next three to four months. During this time, the fetus is considered to be maximally radiosensitive. Radiographic or CT examination of the abdomen or pelvis should be delayed if possible to a time when fetal sensitivity is reduced, i.e. post-24 weeks' gestation or ideally until the baby is born. Where possible, MRI or US should be used. Radiographic exposure to remote areas such as chest, skull and limbs may be undertaken with minimal fetal exposure at any time during pregnancy. For nuclear medicine studies in the post-partum period, it is advised that breastfeeding be ceased and breast milk discarded for 2 days following the injection of radionuclide.

1.7.2 Anaphylactoid contrast media reactions

Most patients injected intravenously with iodinated contrast media experience normal transient phenomena, including a mild warm feeling plus an odd taste in the mouth. With modern iodinated contrast media, vomiting at the time of injection is uncommon. More significant adverse reactions to contrast media may be classified as mild, intermediate or severe anaphylactoid reactions:

- Mild anaphylactoid reactions: mild urticaria and pruritis
- Intermediate reactions: more severe urticaria, hypotension and mild bronchospasm
- Severe reactions: more severe bronchospasm, laryngeal oedema, pulmonary oedema, unconsciousness, convulsions, pulmonary collapse and cardiac arrest.

Incidences of mild, intermediate and severe reactions with non-ionic low osmolar contrast media are 3, 0.04 and 0.004 per cent, respectively. Fatal reactions are exceedingly rare (1:170 000). All staff working with iodinated contrast materials should be familiar with CPR, and emergency procedures should be in place to deal with reactions, including resuscitation equipment and relevant drugs, especially adrenaline. Prior to injection of iodinated contrast media, patients should complete a risk assessment questionnaire to identify predisposing factors known to increase the risk of anaphylactoid reactions including:

- History of asthma: increases the risk by a factor of 10
- History of atopy: increases the risk by a factor of 10
- Previous anaphylactoid reaction to iodinated contrast media: 40 per cent risk of further reactions.

A history of allergy to seafood does not appear to be associated with an increased risk of contrast media reactions. There is no convincing evidence that pretreatment with steroids or an antihistamine reduces the risk of contrast media reactions.

1.7.3 Contrast-induced nephropathy

Contrast-induced nephropathy (CIN) refers to a reduction of renal function (defined as greater than 25 per cent increase in serum creatinine) occurring within 3 days of contrast medium injection. Most cases of CIN are self-limiting with resolution in 1–2 weeks. Dialysis may be required in up to 15 per cent. Risk factors for the development of CIN include:

- Pre-existing impaired renal function, particularly diabetic nephropathy
- Dehydration
- Sepsis
- Age >60 years
- Recent organ transplant
- Multiple myeloma.

Estimated glomerular filtration rate (eGFR) is generally seen as a better measure of renal function for risk assessment. eGRF accounts for age and sex and is calculated by formula from serum creatinine. CIN is very rare in patients with eGFR >60 mL/min. eGFR should be measured prior to contrast medium injection if there is a known history of renal disease or if any of the above risk factors is present.

The risk of developing CIN may be reduced by the following measures:

- Risk factors should be identified by risk assessment questionnaire.
- Use of other imaging modalities in patients at risk including US or non-contrast-enhanced CT.
- Use of minimum possible dose where contrast medium injection is required.
- Adequate hydration before and after contrast medium injection.
- Various pretreatments have been described, such as oral acetylcysteine; however, there is currently no convincing evidence that anything other than hydration is beneficial.

1.7.4 MRI safety issues

Potential hazards associated with MRI predominantly relate to the interaction of the magnetic fields with metallic materials and electronic devices. Reports exist of objects such as spanners, oxygen cylinders and drip poles becoming missiles when placed near an MRI scanner; the hazards to personnel are obvious. Ferromagnetic materials within the patient could possibly be moved by the magnetic field causing tissue damage. Common potential problems include metal fragments in the eye and various medical devices such as intracerebral aneurysm clips. Patients with a past history of penetrating eye injury are at risk for having metal fragments in the eye and should be screened prior to entering the MRI room with radiographs of the orbits.

MRI compatible aneurysm clips and other surgical devices have been available for many years. MRI should not be performed until the safety of an individual device has been established. The presence of electrically active implants, such as cardiac pacemakers, cochlear implants and neurostimulators, is generally a contraindication to MRI unless the safety of an individual device is proven. MRI compatible pacemakers are now becoming available.

1.7.5 Nephrogenic systemic sclerosis

Nephrogenic systemic sclerosis (NSF) is a rare complication of some Gd-based contrast media in patients with renal failure. Onset of symptoms may occur from one day to three months following injection. Initial symptoms consist of pain, pruritis and erythema, usually in the legs. As NSF progresses there is thickening of skin and subcutaneous tissues, and fibrosis of internal organs including heart, liver and kidneys. Identifying patients at risk, including patients with known renal disease, diabetes, hypertension and recent organ transplant, may reduce the risk of developing NSF following injection of Gd-based contrast media. eGFR should be measured in those at risk. Decisions can then be made regarding injection, choice of Gd-based medium, and possible use of alternative imaging tests.

1.7.6 Risk reduction in MRI

A standard questionnaire to be completed by the patient prior to MRI should cover relevant factors such as:

- Previous surgical history
- Presence of metal foreign bodies including aneurysm clips, etc.
- Presence of cochlear implants and cardiac pacemakers
- Possible occupational exposure to metal fragments and history of penetrating eye injury

- Previous allergic reaction to Gd-based contrast media
- Known renal disease or other risk factors relevant to NSF as outlined above.