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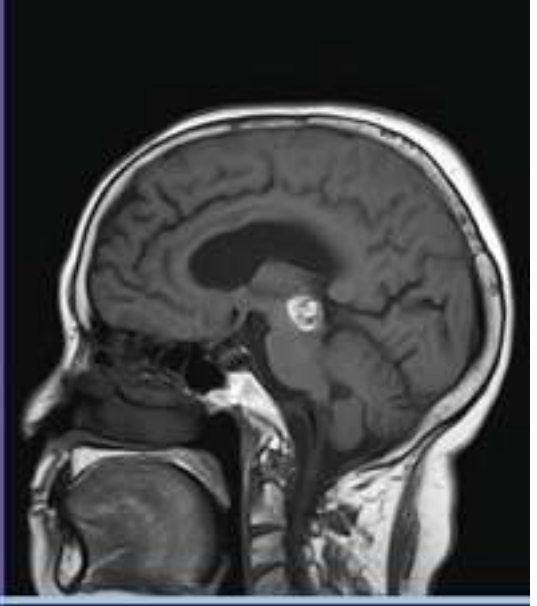
Andrew Hatrick
Peter Armstrong
Martin Wastie



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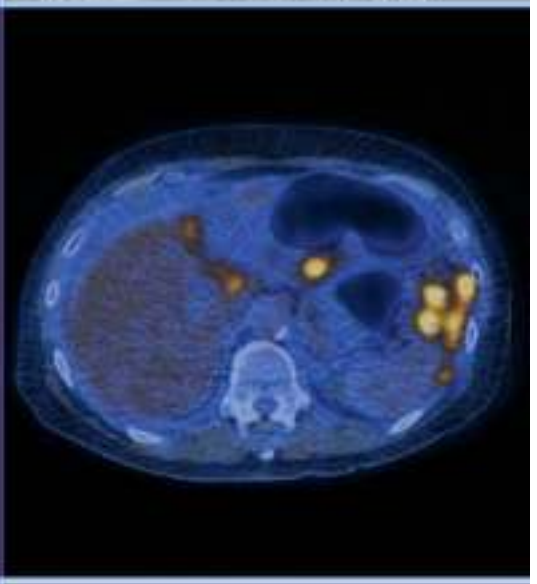

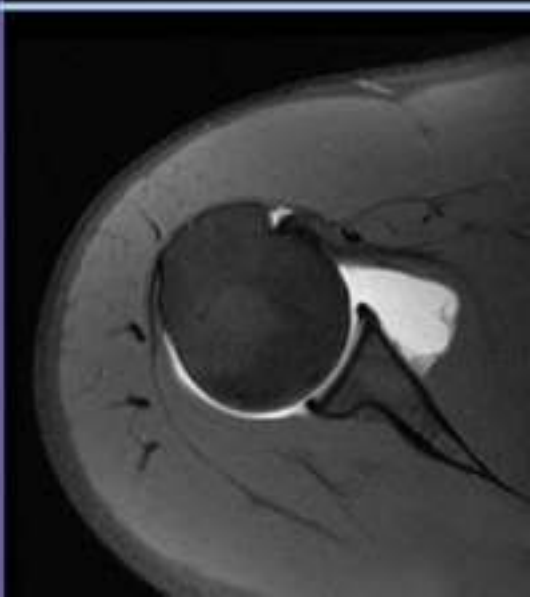

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ANDREA ROCKALL
BSc, MBBS, MRCP, FRCR
Professor of Radiology
Imperial College, London, UK

ANDREW HATRICK
MA, MB BChir, MRCP, FRCR
Consultant General and Interventional Radiologist
Frimley Park Hospital NHS Foundation Trust
Frimley, UK

PETER ARMSTRONG
MBBS, FMed Sci, FRCP, FRCR
Formerly Professor of Radiology
Medical College of St Bartholomew's
and the Royal London Hospitals, London, UK
Formerly Professor and Vice-Chairman
Department of Radiology, University of Virginia
Charlottesville, Virginia, USA

MARTIN WASTIE
MB BChir, FRCP, FRCR
Formerly Professor of Radiology
University of Malaya Medical Centre
Kuala Lumpur, Malaysia
Formerly Consultant Radiologist
University Hospital, Nottingham, UK

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Preface

Medical imaging is central to many aspects of patient management. Medical students and junior doctors can be forgiven their bewilderment when faced with the daunting array of information which goes under the heading 'Diagnostic imaging'. Plain film examinations remain the most frequently requested imaging investigations that non-radiologists may be called on to interpret and we continue to give them due emphasis. However, the use of cross-sectional imaging techniques continues to increase and, in some situations, has taken over from the plain film. The growing use of ultrasound, computed tomography (CT), magnetic resonance imaging (MRI), radionuclide imaging, including positron emission tomography (PET), and interventional radiology is reflected in the new edition.

With the widespread availability of most of the various imaging techniques, there are often several ways of investigating the same condition. We have avoided being too prescriptive as practice varies depending on the available equipment as well as the preferences of the clinicians and radiologists. It is important, however, to appreciate not only the advantages but also the limitations of modern medical imaging.

We have continued to try to meet the needs of the medical student and doctors in training by explaining the techniques used in diagnostic imaging and the indications for their use. We aim to help the reader understand the principles of interpretation of imaging investigations. New for this edition is the availability of online material, including multiple choice questions for each chapter, allowing readers to test their knowledge.

It is beyond the scope of a small book such as this one to describe fully the pathology responsible for the various imaging appearances and the role of imaging in clinical management. Consequently, we encourage our readers to study this book in association with the study of these other subjects.

Andrea Rockall
Andrew Hatrick
Peter Armstrong
Martin Wastie

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List of Abbreviations

ADC	apparent diffusion coefficient
AIDS	acquired immune deficiency syndrome
ALARA	'as low as reasonably achievable' principle
AP	anteroposterior
ARDS	adult respiratory distress syndrome
AVM	arteriovenous malformation
BBB	blood–brain barrier
CFA	cryptogenic fibrosing alveolitis
CPPD	calcium pyrophosphate dihydrate
CSF	cerebrospinal fluid
CT KUB	non-contrast computed tomography of the kidneys, ureters and bladder
CT	computed tomography
CTR	cardiothoracic ratio
CXR	chest radiograph
3D	three-dimensional
DCE-MRI	dynamic contrast-enhanced magnetic resonance imaging
DEXA	dual-energy x-ray absorption
DMSA	dimercaptosuccinic acid
DTPA	diethylene triamine pentacetic acid
DWI	diffusion-weighted imaging
ERCP	endoscopic retrograde cholangiopancreatography
EUS	endoscopic ultrasound
EVAR	endovascular aneurysm repair
FAST	focused assessment with sonography for trauma
FDG	F-18 fluorodeoxyglucose
FDG-PET	fluorodeoxyglucose positron emission tomography
FLAIR	fluid attenuated inversion recovery
FNA	fine needle aspiration
GI	gastrointestinal
GIST	gastrointestinal stromal tumour
HCC	hepatocellular carcinoma
HMPAO	hexamethylpropyleneamine oxime
HOCM	hypertrophic obstructive cardiomyopathy
HRCT	high resolution computed tomography
^{123}I	iodine-123
^{131}I	iodine-131
IPF	idiopathic pulmonary fibrosis
IUCD	intrauterine contraceptive device
IVC	inferior vena cava
IVU	intravenous urography
^{81m}Kr	krypton-81m
MAG-3	mercaptoacetyl triglycine
MDCT	multidetector CT
MEN	multiple endocrine neoplasia
MIBG	meta-iodobenzylguanidine
MIP	maximum intensity projection
MRA	magnetic resonance angiography
MRCP	magnetic resonance cholangiopancreatography
MRI	magnetic resonance imaging
NHS	National Health Service
PA	posteroanterior
PEG	percutaneous endoscopic gastrostomy
PET	positron emission tomography
PTC	percutaneous transhepatic cholangiogram
PUJ	pelviureteric junction
RIG	radiologically inserted gastrostomy
SCIWORA	spinal cord injury without radiological abnormality
SPECT	single photon emission computed tomography
^{99m}Tc	technetium-99m
TCC	transitional cell carcinoma
TIPSS	transjugular intrahepatic portosystemic shunt
TRUS	transrectal ultrasound
UIP	interstitial pneumonia

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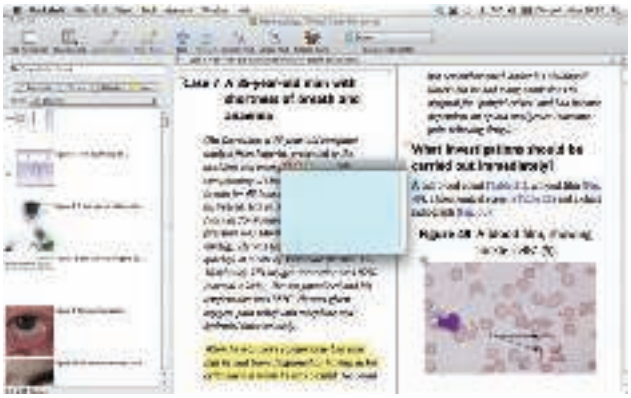

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1

Technical Considerations

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. 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. Box 1.1 provides important points when requesting imaging investigations.

Box 1.1 Best practice when requesting imaging investigations

- Only request an examination if it is likely to affect patient management
- The time interval between follow-up examinations should be appropriate and depends on the natural history of disease
- Localize the clinical problem as specifically as possible prior to imaging in order to reduce over-investigation and excess radiation exposure
- Careful consideration should be given to which imaging procedure is likely to give the relevant diagnostic information most easily
- Any investigations that have been requested but become unnecessary should be cancelled
- Examinations that minimize or avoid ionizing radiation should be chosen when possible
- Good communication with the radiologists is key to ensuring appropriate investigation pathways

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

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tissues. Traditionally, images were produced using a silver-based photographic emulsion but now they are recorded digitally and viewed on computer screens in most centres.

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 (anteroposterior) view is 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 on the ward 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 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 ten-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 by far the most frequent. The operator selects the level and thickness to be imaged: the usual thickness is between 1.25 and 2 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 acquires multiple slices (64, 128, 256 or 320 depending on the machine) 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. A relatively new development is dual source (or dual energy) CT. This technique allows a virtual non-contrast CT image to be derived from CT acquired with intravenous iodinated contrast medium (see later in chapter) allowing a reduction in radiation dose in certain CT protocols.

The data obtained from the multislice CT exposures are reconstructed into an image by computer manipulation. The computer calculates the attenuation (absorption) value of each picture element (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 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*. CT 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

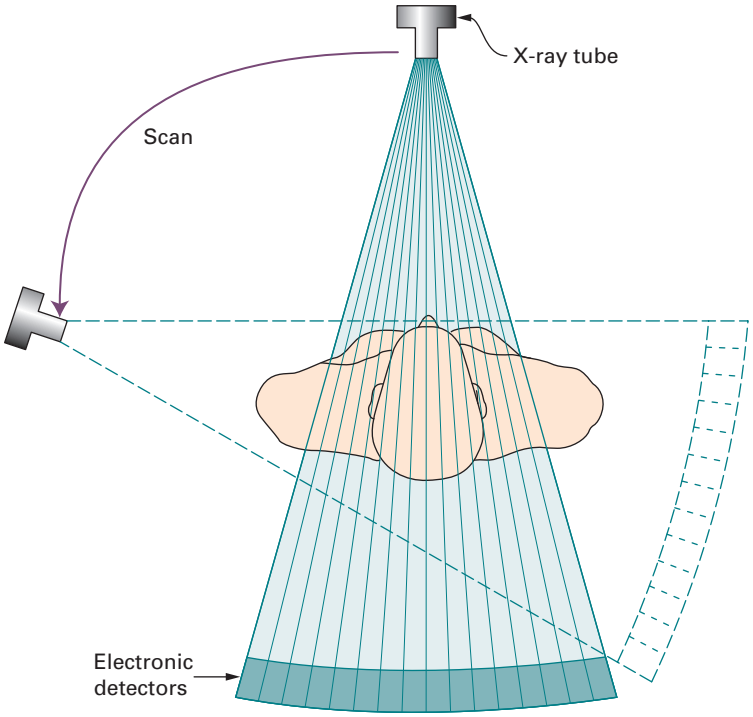


Fig. 1.1 Principle of CT. The x-ray tube and detectors move around the patient enabling a picture of x-ray absorption in different parts of the body to be built up.

areas no useful information is provided. The effects of varying window width and level are illustrated in Figs 1.5 and 2.6.

Computed tomography 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 diagnostic 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.

Contrast agents in conventional radiography and computed tomography

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 on conventional radiographic images; 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,

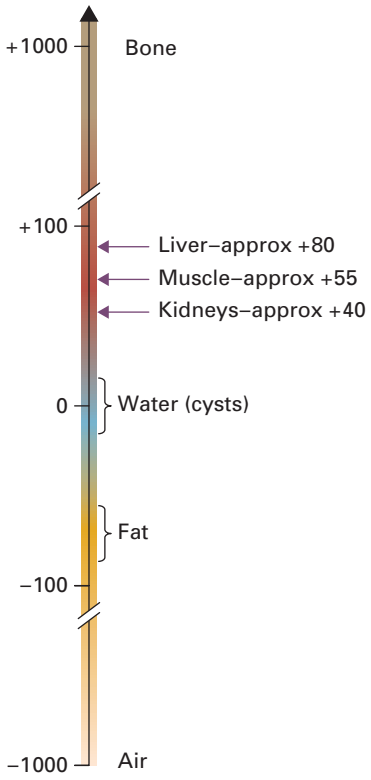


Fig. 1.2 Scale depicting the CT density (Hounsfield units) of various normal tissues in the body.

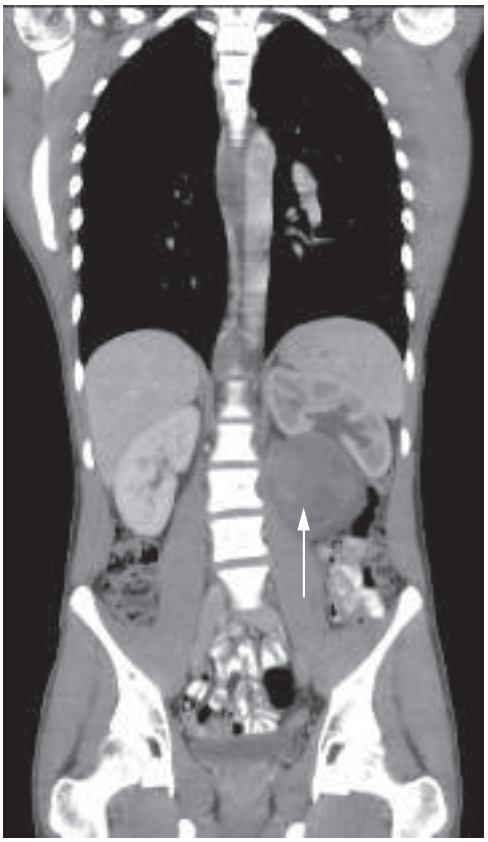


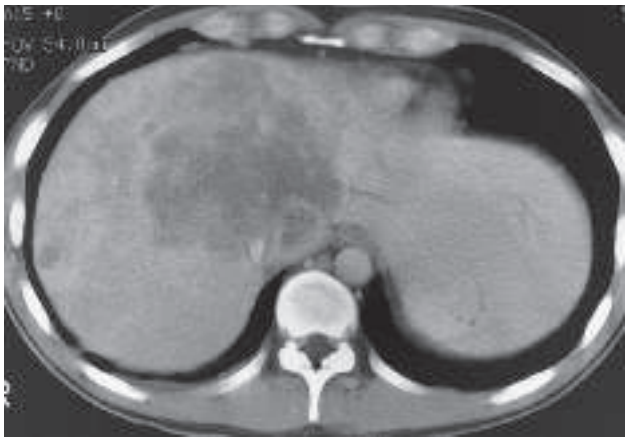
Fig. 1.3 Coronal reconstruction of CT of the chest, abdomen and pelvis. The images were obtained in the axial plane using very thin sections and then reconstructed into the desired plane – a coronal plane in this example. The illustrated section is through the posterior abdomen and shows the kidneys. There is a retroperitoneal mass (arrow) displacing the left kidney and causing hydronephrosis.

though the current low osmolality, non-ionic contrast media have exceedingly low complication rates.

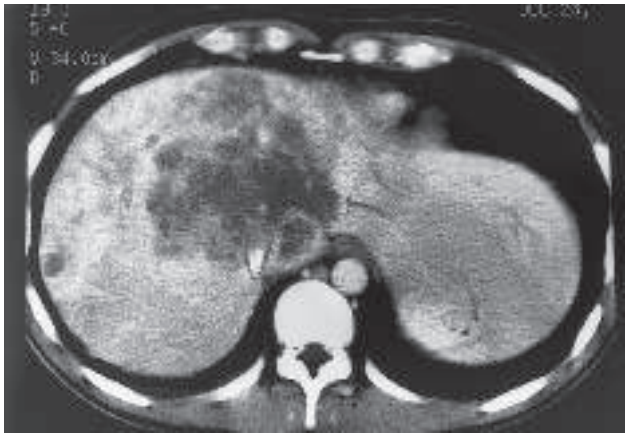
Some patients experience a feeling of warmth spreading over the body as the iodinated contrast medium is injected. Contrast inadvertently injected outside the vein is painful and should be carefully guarded against. A few patients develop an urticarial rash, which usually subsides spontaneously.

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 and an alternative method of imaging should be considered. Patients at higher risk are observed following the procedure. 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.

Fig. 1.4 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 plain film.



(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 HU 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).

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, which 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 to 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 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

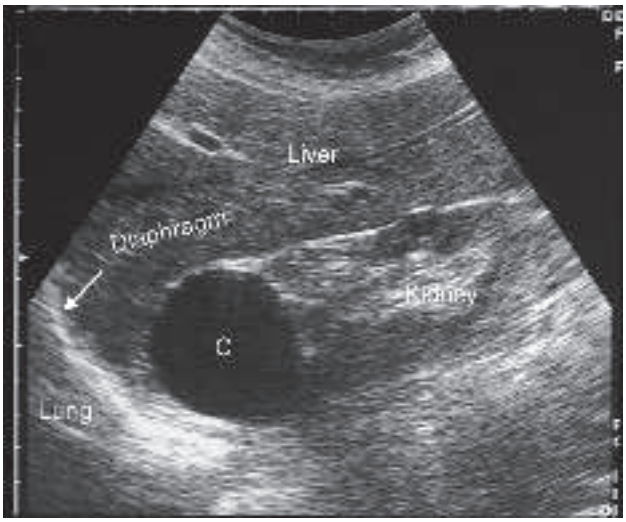


Fig. 1.6 Ultrasound scan of longitudinal section through the liver and right kidney. A cyst (C) is present in the upper pole of the kidney.

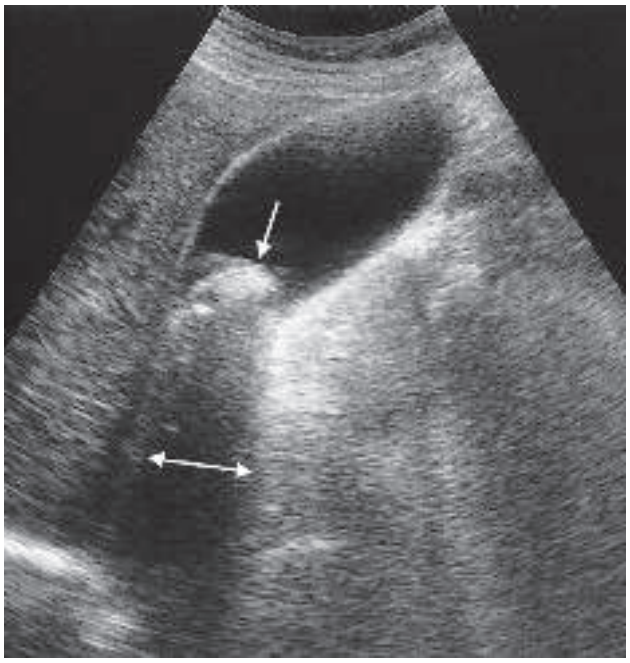


Fig. 1.7 Ultrasound scan of gall bladder showing a large stone in the neck of the gall bladder (downward pointing arrow). Note the acoustic shadow behind the stone (horizontal double-headed arrow).

reduced echoes, referred to as an *acoustic shadow*, is seen behind the stone.

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 or video 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 fetal anatomy 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).

Small ultrasound probes, which may be placed very close to the region of interest, produce 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 duode-

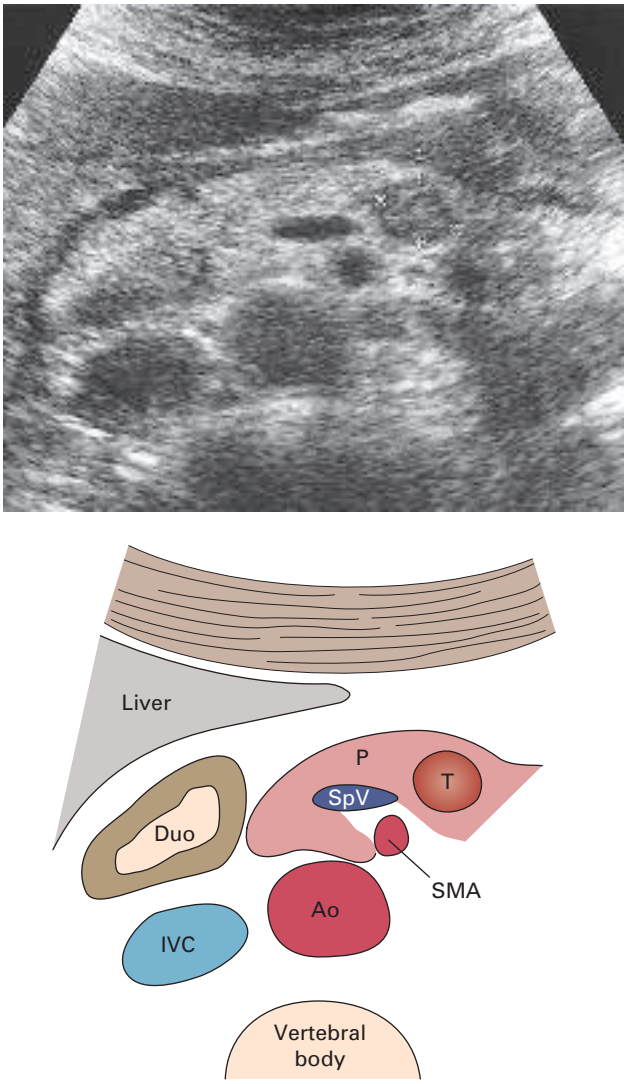


Fig. 1.8 Ultrasound scan of pancreas showing a 1 cm tumour (T) (an insulinoma) at the junction of the head and body of the pancreas. Ao, aorta; Duo, duodenum; IVC, inferior vena cava; P, pancreas; SMA, superior mesenteric artery; SpV, splenic vein.

num. 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 have been 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 that corresponds to the speed of movement 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 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 (Fig. 1.9). 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 (Box 1.2). 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 (Fig. 1.10).

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 (Fig. 1.9) 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.

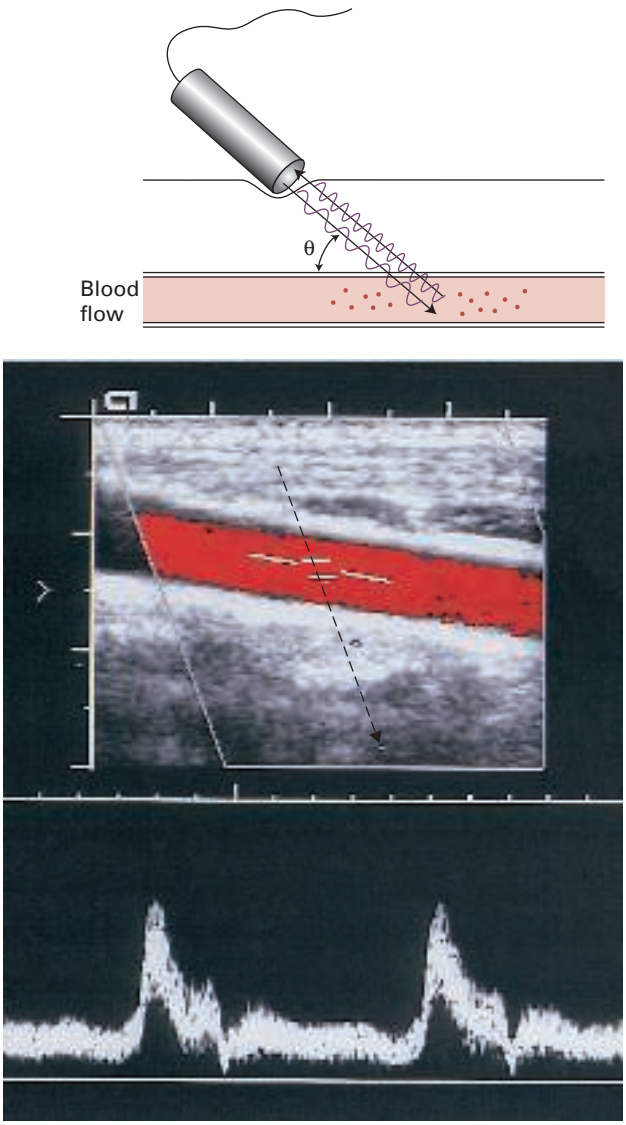


Fig. 1.9 Principle of Doppler ultrasound. In this example, flowing blood is detected in a normal carotid artery in the neck. With blood flowing away from the transducer, the frequency of the received sound is reduced, whereas with blood flowing towards the transducer, the frequency of the received sound is increased. For anatomical images, the flowing blood is colour coded according to the direction of flow. (θ is the angle between the vessel and the transmitted sound wave: an angle known as the Doppler angle. The angle of the beam is indicated by the fine zig-zag line across the image.) The flow–velocity waveform has been taken from the gate within the artery. The peaks represent systolic blood flow.

Box 1.2 Doppler frequency shift formula

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

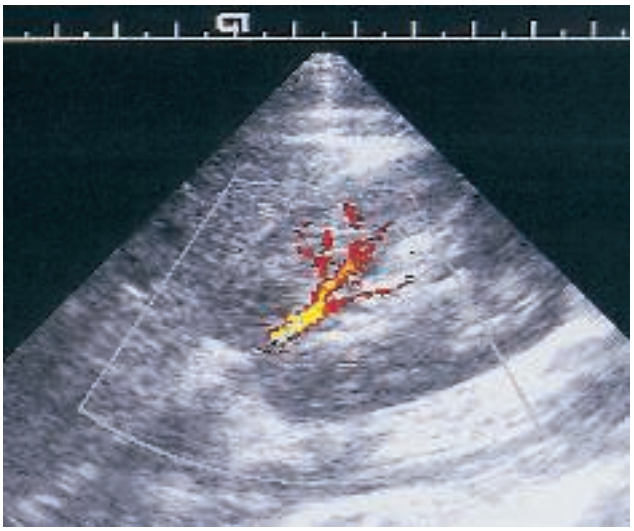
As c, the speed of sound in tissues, and Fi, the incident frequency of sound, are constant, and if θ, the Doppler angle, is kept constant, the frequency shift depends directly on the blood flow velocity V

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.

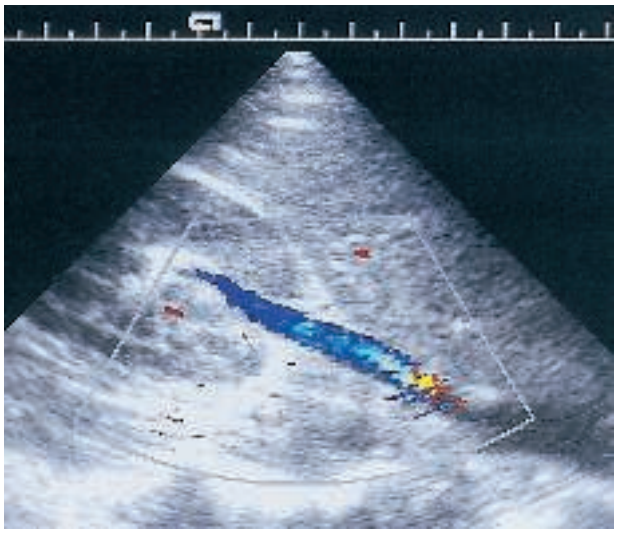
Radionuclide imaging

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 decay of the nucleus. Many naturally occurring radioactive isotopes, e.g. potassium-40 and 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.

Radionuclides can be chemically tagged to certain substances that concentrate selectively in different parts of the body. Occasionally, the radionuclide in its ionic form will selectively concentrate in an organ, so there is no need to attach it to another compound. Such a radionuclide 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.



(a)



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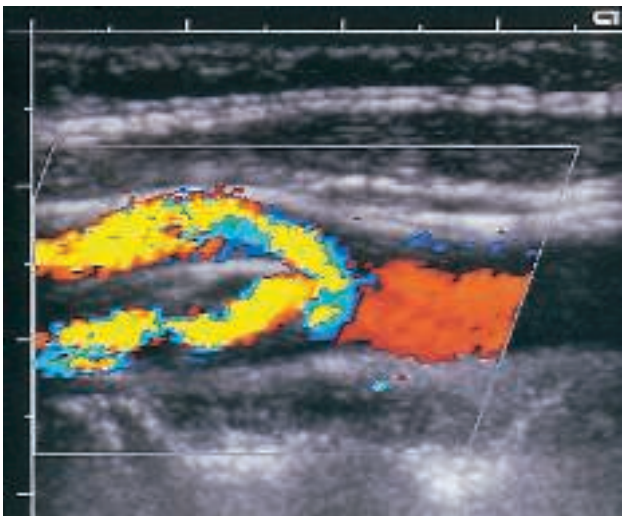

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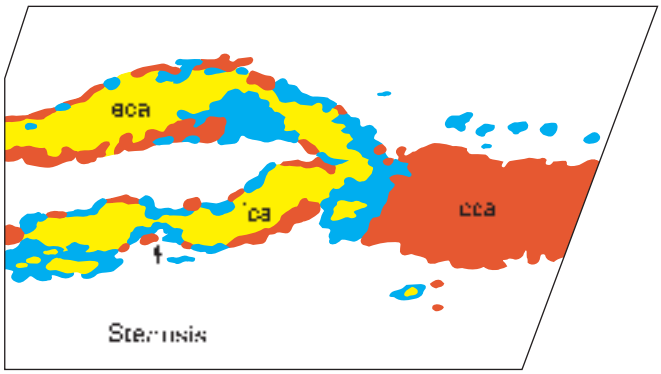

Fig. 1.10 Colour Doppler. (a) Normal renal artery. (b) Normal renal vein. (c) Bifurcation of the common carotid artery showing stenosis of the internal carotid artery. The flowing blood is revealed by colour. The precise colour depends on the speed and direction of the blood flow. cca, common carotid artery; eca, external carotid artery; ica, internal carotid artery.

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. 1.11). 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-81m, 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 electri-

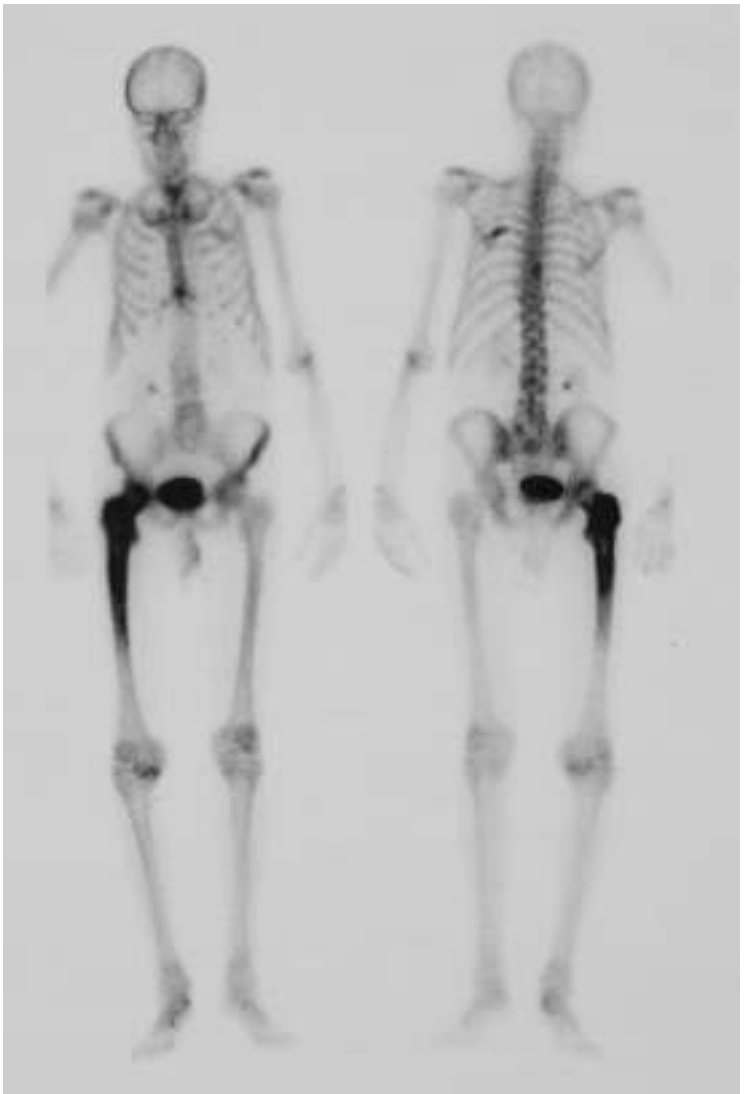

Fig. 1.11 Radionuclide bone scan. The patient has received an intravenous injection of a ^{99m}Tc-labelled bone-scanning agent (a complex organic phosphate). This agent is taken up by bone in proportion to bone turnover and blood flow. The increased uptake in the femur in this patient was due to Paget's disease.