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Technical Considerations

The use of the imaging department

Good communication between clinicians and radiologists is vital because the radiology department needs to understand the clinical problem in order to carry out appropriate tests and to interpret the results in a meaningful way. Also, clinicians need to understand the strengths and limitations of the answers provided.

Sensible selection of imaging investigations is of great importance. There are two opposing philosophies. One approach is to request a battery of investigations, aimed in the direction of the patient's symptoms, in the hope that something will turn up. The other approach is 'trial and error': decide one or two likely diagnoses and carry out the appropriate test to support or refute these possibilities. Each course has its proponents; we favour the selective approach as there is little doubt that the answers are usually obtained less expensively and with less distress to the patient. This approach depends on critical clinical evaluation; the more experienced the doctor, the more accurate he or she becomes in choosing appropriate tests.

Laying down precise guidelines for requesting imaging examinations is difficult because patients are managed differently in different centres and the information required varies significantly.

- An examination should only be requested when there is a reasonable chance that it will affect the management of the patient. There should be a question attached to every request, e.g. for a chest examination – what is the cause of this patient's haemoptysis?
- The time interval between follow-up examinations should be sensible and related to the natural history of the disease in question, e.g. once pneumonia has been diagnosed, chest examinations to assess progress can safely be left 7–14 days, unless clinical features suggest a complication.
- The localization of problems should be as specific as possible. Poor localization may lead to over-investigation or excessive radiation exposure.
- Careful consideration should be given to which diagnostic imaging procedure will give the relevant information most easily. It may be reasonable to construct a programme of investigations but the radiologist should always be asked to cancel any remaining tests once the desired positive result is obtained.
- Examinations which minimize or avoid ionizing radiation should be chosen whenever possible.

Conventional radiography

X-rays are absorbed to a variable extent as they pass through the body. The visibility of both normal structures and disease depends on this differential absorption. With conventional radiography there are four basic densities – gas, fat, all other soft tissues and calcified structures. X-rays that pass through air are least absorbed and, therefore, cause the most blackening of the radiograph, whereas calcium absorbs the most and so the bones and other calcified structures appear virtually white. The soft tissues, with the exception of fat, e.g. the solid viscera, muscle, blood, a variety of fluids, bowel wall, etc., all have similar absorptive capacity and appear the same shade of grey on conventional radiographs. Fat absorbs slightly fewer x-rays and, therefore, appears a little blacker than the other soft tissues. Images can be produced using a silver-based photographic emulsion or they can be recorded digitally and viewed on computer screens.

Projections are usually described by the path of the x-ray beam. Thus, the term PA (posteroanterior) view designates that the beam passes from the back to the front, the standard projection for a routine chest film. An AP

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(anteroposterior) view is one taken from the front. The term 'frontal' refers to either PA or AP projection. The image on an x-ray film is two-dimensional. All the structures along the path of the beam are projected on to the same portion of the film. Therefore, it is often necessary to take at least two views to gain information about the third dimension. These two views are usually at right angles to one another, e.g. the PA and lateral chest film. Sometimes two views at right angles are not appropriate and oblique views are substituted.

Portable x-ray machines can be used to take films of patients in bed or in the operating theatre. Such machines have limitations on the exposures they can achieve. This usually means longer exposure times and poorer quality films. The positioning and radiation protection of patients in bed is often inferior to that which can be achieved within the x-ray department. Consequently, portable films should only be requested when the patient cannot be moved safely or comfortably to the x-ray department.

Computed tomography

Computed tomography (CT) also relies on x-rays transmitted through the body. It differs from conventional radiography in that a more sensitive x-ray detection system is used, the images consist of sections (slices) through the body, and the data are manipulated by a computer. The x-ray tube and detectors rotate around the patient (Fig. 1.1). The outstanding feature of CT is that very small differences in x-ray absorption values can be visualized. Compared with conventional radiography, the range of densities recorded is increased approximately 10-fold. Not only can fat be distinguished from other soft tissues, but also gradations of density within soft tissues can be recognized, e.g. brain substance from cerebrospinal fluid, or tumour from surrounding normal tissues.

The patient lies with the body part to be examined within the gantry housing the x-ray tube and detectors. Although other planes are sometimes practicable, axial sections are

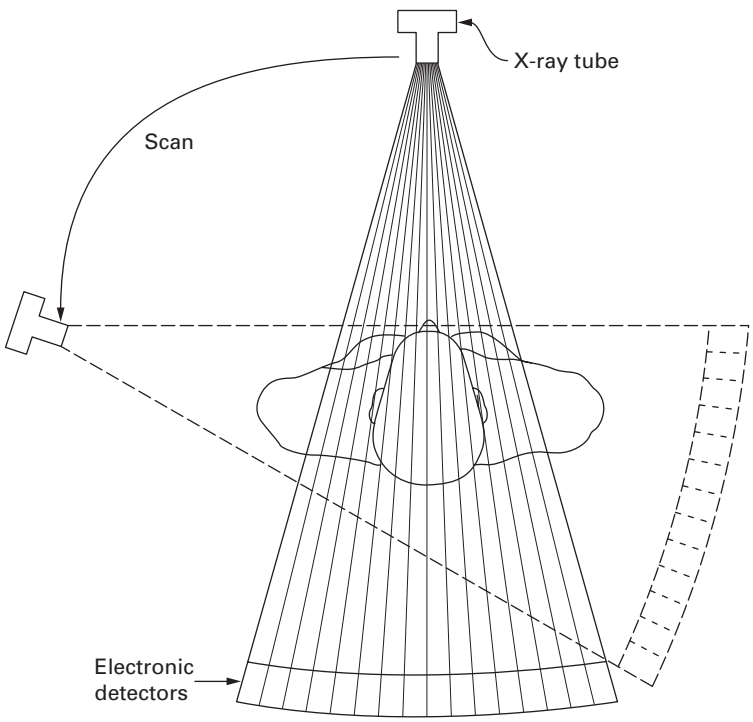


Fig. 1.1 Principle of CT. The x-ray tube and detectors move around the patient enabling a picture of x-ray absorption in different parts of the body to be built up. The time taken for the exposure is in the order of a second or so.

by far the most frequent. The operator selects the level and thickness to be imaged: the usual thickness is less than 1.25 mm (often viewed by aggregating adjacent sections so they become 5 mm thick). The patient is moved past an array of detectors within the machine. In effect, the data at multiple adjacent levels are collected continuously, during which time the x-ray beam traces a spiral path to create a 'volume of data' within the computer memory. Multidetector (multislice) CT is a relatively recent innovation whereby up to 64 or more sections (slices) can be acquired during one rotation of the x-ray tube. Multidetector CT enables the examination to be performed in a few seconds, thereby enabling hundreds of thin sections to be obtained in one breath-hold.

The data obtained from each set of exposures are reconstructed into an image by computer manipulation. The computer calculates the attenuation (absorption) value of each picture element (known in computer jargon as a pixel). Each pixel is 0.25–0.6 mm in diameter, depending on the resolution of the machine, with a height corresponding to the chosen section thickness. The resulting images are displayed on a monitor and can be photographed and/or stored electronically. The attenuation values are expressed on an arbitrary scale (Hounsfield units) with water density being zero, air density being minus 1000 units and bone density being plus 1000 units (Fig. 1.2). The range and level of densities to be displayed can be selected by controls on the computer. The range of densities visualized on a particular image is known as the *window width* and the mean level as the *window level* or *window centre*. Computed tomography is usually performed in the axial plane, but because attenuation values for every pixel are present in the computer memory it is possible to reconstruct excellent images in other planes, e.g. coronal (Fig. 1.3), sagittal or oblique, and even three-dimensional (3D) images (Fig. 1.4).

The human eye can only appreciate a limited number of shades of grey. With a wide window all the structures are visible, but fine details of density difference cannot be appreciated. With a narrow window width, variations of just a few Hounsfield units can be seen, but much of the image is either totally black or totally white and in these areas no useful information is provided. The effects of varying window width and level are illustrated in Figs 1.5 and 2.5, p. 21.

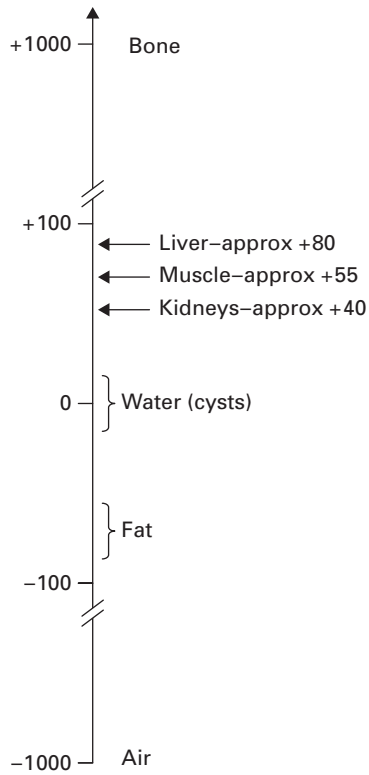


Fig. 1.2 Scale depicting the CT density (Hounsfield units) of various normal tissues in the body.

CT angiography

Rapid intravenous injections of contrast media result in significant opacification of blood vessels, which, with multiplanar or 3D reconstructions, can be exploited to produce angiograms. CT angiography, along with magnetic resonance angiography, is gradually replacing conventional angiography.

Artefacts

There are numerous CT artefacts. The most frequent are those produced by movement and those from objects of very high density, such as barium in the bowel, metal implants, dental fillings or surgical clips. Both types give rise to radiating linear streaks. The major problem is the resulting degradation of the image.

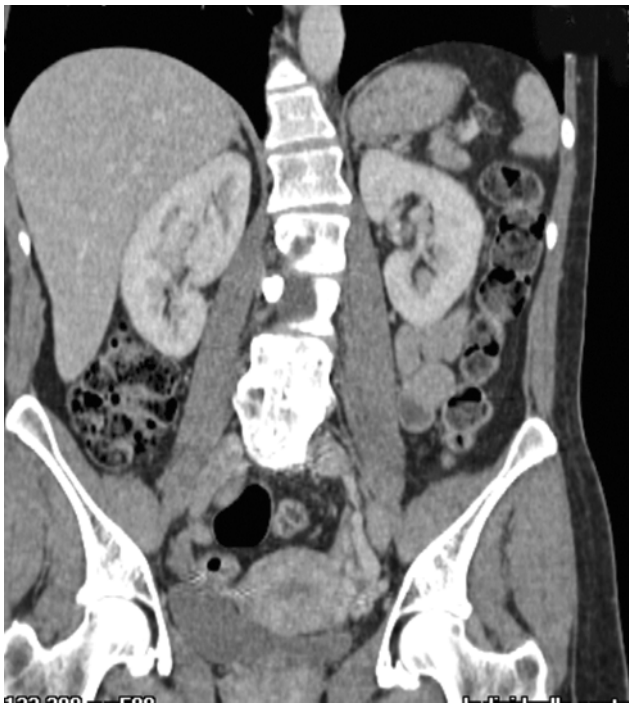


Fig. 1.3 Coronal reconstruction of CT of abdomen and pelvis. The images were obtained in the axial plane using very thin sections and then reconstructed into the desired plane – a coronal plane in this example. The illustrated section is through the posterior abdomen and shows the kidneys very well.

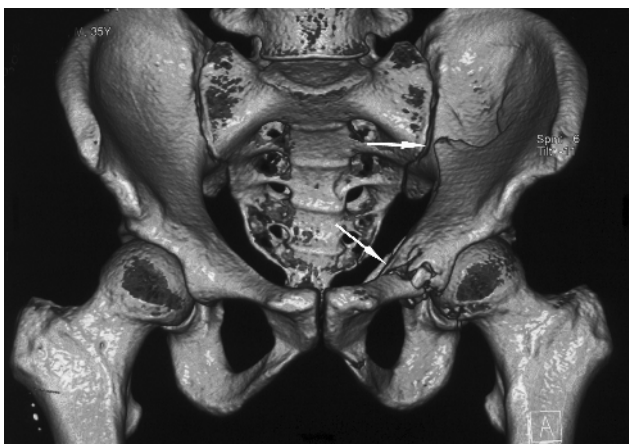
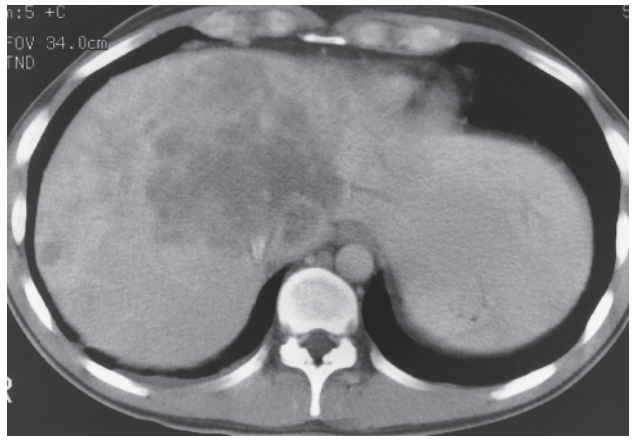
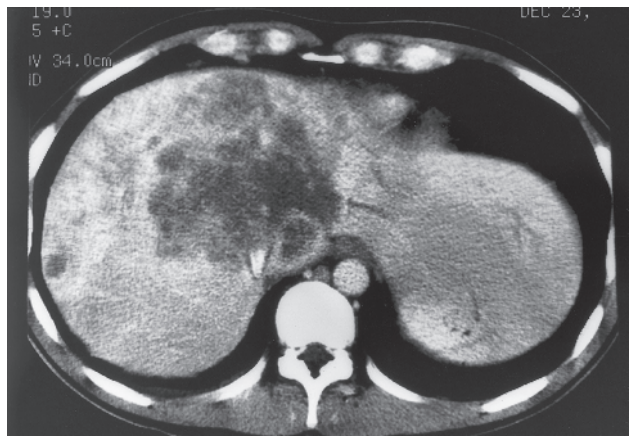


Fig. 1.4 (*Left*) Shaded surface 3D CT reconstruction. The images can be viewed in any desired projection and give a better appreciation of the pelvis. Two fractures are demonstrated in the left innominate bone (arrows), which were hard to diagnose on the plain film. Further views of this fracture can be seen in Fig. 12.13, p. 379.



(a)



(b)

Fig. 1.5 Effect of varying window width on CT. In (a) and (b) the level has been kept constant at 65 Hounsfield units (HU). The window width in (a) is 500 whereas in (b) it is only 150 HU. Note that in the narrow window image (b), the metastases are better seen, but that structures other than the liver are better seen in (a).

Contrast agents in conventional radiography and CT

Radiographic contrast agents are used to visualize structures or disease processes that would otherwise be invisible or difficult to see. Barium is widely used to outline the gastrointestinal tract; all the other radio-opaque media rely on iodine in solution to absorb x-rays. Iodine-containing solutions are used for urography, angiography and intravenous contrast enhancement at CT. Usually they are given in large doses, often with rapid rates of injection. As their only purpose is to produce opacification, ideally they should be pharmacologically inert. This has not yet been totally achieved, though the current low-osmolality agents, such as the non-ionic media, have exceedingly low complication rates.

Some patients experience a feeling of warmth spreading over the body as the iodinated contrast medium is injected. Contrast inadvertently injected outside the vein is painful and should be carefully guarded against. A few patients develop an urticarial rash, which usually subsides spontaneously.

Bronchospasm, laryngeal oedema or hypotension occasionally develop and may be so severe as to be life-threatening. It is therefore essential to be prepared for these dangerous reactions and to have available appropriate resuscitation equipment and drugs. Patients with known allergic manifestations, particularly asthma, are more likely to have an adverse reaction. Similarly, patients who have had a previous reaction to contrast agents have a higher than average risk of problems during the examination. Such patients are given non-ionic agents and premedicated with steroids. Intravenous contrast agents may have a deleterious effect on renal function in patients with impaired kidneys. Therefore, their use should be considered carefully on an individual basis and the patient should be well hydrated prior to injection.

Ultrasound

In diagnostic ultrasound examinations, very high frequency sound is directed into the body from a transducer placed in contact with the skin. In order to make good acoustic contact, the skin is smeared with a jelly-like substance. As the sound travels through the body, it is reflected by the tissue interfaces to produce echoes which are picked up by the same transducer and converted into an electrical signal.

As air, bone and other heavily calcified materials absorb nearly all the ultrasound beam, ultrasound plays little part in the diagnosis of lung or bone disease. The information from abdominal examinations may be significantly impaired by gas in the bowel that interferes with the transmission of sound.

Fluid is a good conductor of sound, and ultrasound is, therefore, a particularly good imaging modality for diagnosing cysts, examining fluid-filled structures such as the bladder and biliary system, and demonstrating the fetus in its amniotic sac. Ultrasound can also be used to demonstrate solid structures that have a different acoustic impedance from adjacent normal tissues, e.g. metastases.

Ultrasound is often used to determine whether a structure is solid or cystic (Fig. 1.6). Cysts or other fluid-filled structures produce large echoes from their walls but no echoes from the fluid contained within them. Also, more echoes than usual are received from the tissues behind the cyst, an effect known as *acoustic enhancement*. Conversely, with a calcified structure, e.g. a gall stone (Fig. 1.7), there is a great reduction in the sound that will pass through, so a band of reduced echoes, referred to as an *acoustic shadow*, is seen behind the stone.

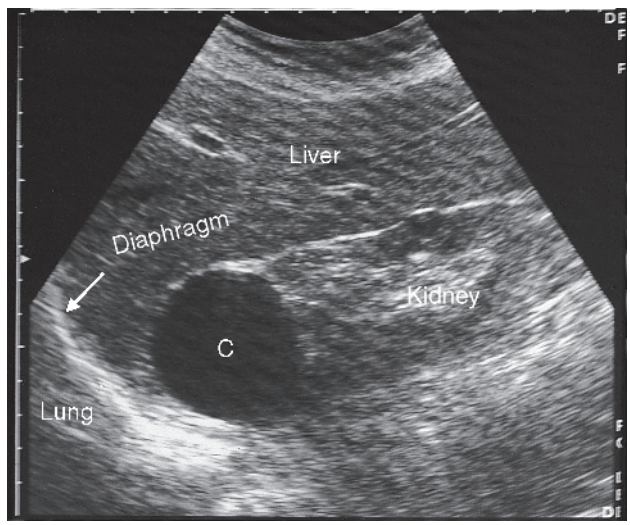


Fig. 1.6 Ultrasound scan of longitudinal section through the liver and right kidney. A cyst (C) is present in the upper pole of the kidney.

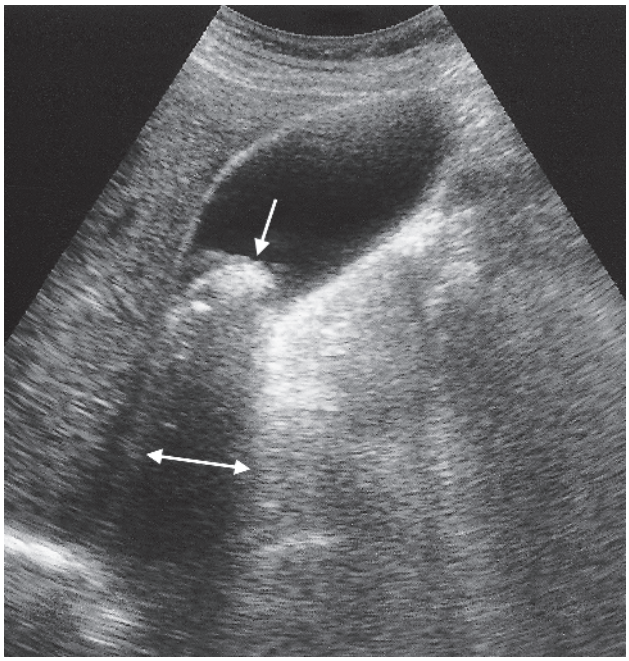


Fig. 1.7 Ultrasound scan of gall bladder showing a large stone in the neck of the gall bladder (downward pointing arrow). Note the acoustic shadow behind the stone (horizontal arrows).

Ultrasound is produced by causing a special crystal to oscillate at a predetermined frequency. Very short pulses of sound lasting about a millionth of a second are transmitted approximately 500 times each second. The crystal not only transmits the pulses of sound but also 'listens' to the returning echoes, which are electronically amplified to be recorded as signals on a television monitor. Photographic reproductions of the image can provide a permanent record.

The time taken for each echo to return to the transducer is proportional to the distance travelled. Knowledge of the depth of the interface responsible for the echoes allows an image to be produced. Also, by knowing the velocity of sound in tissues, it is possible to measure the distance between interfaces. This is of great practical importance in obstetrics, for example, where the measurement of the fetal head has become the standard method of estimating fetal age.

During the scan, the ultrasound beam is electronically swept through the patient's body and a section of the internal anatomy is instantaneously displayed. The resulting image is a slice, so in order to obtain a 3D assessment a number of slices must be created by moving or angling the transducer.

Unlike other imaging modalities, there are no fixed projections and the production of the images and their subsequent interpretation depend very much on the observations of the operator during the examination. Ultrasound images are capable of providing highly detailed information, e.g. very small lesions can be demonstrated (Fig. 1.8).

A recent advance is the development of small ultrasound probes which may be placed very close to the region of interest, thus producing highly detailed images but with a limited range of a few centimetres. Examples are rectal probes for examining the prostate and transvaginal probes for the examination of the pelvic structures. Tiny ultrasound probes may be incorporated in the end of an endoscope. Lesions of the oesophagus, heart and aorta may be demonstrated with an endoscope placed in the oesophagus, and lesions of the pancreas may be detected with an endoscope passed into the stomach and duodenum. Special ultrasound probes have also been developed that can be inserted into arteries to detect atheromatous disease.

Three-dimensional ultrasound has been recently developed and is used primarily in obstetrics to obtain 3D images of the fetus. A conventional ultrasound transducer is used, which is moved slowly across the body recording simultaneously the location and ultrasound image. A 3D image can be constructed from the data received.

At the energies and doses currently used in diagnostic ultrasound, no harmful effects on any tissues have been demonstrated.

Ultrasound contrast agents are currently being developed. These agents contain microscopic air bubbles that enhance the echoes received by the probe. The air bubbles are held in a stabilized form, so they persist for the duration of the examination and blood flow and perfusion to organs can be demonstrated. The technique is used to help characterize liver and renal abnormalities and in the investigation of cardiac disease.

Doppler effect

Sound reflected from a mobile structure shows a variation in frequency which corresponds to the speed of move-

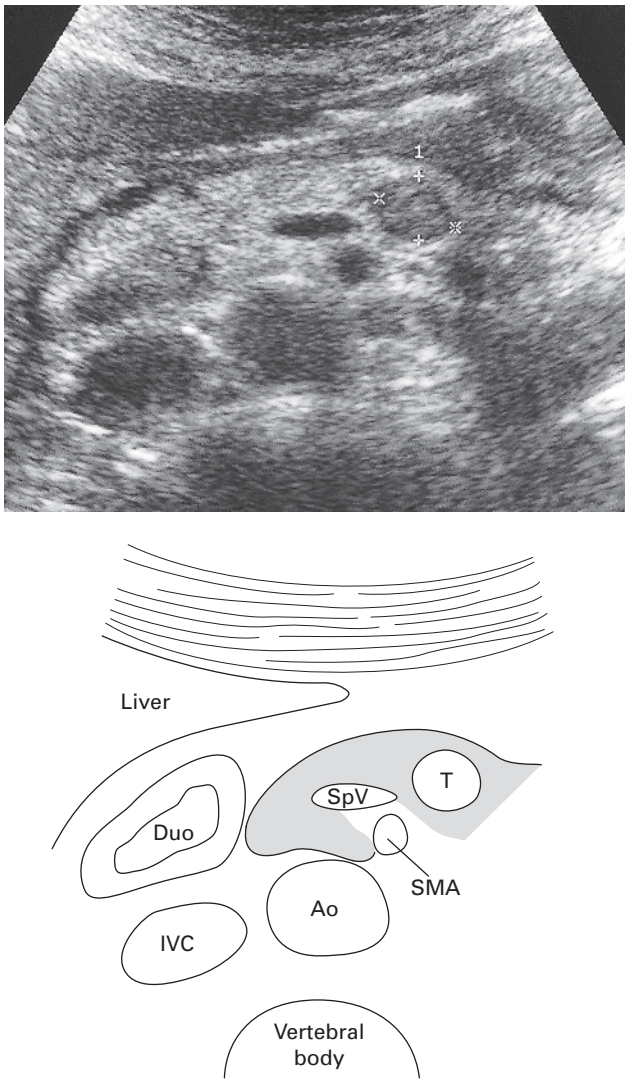


Fig. 1.8 Ultrasound scan of pancreas showing 1 cm tumour (T) (an insulinoma) at the junction of the head and body of the pancreas. The pancreas is shaded in the diagram. Ao, aorta; Duo, duodenum; IVC, inferior vena cava; SMA, superior mesenteric artery; SpV, splenic vein.

ment of the structure. This shift in frequency, which can be converted to an audible signal, is the principle underlying the Doppler probe used in obstetrics to listen to the fetal heart.

The Doppler effect can also be exploited to image blood flowing through the heart or blood vessels. Here the sound is reflected from the blood cells flowing in the vessels (Plate 1). If blood is flowing towards the transducer the received signal is of higher frequency than the transmitted frequency, whilst the opposite pertains if blood is flowing away from the transducer. The difference in frequency between the sound transmitted and received is known as the Doppler frequency shift.* The direction of blood flow can readily be determined and flow towards the transducer is, by convention, coloured red, whereas blue indicates flow away from the transducer.

When a patient is being scanned, the Doppler information in colour is superimposed onto a standard ultrasound image (Plate 3).

During the examination the flow velocity waveform can be displayed and recorded. As the waveforms from specific arteries and veins have characteristic shapes, flow abnormalities can be detected. If the Doppler angle (Plate 1a) is known then the velocity of the flowing blood can be calculated and blood flow can be calculated provided the diameter of the vessel is also known.

Doppler studies are used to detect venous thrombosis, arterial stenosis and occlusion, particularly in the carotid arteries. In the abdomen, Doppler techniques can determine whether a structure is a blood vessel and can help in assessing tumour blood flow. In obstetrics, Doppler ultrasound is used particularly to determine fetal blood flow through the umbilical artery. With Doppler echocardiography it is possible to demonstrate regurgitation through incompetent valves and pressure gradients across valves can be calculated.

Radionuclide imaging

The radioactive isotopes used in diagnostic imaging emit gamma-rays as they decay. Gamma rays are electromagnetic radiation, similar to x-rays, produced by radioactive

*The formula is:

$$\text{frequency shift} = \frac{2Fi \times V \times \cos\theta}{c}$$

(As c, the speed of sound in tissues, and Fi, the incident frequency of sound, are constant and if θ, the Doppler angle, is kept constant, the frequency shift depends directly on the blood flow velocity V.)

decay of the nucleus. Many naturally occurring radioactive isotopes, e.g. potassium-40, uranium-235, have half lives of hundreds of years and are, therefore, unsuitable for diagnostic imaging. The radioisotopes used in medical diagnosis are artificially produced and most have short half lives, usually a few hours or days. To keep the radiation dose to the patient at a minimum, the smallest possible dose of an isotope with a short half life should be used. Clearly, the radiopharmaceuticals should have no undesirable biological effects and should be rapidly excreted from the body following completion of the investigation.

Radionuclide imaging depends on the fact that certain substances concentrate selectively in different parts of the body. Radionuclides can be chemically tagged to these substances. Occasionally, the radionuclide in its ionic form will selectively concentrate in an organ, so there is no need to attach it to another compound. The radionuclide most commonly used is technetium-99m (^{99m}Tc). It is readily prepared, has a convenient half life of 6 hours and emits gamma-radiation of a suitable energy for easy detection. Other radionuclides that are used include indium-111, gallium-67, iodine-123 and thallium-201.

Technetium-99m can be used in ionic form (as the pertechnetate) to detect ectopic gastric mucosa in Meckel's diverticulum, but it is usually tagged to other substances. For example, a complex organic phosphate labelled with ^{99m}Tc will be taken up by the bones and can be used to visualize the skeleton (Fig. 1.9). Particles are used in lung perfusion images; macroaggregates of albumin with a particle size of 10–75 μm when injected intravenously are trapped in the pulmonary capillaries. If the macroaggregates are labelled with ^{99m}Tc, then the blood flow to the lungs can be visualized. It is also possible to label the patient's own red blood cells with ^{99m}Tc to assess cardiac function, or the white cells with indium-111 or ^{99m}Tc for abscess detection. Small quantities of radioactive gases, such as xenon-133, xenon-127 or krypton-81 m, can be inhaled to assess ventilation of the lungs. All these radiopharmaceuticals are free of side-effects.

The gamma rays emitted by the isotope are detected by a gamma camera, enabling an image to be produced. A gamma camera consists of a large sodium iodide crystal, usually 40 cm in diameter, coupled to a number of photomultiplier tubes. Light is produced when the gamma rays strike and activate the sodium iodide crystal, and the light is then electronically amplified and converted to an electrical pulse. The electrical pulse is further amplified and analyzed by a processing unit so that a recording can be made. Invariably, some form of computer is linked to the gamma camera to enable rapid serial images to be taken and to perform computer enhancement of the images when relevant.

In selected cases emission tomography is performed. In this technique, the gamma camera moves around the patient. A computer can analyze the information and produce sectional images similar to CT. Emission tomography can detect lesions not visible on the standard views. Because only one usable photon for each disintegration is emitted, this technique is also known as single photon emission computed tomography (SPECT).

Nuclear medicine techniques are used to measure function and to produce anatomical images. Even the anatomical images are dependent on function; for example, a bone scan depends on bone turnover. The anatomical information they provide, however, is limited by the relatively poor spatial resolution of the gamma camera compared with other imaging modalities.

Positron emission tomography

Positron emission tomography (PET) uses short-lived positron emitting isotopes, which are produced by a cyclotron immediately before use. Two gamma rays are produced from the annihilation of each positron and can be detected by a specialized gamma camera. The resulting images reflect the distribution of the isotope (Fig. 1.10a). By using isotopes of biologically important elements such as carbon or oxygen, PET can be used to study physiological processes such as blood perfusion of tissues, and metabolism of substances such as glucose, as well as complex biochemical pathways such as neurotransmitter storage and binding. The most commonly used agent is F-18 fluorodeoxyglucose (FDG). This is an analogue of glucose and is taken up by cells in proportion to glucose metabolism, which is increased in tumour cells. Because muscle activity results in the uptake of FDG, the patient rests quietly in the interval between injection of the FDG and scanning.

The images must be interpreted carefully as non-cancerous conditions may show uptake resembling cancer. Positron emission tomography using FDG is the most sensitive technique for staging solid tumours such as bronchial carcinoma (Plate 2) and in follow-up of malignancies,

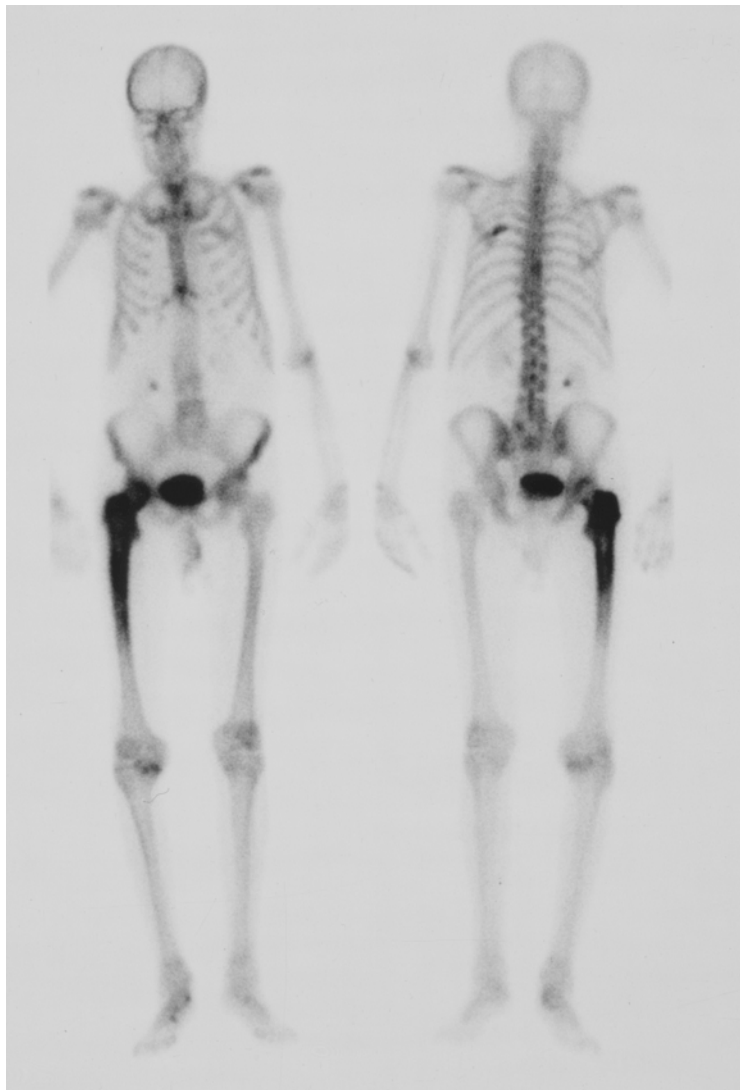
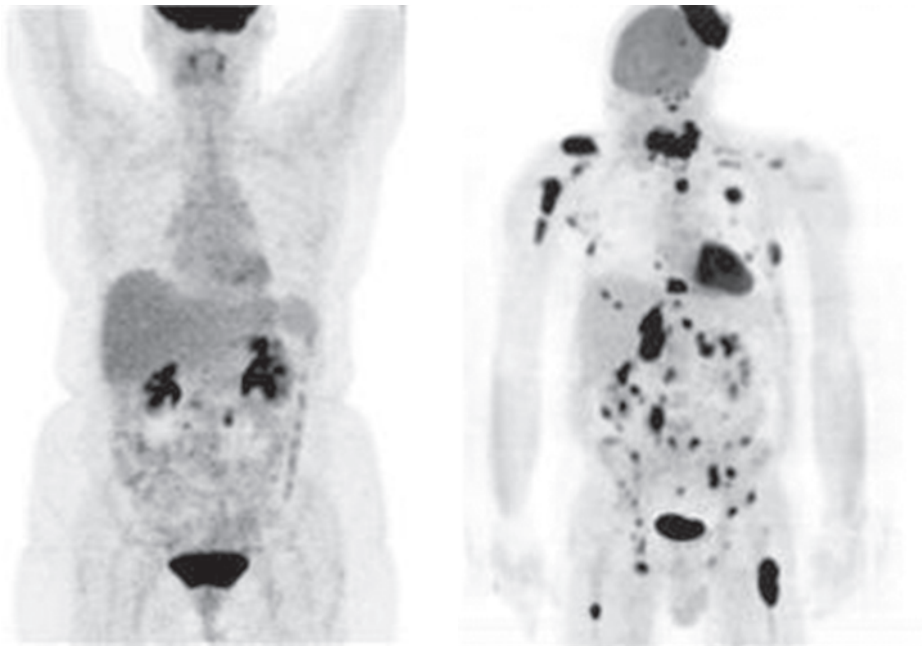


Fig. 1.9 Radionuclide bone scan. The patient has received an intravenous injection of a ^{99m}Tc-labelled bone scanning agent (a complex organic phosphate). This agent is taken up by bone in proportion to bone turnover and blood flow. The increased uptake in the femur in this patient was due to Paget's disease.

particularly lymphoma (Fig. 1.10b), where other imaging techniques may be unable to distinguish active disease from residual fibrosis.

Positron emission tomography is also used in the evaluation of ischaemic heart disease and in brain disorders such as dementia, epilepsy and Parkinson's disease.

PET demonstrates biological function while CT gives anatomical information. If PET and CT are fused, the lesions detected by PET can be precisely localized by CT (Plate 2). Modern equipment allows both PET and CT to be performed sequentially on the same machine.



(a) (b)

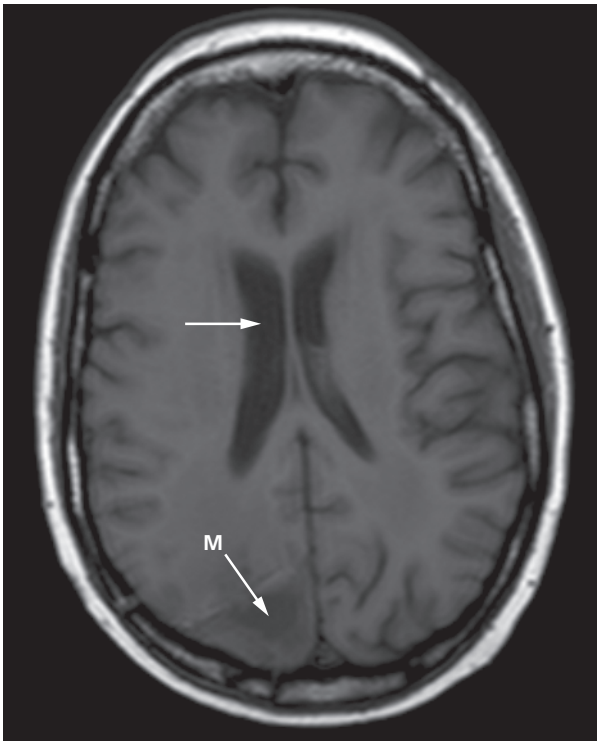
Fig. 1.10 FDG PET scans. (a) Normal. There is intense uptake in the brain. The neck uptake is in the tonsils. The FDG is excreted by the kidneys. (b) Lymphoma, showing multiple visceral, nodal, bone and scalp deposits.

Magnetic resonance imaging

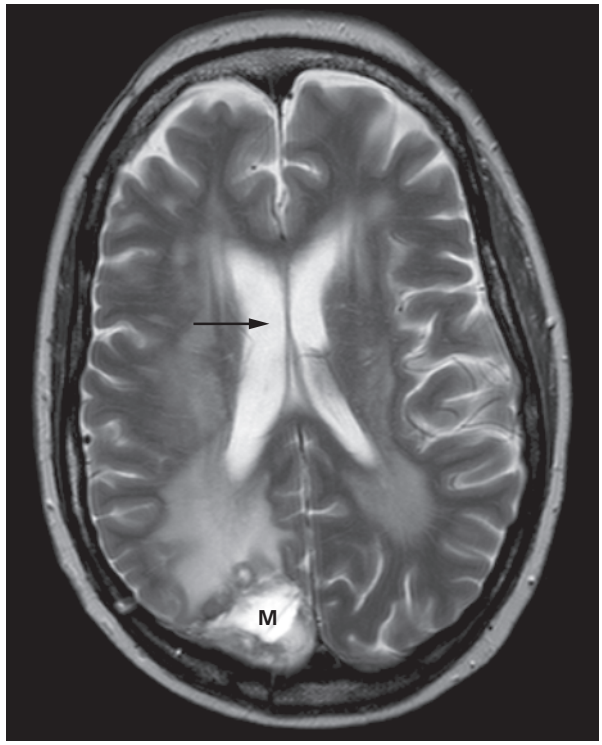
The basic principles of magnetic resonance imaging (MRI) depend on the fact that the nuclei of certain elements align with the magnetic force when placed in a strong magnetic field. At the field strengths currently used in medical imaging, hydrogen nuclei (protons) in water molecules and lipids are responsible for producing anatomical images. If a radiofrequency pulse at the resonant frequency of hydrogen is applied, a proportion of the protons change alignment, flipping through a preset angle, and rotate in phase with one another. Following this radiofrequency pulse, the protons return (realign) to their original positions. As the protons realign (relax), they induce a radio signal which, although very weak, can be detected and localized by antenna coils placed around the patient. An image representing the distribution of the hydrogen protons can be built up (Fig. 1.11). The strength of the signal depends not only on proton density but also on two relaxation times, T1 and T2; T1 depends on the time the protons take to return to the axis of the magnetic field, and T2 depends on the time the protons take to dephase. A T1-weighted image is one in which the contrast between tissues is due mainly to their T1 relaxation properties, while in a T2-weighted image the contrast is due to the T2 relaxation properties (see Box 1.1). Some sequences produce images which approximate mainly to proton density. Most pathological processes show increased T1 and T2 relaxation times and, therefore, these processes appear lower in signal (blacker) on a T1-weighted scan and higher in signal intensity (whiter) on a T2-weighted scan than the normal surrounding tissues. The

Box 1.1 Appearance of water and fat on different magnetic resonance (MR) sequences

Sequence	Water signal intensity	Fat signal intensity
T1-weighted	Low	High
T2-weighted	High	High
T1 with fat saturation	Low	Low
T2 with fat saturation	High	Low



(a)



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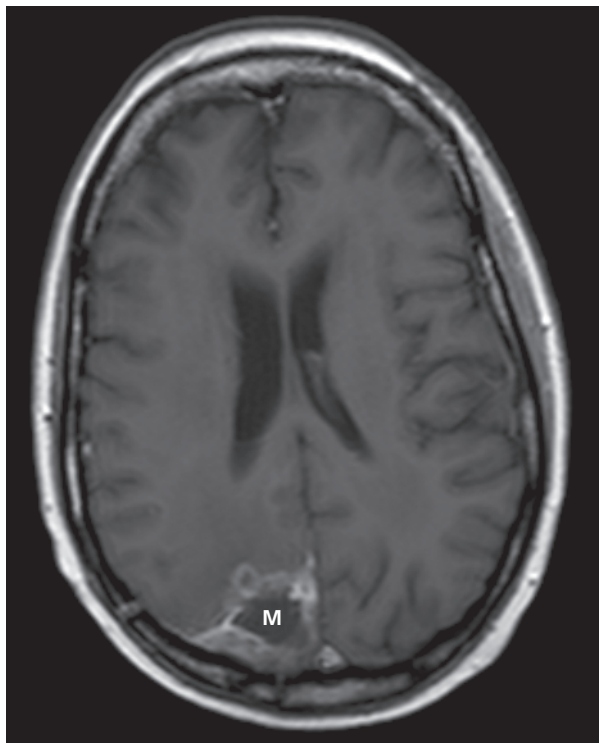


(c)

Fig. 1.11 MRI of the brain. (a) Axial T1-weighted image. (b) Axial T2-weighted image. (c) Axial T1-weighted image following gadolinium. Note that the cerebrospinal fluid within the lateral ventricles is of low signal intensity on T1 and high signal intensity on T2-weighted images (arrows). Note also that the intensity of the white and grey matter of the brain differs on the two images. There is a metastasis from a breast carcinoma (M) in the right occipital pole, showing oedema around the mass on the T2-weighted image and enhancement on the post contrast image.

T1- and T2-weighting of an image can be selected by appropriately altering the timing and sequence of radiofrequency pulses.

There are many other sequences with a bewildering variety of names and acronyms. They are designed to highlight different tissue characteristics, e.g. to demonstrate water content (HASTE sequence), diminish the signal from fat and so highlight pathology or contrast enhancement (fat suppression or STIR sequence, see Fig. 4.43, p. 156), or demonstrate the combination of water and lipid content in the same voxel (chemical shift imaging, see Fig. 8.17, p. 283). Dynamic contrast-enhanced scans using gadolinium contrast medium (see below) may be used to demonstrate the anatomy of the large vessels as well as the enhancement characteristics of tumour angiogenesis (Fig. 1.11c). More recent developments include diffusion-weighted imaging and MR spectroscopy, which can further characterize tissues and are often used in tumour assessment.

A typical MRI scanner (Fig. 1.12) consists of a large circular magnet. Inside the magnet are the radiofrequency transmitter and receiver coils, as well as gradient coils to allow spatial localization of the MRI signal. Ancillary equipment converts the radio signal into a digital form, which the computer can manipulate to create an image. One advantage of MRI over CT is that the information can be directly imaged in any plane. In most instances, MRI requires a longer scan time (often several minutes) compared with CT, with the disadvantage that the patient has to keep still during the scanning procedure. Unavoidable movements from breathing, cardiac pulsation and peristalsis often degrade the image. Techniques to speed up scan times and limit the effect of motion by the use of various electronic methods have been introduced. Cardiac gating and breath-hold sequences are now readily available.

Magnetic resonance imaging gives very different information to CT. The earliest successful application was for scanning the brain and spinal cord, where MRI has significant advantages over CT and few disadvantages. Magnetic resonance imaging is now also an established technique for imaging the spine, bones, joints, pelvic organs, liver, biliary system, urinary tract and heart. At first sight it may seem rather surprising that MRI provides valuable information in skeletal disease as calcified tissues do not generate any signal at MRI. This seeming paradox is explained by the fact that MRI provides images of the bone marrow and the soft tissues inside and surrounding joints (Fig. 1.13).

The physical basis of imaging blood vessels with MRI is complicated and beyond the scope of this book. Suffice it to say that, with some sequences, fast-flowing blood produces no signal (Fig. 1.14), whereas with others it produces a bright signal. This 'motion effect' can be exploited to image blood vessels. Such flow-sensitive sequences are mostly used for head and neck imaging, for example, intracranial arteriovenous malformations and stenoses of the carotid arteries can be readily demonstrated without contrast media. The resulting images resemble a conventional angiogram (Fig 1.15).

Magnetic resonance imaging of the heart uses electronic gating to obtain images during a specific portion of the

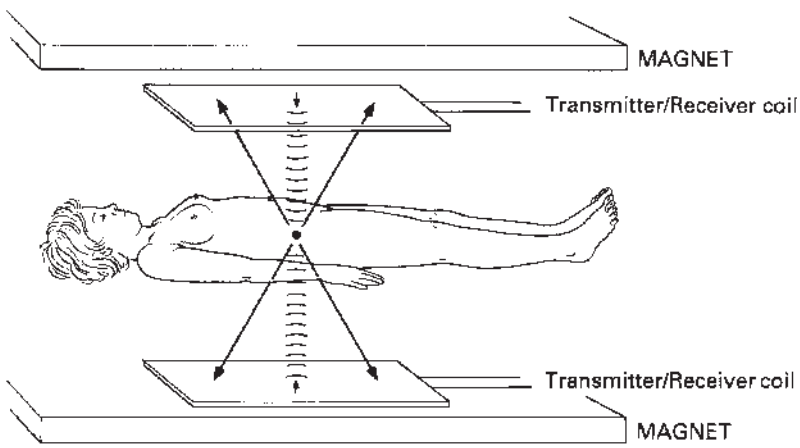
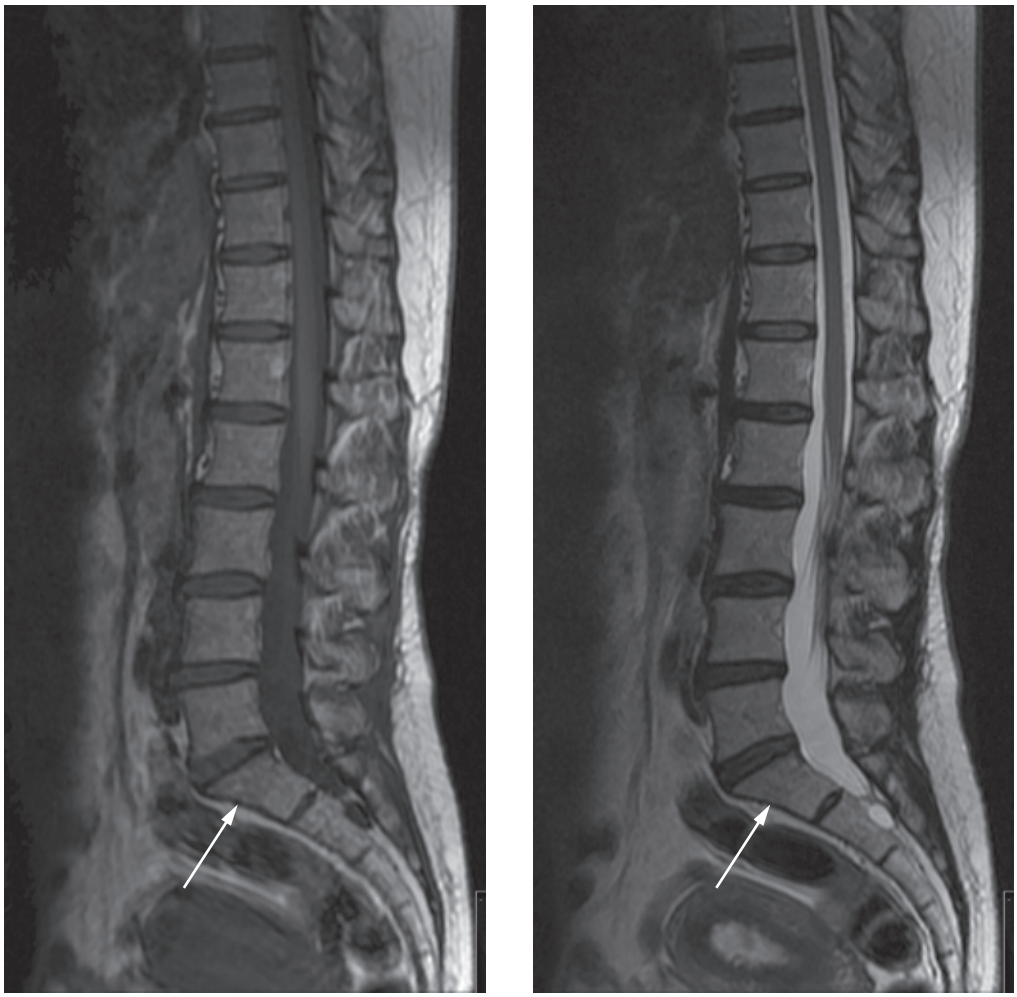


Fig. 1.12 Diagram of an MRI machine. The patient lies within a strong magnet (usually a cylindrical magnet). The radiofrequency transmitter coils send radiowaves into the patient and the same coils receive signals from within the patient. The intensity and source of these signals can be calculated and displayed as an image.



(a) (b)

Fig. 1.13 MRI of sagittal section of the lumbar spine. (a) On this T1 sequence, spinal cord is grey, cerebrospinal fluid (CSF) is nearly black and subcutaneous fat is white. (b) T2-weighted sequence. Here the CSF is white. Cortical bone (arrow) returns no signal and appears as a black line on both sequences. The fat in the bone marrow produces a signal that enables the vertebrae to be visualized.

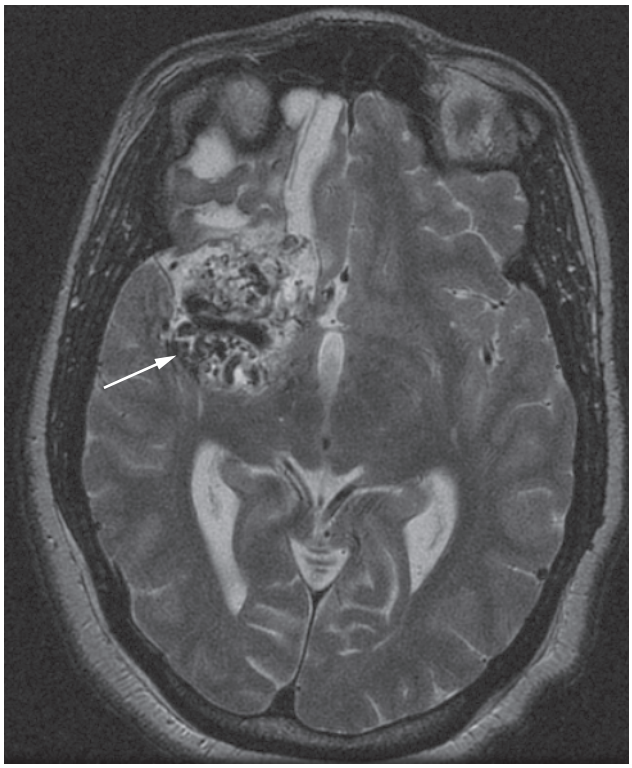


Fig. 1.14 MRI of brain showing an arteriovenous malformation (arrow) in the right cerebral hemisphere. The fast-flowing blood in the malformation is responsible for absence of signal (signal void). The image is a T2-weighted image, and is normal apart from the arteriovenous malformation and its consequences.

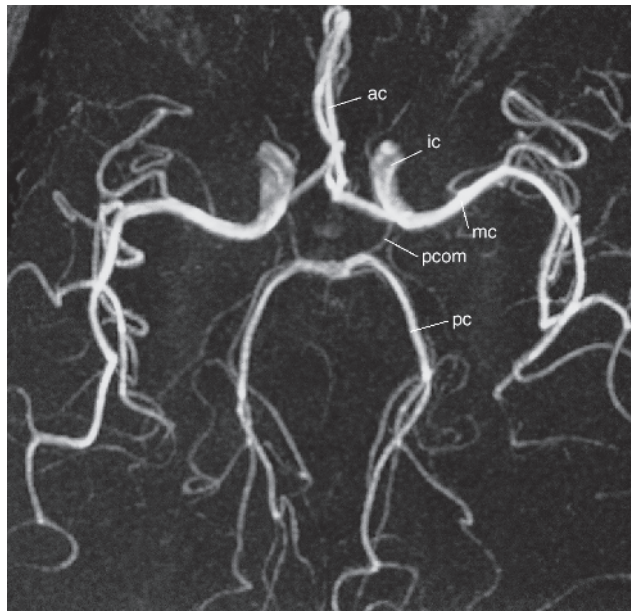


Fig. 1.15 MR angiogram of the intracranial arteries. No contrast medium was used to obtain this image. ac, anterior cerebral; ic, internal cerebral; mc, middle cerebral; pc, posterior cerebral; pcom, posterior communicating artery.

cardiac cycle. With this technique it is possible to limit the degradation of the image by cardiac motion and demonstrate the cardiac chambers, valves and myocardium. Alternatively, the beating heart can be directly visualized as a cine image.

One of the advantages of MRI is that it involves no ionizing radiation, and no adverse biological effects from diagnostic MRI have been demonstrated. The strong magnetic fields, however, mean that it is at present contraindicated in patients with certain implantable devices, including cardiac pacemakers, certain types of aneurysm clip and intraocular metallic foreign bodies.

Contrast agents for MRI

Just as contrast media have been of great value in CT, magnetic contrast materials are providing useful diagnostic information with MRI. The most widely used agents are gadolinium compounds which only cross the blood–brain barrier when it is damaged by disease (Fig. 1.11c), and which concentrate in tissues and disease processes with a high blood supply. Tissues which concentrate the agent show very high signal intensity (i.e. they appear white) on T1-weighted images. Tissue-specific media, such as iron-oxide agents for reticuloendothelial cell imaging, are also used. A particular application of contrast-enhanced MRI is magnetic resonance angiography (MRA), which along with CT angiography, is gradually replacing conventional angiography.

Gadolinium-based contrast agents are generally very safe and anaphylactic reactions are rare. They are contraindicated in pregnancy. Also, it has recently been recog-

nized that patients in renal failure, on dialysis, or awaiting liver transplantation are at risk of developing nephrogenic systemic fibrosis (NSF), which can be fatal. In these patients, the MR scan is done without the use of gadolinium-based contrast agents.

Picture archiving and communication systems (PACS)

Digital recording has developed dramatically over the past two decades. CT, ultrasound, MRI, nuclear medicine and angiography are nowadays all digital techniques. Even conventional radiographs can be based on digital information.

Digital data can be processed by a computer which allows electronic transmission of images between buildings, towns and even countries, and most importantly allows computer storage. A fully digital department obviates the need for x-ray films; it enables images as well as their reports to be viewed on video screens.

Radiation hazards

X-rays used in conventional radiography and CT, as well as gamma-rays and other radionuclide emissions, are harmful. Natural radiation from the sun, radioactivity in the environment, together with atmospheric radioactivity from nuclear bombs and other man-made ionizing radiations contribute a genetic risk over which an individual doctor has no control. However, ionizing radiation for medical purposes is of several times greater magnitude than all other sources of man-made radiation and is under the control of doctors. It is their responsibility to limit the use of x-rays and other ionizing radiations to those situations where the benefit clearly outbalances the risks. Unnecessary radiation is to be deplored. The principle to be used is the so-called ALARA principle: 'as low as reasonably achievable'. This is achieved by the use of appropriate equipment and good technique – limiting the size of the x-ray beam to the required areas, limiting the number of films to those that are necessary, keeping repeat examinations to a minimum and ensuring that the examination has not already been performed. Just as important as these factors, all of which are really the province of those who work in the x-ray department, is the avoidance of unnecessary requests for x-ray examinations, particularly those that involve high radiation exposure such as barium enema, lumbar spine x-rays and CT examinations. If possible, alternative techniques such as ultrasound or MRI should be considered. In other words, the imaging examination being requested must be justified.

Radiation is particularly harmful to dividing cells. Genetically adverse mutations may occur following radiation of the gonads, resulting in congenital malformations and a genetic risk to the population. There is no threshold for the mutation rate, hence there is no such thing as a safe radiation dose.

Radiation to the developing fetus can have catastrophic effects. As well as the increased incidence of malformations induced in the developing fetus, it has been shown that the frequency with which leukaemia and other malignant neoplasms develop within the first 10 years of life is increased in children exposed to diagnostic x-rays while *in utero*, probably by about 40% compared with the normal population. X-raying a fetus should, therefore, be kept to the absolute minimum and preferably avoided.

Radiation-induced cancer is of general concern. It is not known whether exposures of the magnitude used for individual diagnostic examinations induces cancers, but recent estimates suggest that a standard CT examination might be associated with a risk of cancer induction of 1 in 2000. If all radiation-reducing methods were followed, including the elimination of unnecessary examinations, then in the UK it might be possible to reduce the number of cancer fatalities by over 100 cases per year.