Section 1 The basics

Chapter 1 An introduction to the technology of imaging

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Introduction

Imaging techniques available to the radiologist are changing rapidly, due largely to advances in imaging and computer technology. Three of the five imaging modalities described in this chapter did not exist in recognizable form 30 years ago. This chapter is a brief overview of the major medical imaging techniques in current use with reference to the underlying principles, equipment, the type of information that they yield, and their advantages and limitations.

X-rays

X-rays were discovered by a physicist named Wilhelm Roentgen in November 1895, using a type of cathode ray tube invented in 1877 by Crooke. With this "new kind of ray," he produced a photograph of his wife's hand showing the bones and her wedding ring, requiring an exposure time of about 30 minutes. Within a month of this discovery, X-rays were being deliberately generated in a number of countries, and were being used for imaging patients by early 1896. A modern X-ray machine is shown in Fig. 1.1.

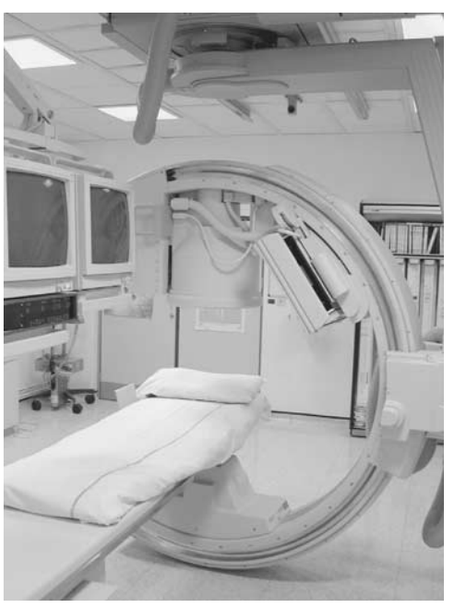

Fig. 1.1. **An example of a fluoroscopy machine that uses X-radiation to produce images of patients. The tube can be rotated around the patient to provide views from different projections. Moving images can be viewed using the image intensifier or static images can be obtained.**

X-ray generation

The basics of the X-ray tube have remained unchanged since Roentgen's time, although the details have changed. X-rays are made up of photons and are a type of electromagnetic radiation like light or radio-waves, although they have higher energy.

The basic X-ray tube is a vacuum tube (Fig. 1.2). A high voltage is passed through a wire, heating it and allowing electrons to be freed and leave the wire at its surface (the cathode). The electrons are accelerated towards a second electrode with a positive charge (the anode) causing a current to flow between the cathode and anode. If the anode

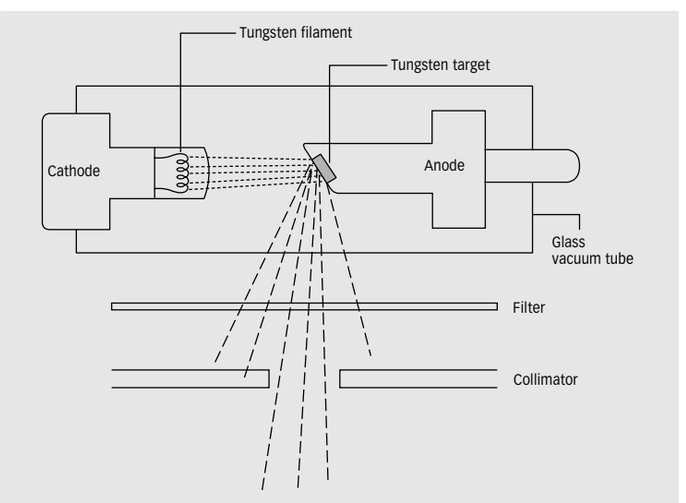

Fig. 1.2. **The essentials of a simple, fixed anode X-ray generation set.**

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(a)

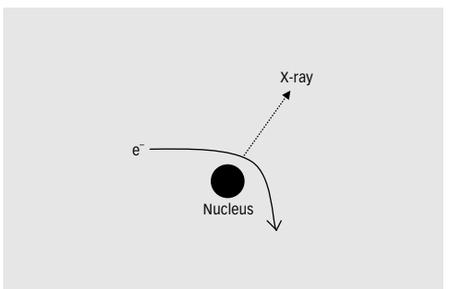

Fig. 1.3. **Diagrams of the production of X-rays. (a) Bremsstrahlung or Braking radiation occurs when the free electron is deflected by the electric field around the nucleus of a target atom, shedding energy in the form of a photon as the free electron is slowed.**

(b)

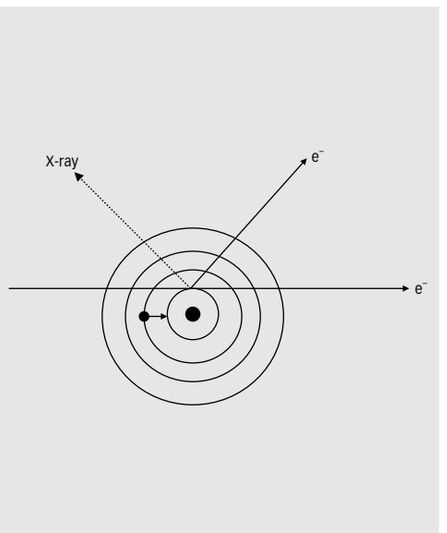

Fig. 1.3. **(b) Characteristic radiation. When a free electron knocks one of the "cloud" of orbital shell electrons out of an atoms, an electron from a higher energy (outer) shell moves to fill the gap, shedding the excess energy in the form of an electromagnetic photon which will be an X-ray photon if the energies are high enough. These X-rays have an energy specific to the transition between the shells, and the pattern of production is therefore characteristic of the anode material.**

is made of the correct material and the electrons are accelerated enough (by at least 1000 volts), X-rays will be produced. Typical materials used for the anode include tungsten and molybdenum, which have high atomic numbers, and high melting points (the X-ray tube gets very hot). Over 90% of the energy supplied is lost as heat.

X-ray photons are produced at the anode when a free electron travelling at high speed interacts with a target atom. Two main interactions occur in the diagnostic X-ray energy range, Bremsstrahlung and characteristic radiation (Fig. 1.3).

The X-rays then leave the tube through a filter (usually made of copper or molybdenum), which removes X-ray photons with undesirable energies, leaving those in the diagnostic range.

Finally, the X-rays pass through a collimator. X-rays produced at the anode travel in all directions, although some features of the design cause them to mainly be directed towards the patient. The collimator is an aperture (usually made of lead) that can be opened and closed so that only the part of the patient to be imaged is exposed to the X-ray beam.

How X-rays produce an image

Production of a radiograph, an X-ray image, is the result of the interaction of X-ray photons with the patient and detection of the remaining photons.

X-ray interactions

There are two main types of interaction that are important in the diagnostic X-ray range (Fig. 1.4). Photoelectric absorption is more important at low energy (low kV) X-ray photon energies and is seen more with elements with high atomic numbers – such as calcium in bones. Compton (incoherent) scattering becomes more important for biological tissues as X-ray photon energies increase (high kV) and is proportional to tissue density.

(a)

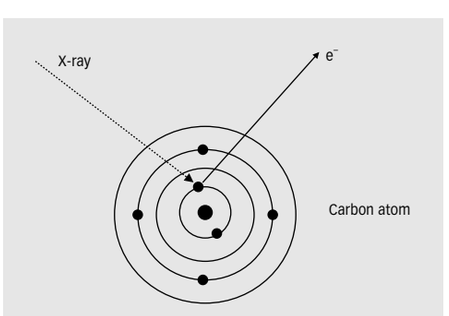

Fig. 1.4. **A representation of the two important types of X-ray (and γ-ray) interaction with biological tissue. (a) Photoelectric absorption occurs when an X-ray photon with sufficient energy is absorbed, breaking the bond of an atomic electron and knocking it out of the electron shell.**

Detection of X-rays

Following irradiation of the patient, some of the X-rays are absorbed, some are scattered (deflected) and some pass through the patient. These effects depend on the nature and thickness of the tissues in their path.

X-ray photons are invisible. There are a number of mechanisms to detect X-ray photons and convert them to a visible image (Fig. 1.5).

Film

Although photographic film is sensitive to X-rays by itself, fluorescent screens are used inside X-ray cassettes that convert X-ray photons to visible light, decreasing the number of X-ray photons required to make an image and therefore the radiation dose to the patient. The light produced then exposes the photographic film by converting crystals of silver halide into elemental silver. These initial specks of silver are grown during processing, and appear black on the film.

(b)

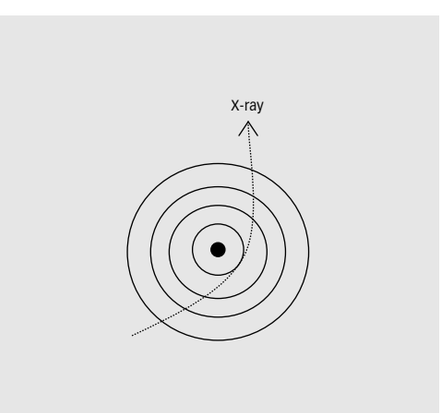

Fig. 1.4. **(b) Compton (incoherent) scattering occurs when the X-ray photon interacts with an atomic electron, resulting in deflection of the photon with a transfer of kinetic energy to the electron. This is known as scattering as the X-ray photon continues in a different direction (which can even be the reverse of the original direction, in the case of a head on collision).**

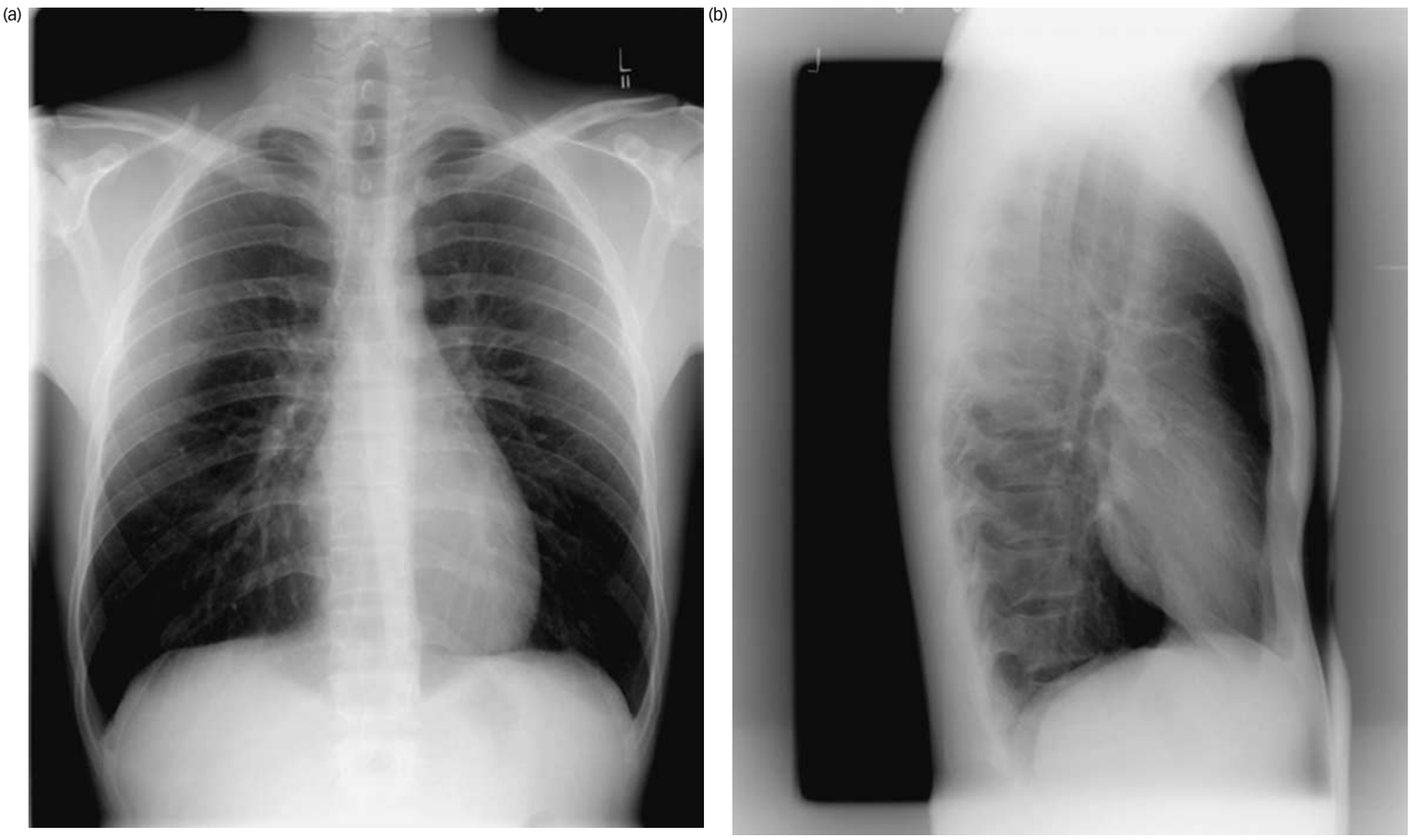

Fig. 1.5. **A radiograph ("plain film") of the chest. This has been acquired on a CR system using an X-ray generation set and europium-activated barium fluorohalide plate read by a laser. Both PA (postero-anterior) and lateral views are shown. The views are named from the direction the X-rays pass through the patient and the location of the detector: in the case of the PA film the X-ray tube is behind the patient and the detector plate in front so the X-rays pass from posterior to anterior.**

Computed radiology (CR)

Special plates are made from europium-activated barium fluorohalides. These plates absorb the X-ray photons emerging from the patient, storing them as a latent image. The plates are then scanned with a laser, causing emission of light that can be read by a light detecting photo-multiplier tube connected to a computer on which the image can be viewed.

Digital radiology (DR)

A number of devices for direct digital acquisition of images exist. CCD (charged coupled device) technology such as is found in modern digital cameras can be adapted to detect X-rays by coating the device with a visible light producing substance such as cesium iodide or by using a fluorescent screen. TFT (thin film transistor) detectors consist of arrays of semiconductor detectors, and another method uses a detector such as amorphous selenium or cesium iodide to capture the photons with amorphous silicon plates to amplify the signal produced.

Digital and computed radiology techniques are being used increasingly in clinical departments, with a consequent reduction in the use of photographic film.

Fluoroscopy – image intensifier

Image intensifiers use a fluoroscopic tube to form an image. The input screen is covered with a material that emits light photons when hit by X-ray photons. These are then converted to electrons, focused using an electron lens and accelerated towards an anode where they strike an output phosphor producing light, that is then viewed by a video camera and transmitted to viewing screen or film exposure system. Fluoroscopy allows real-time visualization of moving anatomic structures and monitoring of radiological procedures such as barium studies and angiography.

Advantages and limitations of plain X-ray

Plain radiography is readily available in the hospital setting and is frequently the first line of imaging investigation. It has a higher spatial resolution than all other imaging modalities. It is most useful for structures with high-density contrasts between tissue types, particularly those tissues in which fine detail is important, such as in viewing bone, and in the chest. Plain radiography is relatively poor for examining soft tissues, due to its limited contrast resolution. It is possible to distinguish only four natural densities in diagnostic radiography: calcium (bone), water (soft tissue), fat, and air. Plain film radiography provides a two-dimensional representation of three-dimensional structures; all structures projected in a direct line between the X-ray tube and the image receptor will overlap. This can be partially overcome by obtaining views from different angles, or by turning the patient or the X-ray tube and image intensifier in fluoroscopy.

Conventional tomography

Simultaneously moving both the X-ray tube and the film about a pivot point causes blurring of structures above and below the focal plane. Objects within the focal plane show increased detail because of the blurring of surrounding structures, providing an image of a slice of the patient (Fig. 1.6). Movements of the X-ray tube and film can be linear, elliptical, spiral, or hypocycloidal. With the advent of cross-sectional imaging techniques such as CT and MRI, most imaging departments now only use linear tomography, as part of an intravenous urogram (see below).

Contrast enhancing agents

To allow visualization of specific structures using X-rays, a number of contrast agents have been used. A good contrast agent should increase contrast resolution of organs under examination without poisoning or otherwise damaging the patient. The best contrast agents for use with X-rays have a high atomic weight as these have a high proportion of photoelectric absorption in the diagnostic X-ray range. Unfortunately, most molecules that contain these atoms are very toxic. Iodine (atomic weight 127) is the only element that has proved satisfactory for general intravascular use; extensive research and development has resulted in complex iodinated molecules that are non-toxic, hypoallergenic and do not carry too great osmotic load. The normal physiological turnover of iodine in the body is 0.0001 g per day, while for typical imaging applications 15 g to 150 g or 150 000–1 500 000 times as much may be required. Barium sulphate (atomic weight 137), and iodinated compounds are the only agents in regular use as extravascular agents.

Barium studies

Barium is only used in a modern X-ray department for studies of the gastrointestinal tract. These are usually based on a fluoroscopic image intensifier on which a moving image can be seen. Studies can be performed of the swallowing mechanism and esophagus (barium swallow), the stomach and duodenum (barium meal), the small bowel (small bowel follow through or small bowel enema) and the colon (barium enema). Studies of the stomach and large bowel are usually "double contrast" which allows better visualization of surface detail. Air or carbon dioxide can be introduced into the large bowel and gas-forming granules (usually a combination of calcium carbonate and citric acid) can be swallowed for imaging the stomach, resulting in a thin barium coating of the bowel mucosa (Fig. 1.7).

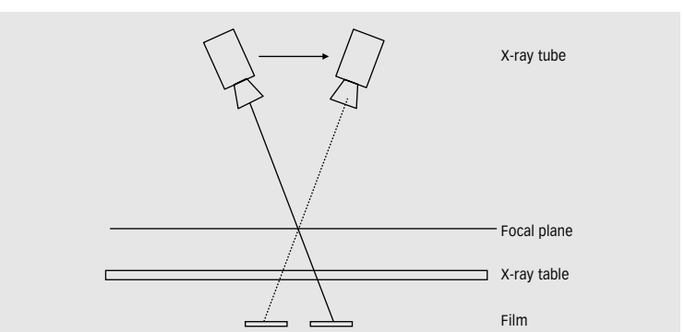

Fig. 1.6. **Conventional tomography. The X-ray tube and film move simultaneously about a pivot point at the level of the focal plane, blurring structures outside the focal plane, and emphasizing the structure of interest.**

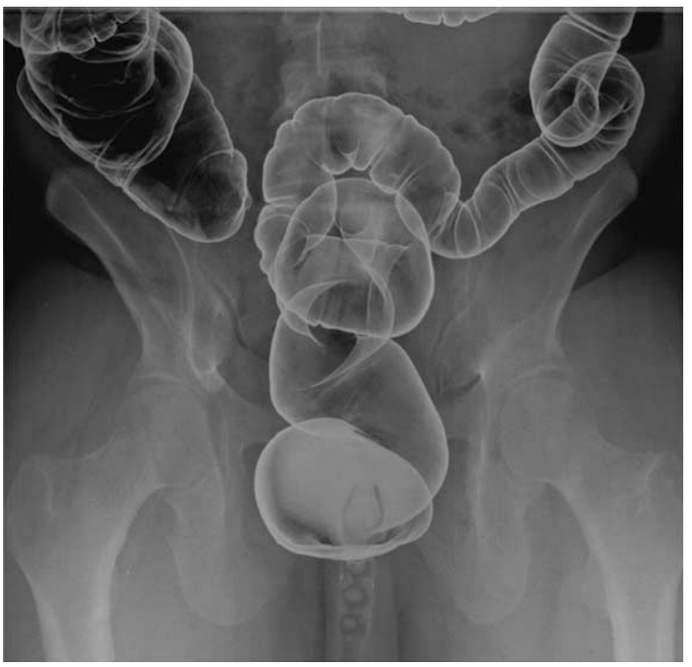

Fig. 1.7. **Barium enema. Barium sulphate has been introduced into the large bowel by a tube placed in the rectum and carbon dioxide gas is then used to expand the bowel, leaving a thin coating of barium on its inside surface. X-ray images are used to examine the lining of the bowel for abnormal growths and other abnormalities.**

Intravenous urography

The kidneys rapidly excrete Iodinated contrast agents. Plain radiographs taken from just a few seconds after a contrast injection into a peripheral vein show the passage of contrast through the kidney, into the ureters and to the bladder (Fig. 1.8).

Angiography

A specially shaped, thin catheter (tube) can be introduced into the arterial or venous system and manipulated using fluoroscopy to almost any blood vessel large enough to have been named. Contrast introduced through these catheters by hand or mechanical injection will be carried in the bloodstream and allows very detailed imaging of the vascular system. The arterial system is usually accessed via puncture of the femoral artery in the groin, although arteries of the upper limb may occasionally be used. Digital subtraction angiography (DSA) is most commonly performed – an initial ("mask") image is taken before the contrast agent is administered and is "subtracted" from later images. This removes the image of the tissues, leaving the contrast-filled structures. Any movement after the mask image is taken destroys the subtracted image. Because angiography is potentially hazardous, the balance between the potential benefit and the risk of the procedure (damage to vessels and other structures, bleeding) must be evaluated with particular care before undertaking the procedure (Fig. 1.9).

Radiation dose

All ionizing radiation exposure is associated with a small risk. A small proportion of the genetic mutations and cancers occurring in the population can be attributed to natural background radiation. Diagnostic

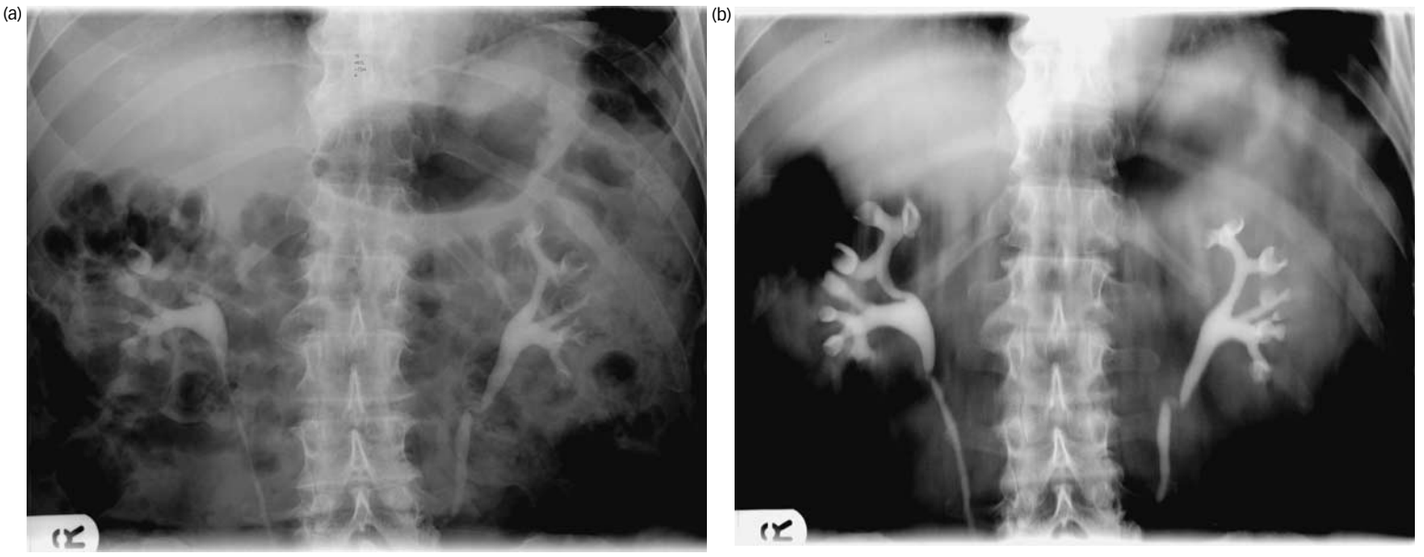

Fig. 1.8. **Intravenous urogram showing (a) standard view of the kidneys and upper part of the urinary collecting system and (b) linear tomogram of the intrarenal collecting system. This blurs out the overlying structures, giving a clearer image of the collecting system and renal outline. An injection of 50 ml of iodine-based contrast medium has been given and these radiographs have been obtained 10–15 minutes later after it has passed through the kidneys and into the renal collecting system.**

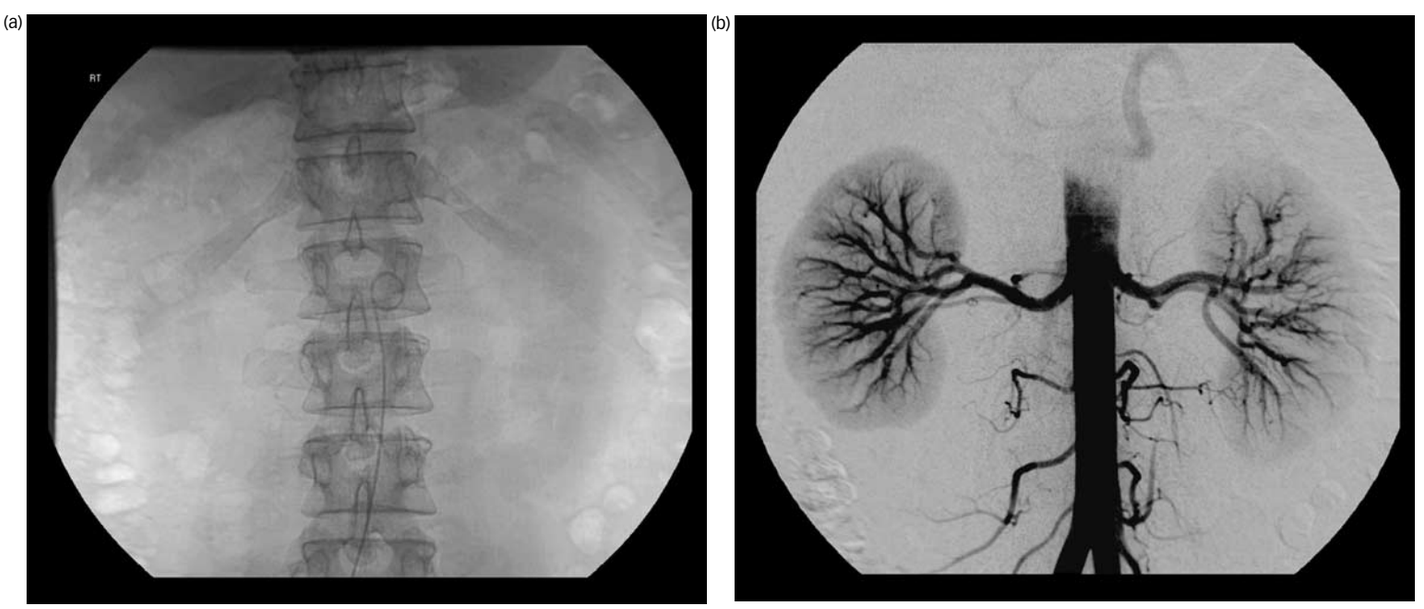

Fig. 1.9. **Renal angiogram. (a) A catheter has been inserted through the right femoral artery into the aorta, (b) iodinated contrast medium has been injected through it, and a rapid sequence of radiographs taken. Digital subtraction of the background shows the passage of contrast medium through the arteries supplying both kidneys.**

medical exposures (using X-rays or γ-rays, see Nuclear Medicine below) are the largest source of man-made radiation exposure to the general population and add about one-sixth to the population dose from background radiation. The dose is calculated as "effective dose," which is a weighted figure depending on the sensitivity of the body tissues involved to radiation induced cancer or genetic effects. Typical doses are given in Fig. 1.10. Children and the developing fetus are particularly susceptible to radiation damage. As with all medical investigations and procedures, the relative risks and potential benefits must be considered carefully, and the clinician directing the procedure (usually the radiologist) is accountable in law for any radiation exposure.

Ultrasound

General principles

Ultrasound is sound of very high frequency. In most diagnostic applications frequencies between two million and twenty million cycles per second are used, 100–1000 times higher than audible sound.

Procedure	Typical effective dose (mSv)	Equivalent number of chest X-rays	Equivalent period of natural background radiation
Limbs and joints	<0.01	<0.5	<1.5 days
Chest	0.02	1	3 days
Lumbar spine	1.3	65	7 months
Pelvis	0.7	35	4 months
Abdomen	1.0	50	6 months
IVU	2.5	125	14 months
Barium enema	7	350	3.2 years
CT head	2.3	115	1 year
CT chest	8	400	3.6 years
CT abdomen or pelvis	10	500	4.5 years
Bone scan	4	200	1.8 years
PET head (FDG)	5	250	2.3 years

Fig. 1.10. **Typical effective doses for some of the commonly performed Imaging investigations. The typical United Kingdom background radiation dose is 2.2 mSv/year (ranges from 1.5 to 7.5 mSv/year depending on geographical location). It has been estimated that the additional lifetime risk of a fatal cancer from an abdominal CT scan could be as much as 1 in 2000 (although the overall lifetime risk of cancer for the whole population is 1 in 3).**

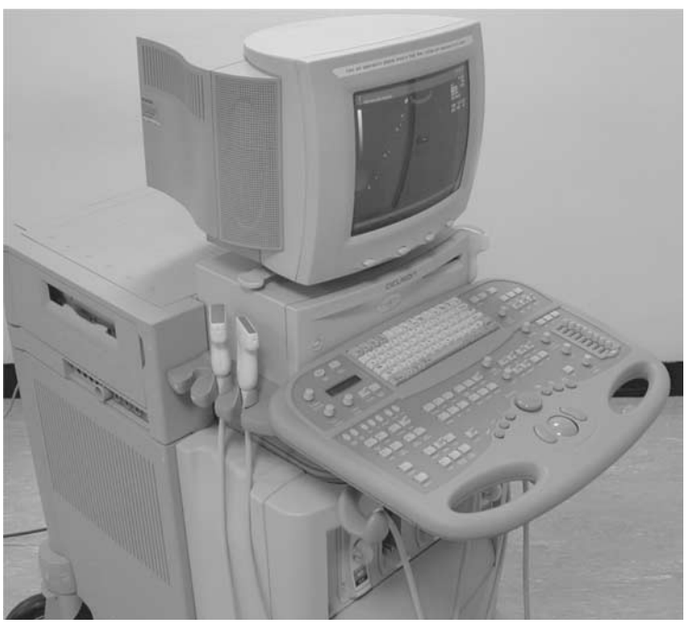

Fig. 1.11. **A diagnostic ultrasound machine.**

Higher frequencies have shorter wavelengths, allowing greater spatial resolution of structures being studied. An example of an ultrasound machine is shown in Fig. 1.11.

Ultrasound transducers

Ultrasound is generated by piezoelectric materials, such as lead zirconate titanate (PZT). These have the property of changing in thickness when a voltage is applied across them. When an electrical pulse is applied, the piezoelectric crystal produces sound at its resonant frequency. These crystals also generate a voltage when struck by an ultrasound wave, so are also used as the receiver. A modern ultrasound probe contains an array of several hundred tiny piezoelectric crystals with metal electrodes on their two surfaces, the sound lenses and matching layers required to form the beam shape and electronics. Piezoelectric crystals can also be found in the speakers inside in-ear headsets, quartz watches, and camera auto-focus mechanisms.

Image formation

Ultrasound travels at near constant speed in soft tissues and this allows the depth of reflectors to be calculated by measuring the delay between transmission of the pulse and return of the echoes.

Attenuation

The tissues absorb ultrasound when the orderly vibration of the sound wave becomes disordered in the presence of large molecules. When this happens, sound energy is converted to heat energy. Absorption depends on the molecular size, which correlates with viscosity of the tissue, and with the frequency. Higher frequencies are more strongly absorbed, so less depth of scanning comes with the improvement in resolution that higher frequencies allow. Ultrasound energy is also lost to the transducer if it is reflected or refracted away.

Reflection

Some of the ultrasound beam is reflected whenever it crosses an interface where the transmission properties change. This is directly related to the physical structure of the tissues on either side of the interface.

Tissue harmonics

Ultrasound is generally considered to be conducted in a linear fashion with no change in the waveform of the pulse as it travels through the tissues. In fact, the wave originating from the transducer becomes distorted as the speed of sound conduction changes with the density of the conducting materials allowing some parts of the wave to travel faster than others. The wave comes to contain higher frequency components, called harmonics, which are much weaker in the parts of the sound beam away from the central echoes. Scanners can transmit at one frequency, receive at a higher frequency and use filters to select out the harmonics in the returning echoes, improving the image resolution and increasing the contrast.

Image display

Gray-scale or B-Mode (B for brightness) is a two-dimensional real time image formed by sweeping the beam through the tissue. The echogenicity of the reflectors is displayed as shades of gray and is the main mode used for ultrasound imaging (Fig. 1.12). Modern ultrasound machines operate at a sufficient speed to produce real-time images of moving patient tissue such as the heart in echocardiography and the moving fetus.

Doppler ultrasound

If a sound wave reflects from a moving target, there is a change in the frequency of the returning sound wave proportional to the velocity of the reflecting target. This is known as the Doppler effect and the changes in frequency can be used to calculate the velocity of the moving target usually flowing blood. The Doppler signal is within the audible range, so can be heard by sending the signal to a loudspeaker. Most commonly used in clinical practice is color flow imaging (color Doppler) where flow information is shown as an overlay on the gray-scale image with the color and shading indicating the direction

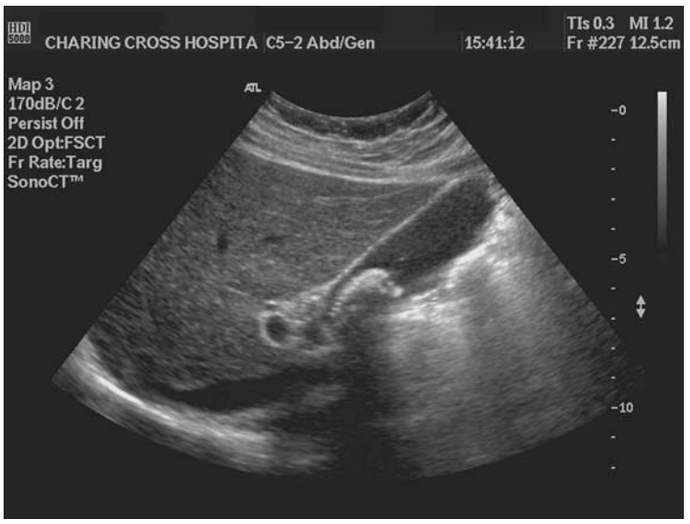

Fig. 1.12. **A stone within the gall bladder shows as a bright echo with black "acoustic shadow" behind it, the result of almost complete reflection of the ultrasound hitting it. The fluid in the gall bladder appears black as the contents of the gall bladder are homogeneous and there are no internal structures to cause echoes or changes in attenuation; the adjacent liver is more complex in structure and causes more reflection of sound, so appears gray.**

and velocity of flow. Spectral Doppler is a graphical display with time on the horizontal axis, frequency on the vertical axis and brightness of the tracing indicating the number of echoes at each specific frequency (and therefore blood cell velocity). A combined gray-scale and spectral Doppler display is known as a duplex scan. Power Doppler imaging discards the direction and velocity information but is about 10× more sensitive to flow than normal color Doppler.

Doppler ultrasound is used to image blood vessels and to examine tissues for vascularity (fig. 1.13 – see color plate section).

Ultrasound contrast agents

Contrast agents have been developed for ultrasound consisting of tiny "microbubbles" of gas small enough to cross the capillary bed of the lungs. These are safe for injection into the bloodstream and are very highly reflective; they can be used to improve the imaging of blood vessels and to examine the filling patterns of liver lesions.

Ultrasound artifacts

Acoustic shadowing

Produced by near complete absorption or reflection of the ultrasound beam, obscuring deeper structures. Acoustic shadows are produced by bone, calcified structures (such as gall bladder and kidney stones), gas in bowel, and metallic structures.

Acoustic enhancement

Structures that transmit sound well such as fluid-filled structures (bladder, cysts) cause an increased intensity of echoes deep to the structure.

Reverberation artifact

Repeated, bouncing echoes between strong acoustic reflectors cause multiple echoes from the same structure, shown as repeating bands of echoes at regularly spaced intervals.

Mirror image artifact

A strong reflector can cause duplication of echoes, giving the appearance of duplication of structures above and below the reflector.

"Ring down" artifact

A pattern of tapering bright echoes trailing from small bright reflectors such as air bubbles.

Advantages and limitations of ultrasound

Ultrasound provides images in real time so can be used to image movement of structures such as heart valves and patterns of blood flow within vessels. As far as is known, ultrasound used at diagnostic intensities does not cause tissue damage and can be used to image sensitive structures such as the developing fetus. Patients usually find ultrasound examination easy to tolerate, as it requires minimal preparation and only light pressure on the skin. Portable ultrasound systems suitable for use at the bedside are widely available.

The main limitation of the technique is that parts of the body accessible to ultrasound examination are limited. Ultrasound does not easily cross a tissue–gas or tissue–bone interface, so can only be used for imaging tissues around such structures with any tissues deep to gas or bone obscured. It is not generally useful in the lungs and head, except in neonates where the open fontanelles provide an acoustic window. Ultrasound is also heavily operator dependent, particularly in overcoming barriers due to the bony skeleton and bowel gas, and in interpreting artifacts, which are common.

Computed tomography

Computed tomography (CT) was invented in the 1970s, earning its chief inventor, Sir Godfrey Hounsfield, the Nobel Prize for medicine in 1979. CT was the first fully digital imaging technique that provided cross-sectional images of any anatomical structure.

Basic principles

Current generation CT scanners use the same basic technology as the first clinical EMI machine in 1972. In conventional CT, the X-ray tube and detector rotate around the patient with the table stationary. The X-ray beam is attenuated by absorption and scatter as it passes through the patient with the detector measuring transmission (fig. 1.14). Multiple measurements are taken from different directions as the tube and detector rotate. A computer reconstructs the image for this single "slice." The patient and table are then moved to the next slice position and the next image is obtained.

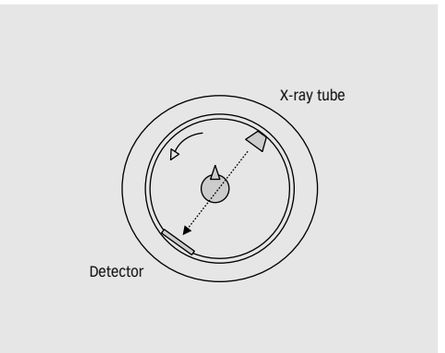

Fig. 1.14. **Diagram of a typical CT scanner. The patient is placed on the couch and the X-ray tube rotates 360° around the patient, producing pulses of radiation that pass through the patient. The detectors rotate with the tube, on the other side of the patient detect the attenuated X-ray pulse. This data is sent to a computer for reconstruction.**

In spiral (helical) CT the X-ray tube rotates continuously while the patient and table move through the scanner. Instead of obtaining data as individual slices, a block of data in the form of a helix is obtained. Scans can be performed during a single breath hold, which reduces misregistration artifacts, such as occur when a patient has a different depth of inspiration between conventional scans. A typical CT scanner is shown in Fig. 1.15.

Image reconstruction

To convert the vast amount of raw data obtained during scanning to the image requires mathematical transformation. Depending on the parameters used (known as "kernels"), it is possible to get either a high spatial resolution (at the expense of higher noise levels) used for lung and bone imaging, or a high signal to noise ratio (at the expense of lower resolution) used for soft tissues.

The CT image consists of a matrix of image elements (pixels) usually 256 × 256 or 512 × 512 pixels. Each of these displays a gray scale intensity value representing the X-ray attenuation of the corresponding block of tissue, known as a voxel (a three-dimensional "volume element").

CT scanners operate at relatively high diagnostic X-ray energies, in the order of 100 kV. At these energies, the majority of X-ray-tissue interactions are by Compton scatter, so the attenuation of the X-ray beam is directly proportional to the density of the tissues. The intensity value is scored in Hounsfield units (HU). By definition, water is 0 HU and air −1000 HU and the values are assigned proportionately. These values can be used to differentiate between tissue types. Air (−1000 HU) and fat (−100 HU) have negative values, most soft tissues have values just higher than water (0 HU), e.g., muscle (30 HU), liver (60 HU), while bone and calcified structures have values of 200–900 HU. The contrast resolution of CT depends on the differences between these values, the larger the better. Although better than plain X-ray in differentiating soft tissue types, CT is not a good as magnetic resonance imaging (MRI). For applications in the lungs and bone (where the differences in attenuation values are large), CT is generally better than MRI.

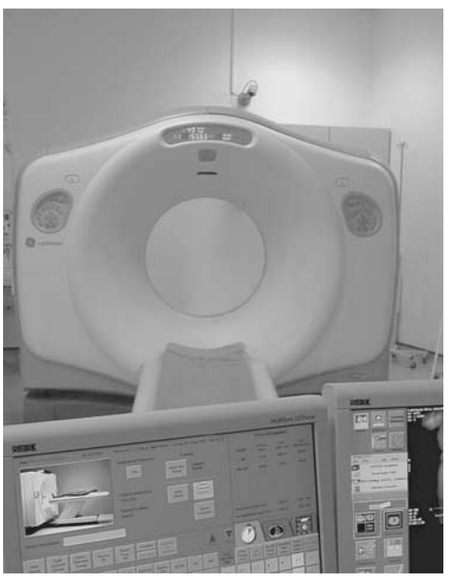

Fig. 1.15. **A multi-slice CT scanner.**

The use of intravenous contrast agents can increase the contrast resolution in soft tissues as different tissues show differences in enhancement patterns. Oral contrast can outline the lumen of bowel and allow differentiation of bowel contents and soft tissues within the abdomen. Usually iodinated contrast agents are used for CT, although a dilute barium solution can be used as bowel contrast.

Window and level

The human eye cannot appreciate anywhere near the 4000 or so gray scale values obtained in a single CT slice. If the full range of reconstructed values were all displayed so as to cover all perceived brightness values uniformly, a great deal of information would be lost as the viewer would not be able to distinguish the tiny differences between differing HU values. By restricting the range of gray scale information displayed, more subtle variations in intensity can be shown. This is done by varying the range ("window width") and centre ("window level") (Fig. 1.16).

Spiral CT and pitch

In conventional, incremental CT the parameters describing the procedure are slice width and table increment (the movement of the table between slices). With spiral CT, the patient, lying on the couch, moves into the scanner as the tube and detectors rotate in a continuous movement, rather than the couch remaining still while each "slice" is acquired. The information during spiral CT is obtained as a continuous stream and is reconstructed into slices.

The parameters for spiral CT are slice collimation (the width of the X-ray beam and therefore the amount of the patient covered per rotation), table feed per rotation, and the reconstruction increment. A spiral CT covers the whole volume even if the table feed is greater than the collimation – it is possible to scan with a table feed up to twice the collimation without major loss of image quality. Often, scans are described by their pitch where pitch = table feed/collimation. Typical values for collimation (slice thickness) are 1–10 mm with rotation times of 0.5–3 seconds.

To reconstruct from the helical volume, it is necessary to interpolate the projections of one scanner rotation. It is not necessary to reconstruct as consecutive slices – slices with any amount of overlap can be created.

Multi-detector CT

CT scanners are now available with multiple rows of detectors (at the time of writing, commonly 64) allowing acquisition of multiple slices in one spiral acquisition. In conjunction with fast rotation speeds, the volume coverage and speed performance are improved allowing, for instance, an abdomen and pelvis to be scanned with an acquisition slice thickness of 1.25 mm in about quarter the time (approximately 10 seconds) that a 10 mm collimation CT scanner could cover the same volume, with the same or lesser radiation dose. The main problem with this type of scanning is the number of images acquired; 300–400 in the example above instead of about 40 with single slice techniques.

Advanced image reconstructions

From the spiral dataset, further reconstructions can be performed. Multiplanar reformats (MPR) can be performed in any selected plane, although usually in the coronal and sagittal planes (Fig. 1.17). Three-dimensional reconstructions can also be obtained using techniques

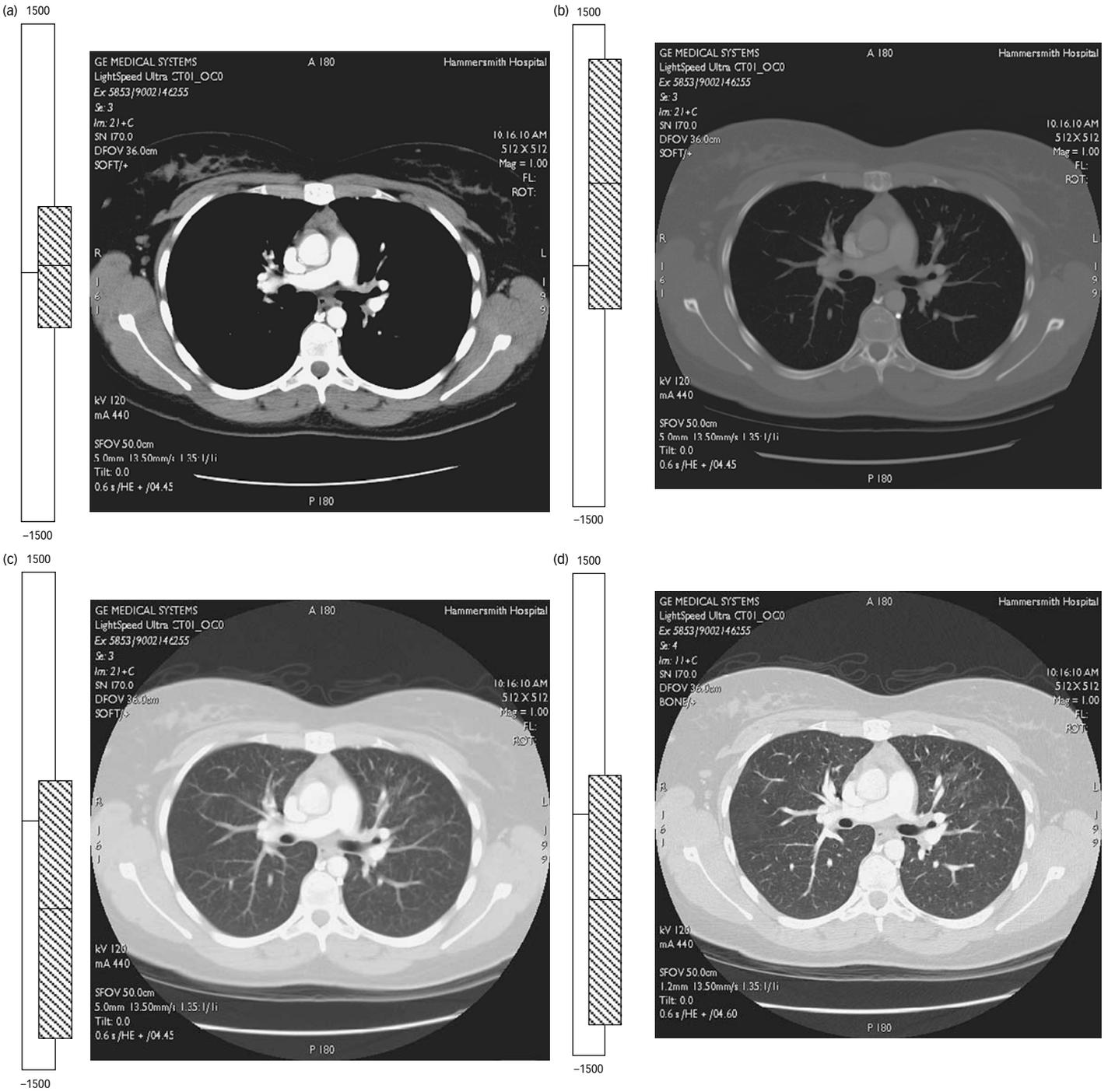

Fig. 1.16. **The effect of changing window levels and reconstruction algorithm on a single axial image through the chest. The dark bar indicated the range of values displayed, the light bar the range of values available. (a) "Soft tissue" window with window level of 350 and centre 50; (b) "bone window" with window level 1500 and centre 500; (c) lung window with window level 1500 and centre −500; and (d) an HRCT (high resolution CT image) – this is a thin slice image reconstructed using an edge enhancement (bone or lung) algorithm, which shows better detail in the lung but increases "noise" levels, window 1500, centre −500.**

such as surface-shaded display and volume rendering (Fig. 1.18 – see color plate section). While the 3-D techniques provide attractive images and are useful in giving an overview of complex anatomical structures, a lot of information from the original axial data set is often discarded. Virtual endoscopy uses a 3-D "central" projection to give the effect of viewing a hollow viscus interiorly (as is seen in endoscopic examination) and is of particular use in patients too frail or ill to have invasive endoscopy.

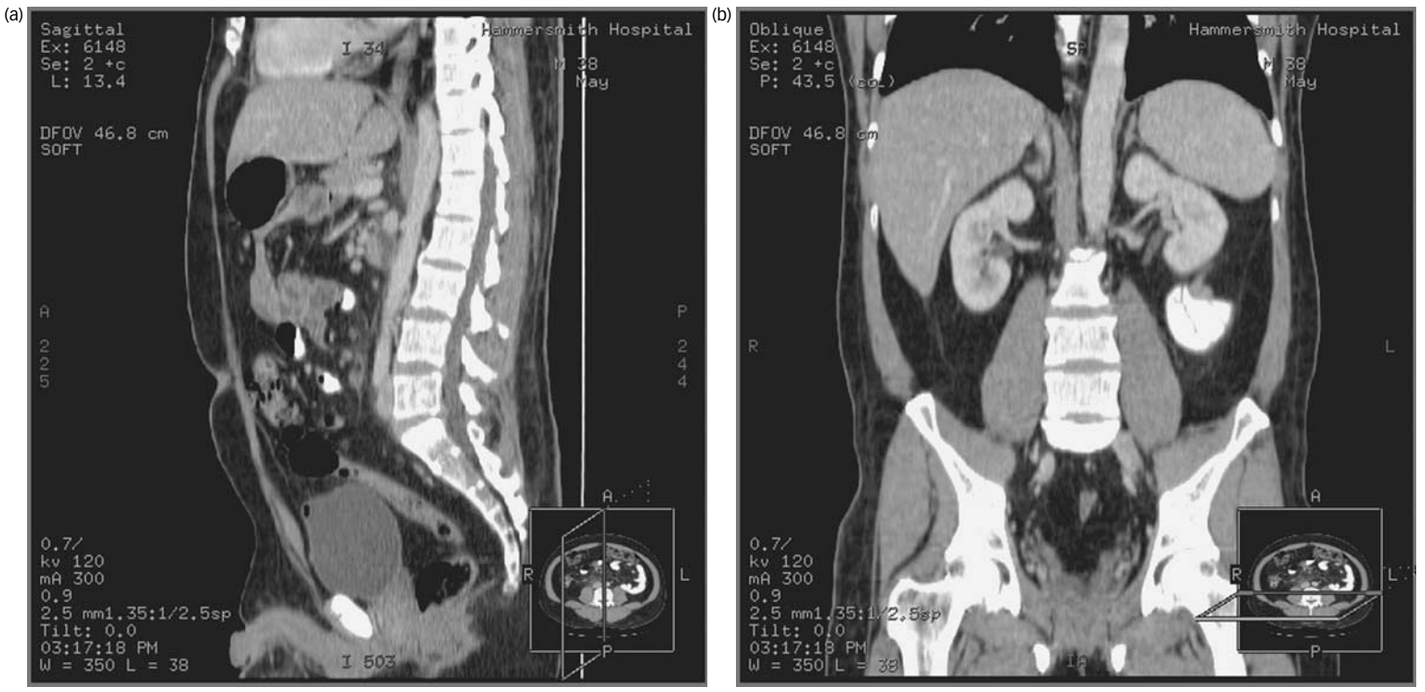

Fig. 1.17. **(a) Sagittal** and **(b) coronal** reformats of a helical scan through the abdomen and pelvis. The data from the axial slices is rearranged to give different projections.

HRCT

High resolution CT or HRCT is used to image the lungs. Thin slices are acquired – usually 1 to 2 mm thick at 10–20 mm intervals. These are reconstructed using edge enhancement (bone or lung) algorithms showing better detail in the lung but increasing "noise" levels (Fig. 1.16). This allows fine details of lung anatomy to be seen. The whole lung volume is not scanned, as there are gaps between the slices.

CT artifacts

Volume averaging

A single CT slice of 10 mm thickness can contain more than one tissue type within each voxel (for example, bone and lung). The CT number for that voxel will be an average of the different sorts of tissue within it, so very small structures can be "averaged out" or if a structure with low CT number is adjacent to one with a high CT number, the apparent tissue density will be somewhere in between. This is known as a "partial volume effect."

Beam hardening artifact

This results from greater attenuation of low-energy photons than high-energy photons as the beam passes through the tissue. The average energy of the X-ray beam increases so there is less attenuation at the end of the beam than at the beginning, giving streaks of low density extending from areas of high density such as bones.

Motion artifact

This occurs when there is movement of structures during image acquisition and shows up as blurred or duplicated images, or as streaking.

Streak artifact

The reconstruction algorithms cannot deal with the differences in X-ray attenuation between very high-density objects such as metal clips or fillings in the teeth and the adjacent tissues and produce high attenuation streaks running from the dense object (Fig. 1.19).

Advantages and limitations of CT

CT provides a rapid, non-invasive method of assessing patients. A whole body scan can be performed in a few seconds on a modern multislice scanner with very good anatomical detail. CT is particularly suited to high X-ray contrast structures such as the bones and the lungs, and remains the cross-sectional imaging modality of choice for assessing these. It has less contrast resolution than MRI for soft tissue structures particularly for intracranial imaging, spinal imaging, and musculoskeletal imaging. CT has no major contraindications (although the use of contrast might have), providing the patient can tolerate the scan. The major disadvantage is in the significant radiation doses required for CT. An abdominal or pelvic CT involves 3–12 mSv of radiation, compared with a chest X-ray's 0.02 mSv or background radiation in the UK averaging 2.5 mSv per year.

Magnetic resonance imaging (MRI)

Nuclear magnetic resonance was first described in 1946 as a tool for determining molecular structure. The ability to produce an image based on the distribution of hydrogen nuclei within a sample, the basis of the modern MRI scanner, was first described in 1973 and the first commercial body scanner was launched in 1978. A modern MRI scanner is shown in Fig. 1.20.