Chapter 1

Introduction to CT physics

Image generation

What is computed tomography (CT)?

Since the first CT scanner was developed in 1972 by Sir Godfrey Hounsfield, the modality has become established as an essential radiological technique applicable in a wide range of clinical situations.

CT uses X-rays to generate cross-sectional, two-dimensional images of the body. Images are acquired by rapid rotation of the X-ray tube 360° around the patient. The transmitted radiation is then measured by a ring of sensitive radiation detectors located on the gantry around the patient (Fig. 1.1). The final image is generated from these measurements utilizing the basic principle that the internal structure of the body can be reconstructed from multiple X-ray projections.

Early CT scanners acquired images a single slice at a time (sequential scanning). However, during the 1980s significant advancements in technology heralded the development of slip ring technology, which enabled the X-ray tube to rotate continuously in one direction around the patient. This has contributed to the development of **helical** or **spiral** CT.

In **spiral CT** the X-ray tube rotates continuously in one direction whilst the table on which the patient is lying is mechanically moved through the X-ray beam. The transmitted radiation thus takes on the form of a helix or spiral. Instead of acquiring data one slice at a time, information can be acquired as a continuous volume of contiguous slices (Fig. 1.2a, b). This allows larger anatomical regions of the body to be imaged during a single breath hold, thereby reducing the possibility of artefacts caused by patient movement. Faster scanning also increases patient throughput and increases the probability of a diagnostically useful scan in patients who are unable to fully cooperate with the investigation.

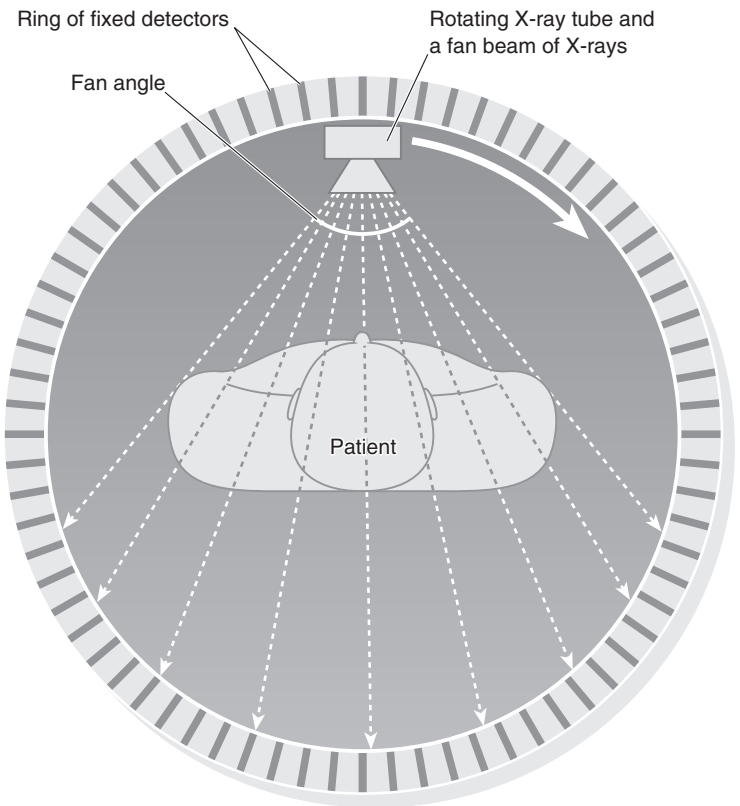


Fig. 1.1 *Ring of detectors ('fourth generation'). Patient in cross-section.*

The next generation of CT scanners is now commercially available. These **multislice** or **multidetector** machines utilize the principles of the helical scanner but incorporate multiple rows of detector rings. They can therefore acquire multiple slices per tube rotation, thereby increasing the area of the patient that can be covered in a given time by the X-ray beam (Fig. 1.3a, b).

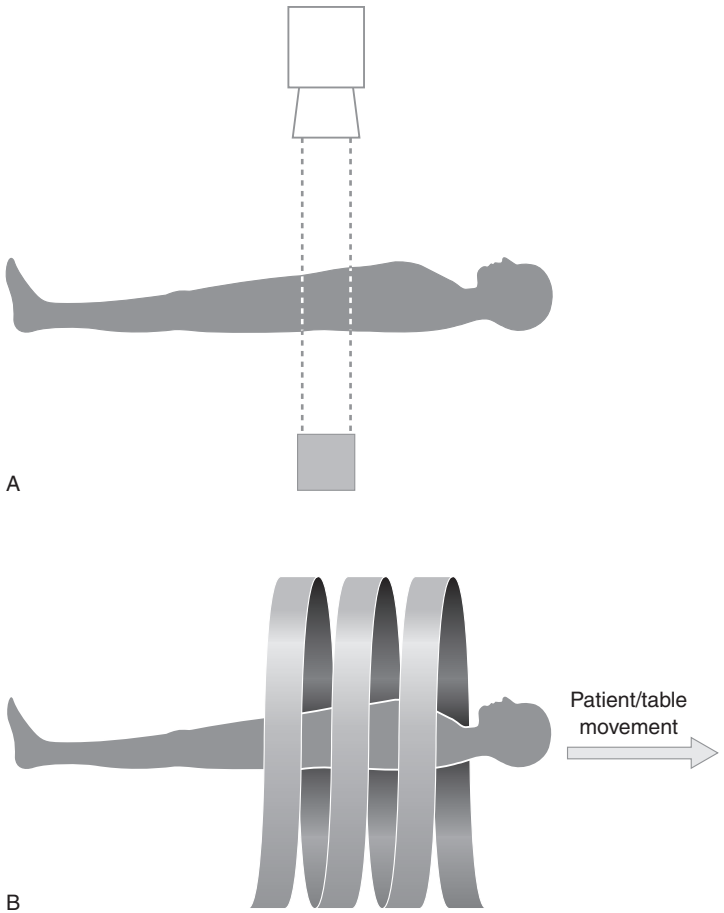


Fig. 1.2 ***(A)*** *Single-slice system (one ring).* ***(B)*** *Single-slice helical CT. The X-ray tube rotates continuously and the patient moves through the X-ray beam at a constant rate.*

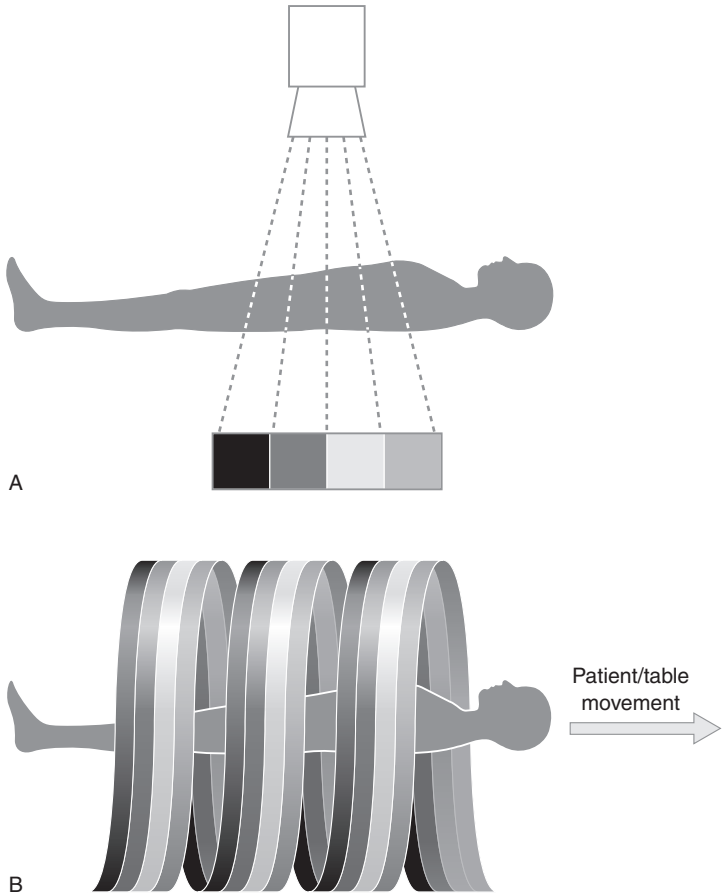


Fig. 1.3 ***(A)*** *Multidetector system (four rings shown here).* ***(B)*** *Multislice helical CT.*

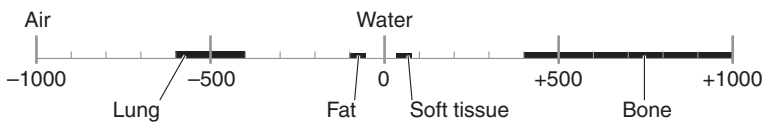
How is a CT image produced?

Every acquired CT slice is subdivided into a matrix of up to 1024 × 1024 volume elements (**voxels**). Each voxel has been traversed during the scan by numerous X-ray photons and the intensity of the transmitted radiation measured by detectors. From these intensity readings, the density or **attenuation value** of the tissue at each point in the slice can be calculated. Specific attenuation values are assigned to each individual voxel. The viewed image is then reconstructed as a corresponding matrix of picture elements (**pixels**).

What is a Hounsfield unit or CT number?

Each pixel is assigned a numerical value (CT number), which is the average of all the attenuation values contained within the corresponding voxel. This number is compared to the attenuation value of water and displayed on a scale of arbitrary units named **Hounsfield units (HU)** after Sir Godfrey Hounsfield.

This scale assigns water as an attenuation value (HU) of zero. The range of CT numbers is 2000 HU wide although some modern scanners have a greater range of HU up to 4000. Each number represents a shade of grey with +1000 (white) and –1000 (black) at either end of the spectrum (Fig. 1.4).



Bone	+400 → +1000
Soft tissue	+40 → +80
Water	0
Fat	–60 → –100
Lung	–400 → –600
Air	–1000

Fig. 1.4 *The Hounsfield scale of CT numbers.*

Window level (WL) and window width (WW)

Whilst the range of CT numbers recognized by the computer is 2000, the human eye cannot accurately distinguish between 2000 different shades of grey. Therefore to allow the observer to interpret the image, only a limited number of HU are displayed. A clinically useful grey scale is achieved by setting the WL and WW on the computer console to a suitable range of Hounsfield units, depending on the tissue being studied.

The term 'window level' represents the central Hounsfield unit of all the numbers within the window width.

The window width covers the HU of all the tissues of interest and these are displayed as various shades of grey. Tissues with CT numbers outside this range are displayed as either black or white. Both the WL and WW can be set independently on the computer console and their respective settings affect the final displayed image.

For example, when performing a CT examination of the chest, a WW of 350 and WL of +40 are chosen to image the mediastinum (soft tissue) (Fig. 1.5a), whilst an optimal WW of 1500 and WL of –600 are used to assess the lung fields (mostly air) (Fig. 1.5b).

What is pitch?

Pitch is the distance in millimetres that the table moves during one complete rotation of the X-ray tube, divided by the slice thickness (millimetres). Increasing the pitch by increasing the table speed reduces dose and scanning time, but at the cost of decreased image resolution (Fig. 1.6a, b).

Image reconstruction

The acquisition of volumetric data using spiral CT means that the images can be postprocessed in ways appropriate to the clinical situation.

- **Multiplanar reformatting (MPR)** – by taking a section through the three-dimensional array of CT numbers acquired with a series of contiguous slices, sagittal, coronal and oblique planes can be viewed along with the standard transaxial plane (Fig. 1.7).

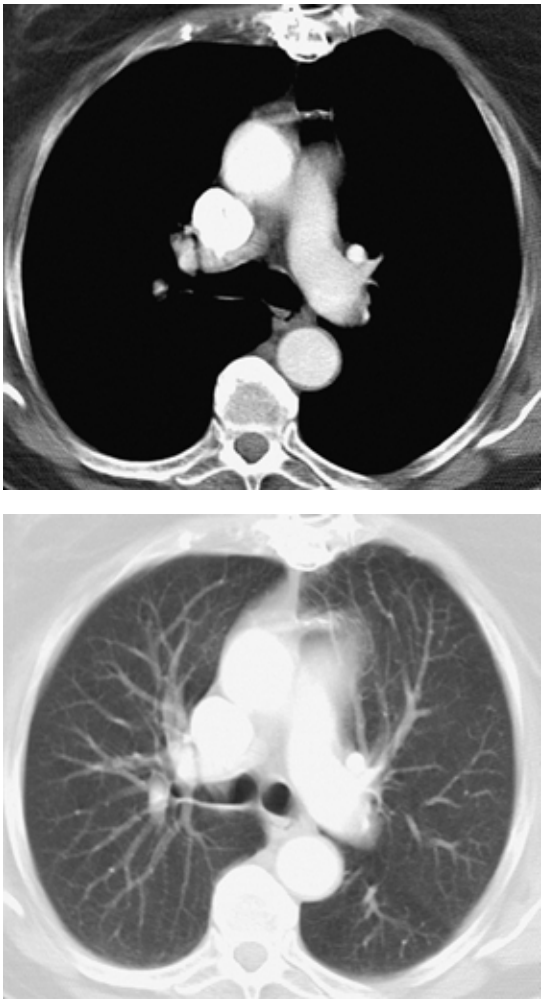


Fig. 1.5 *These two images are of the same section, viewed at different window settings.* ***(A)*** *A window level of +40 with a window width of 350 reveals structures within the mediastinum but no lung parenchyma can be seen.* ***(B)*** *The window level is –600 with a window width of 1500 Hounsfield units. This enables details of the lung parenchyma to be seen, at the expense of the mediastinum.*

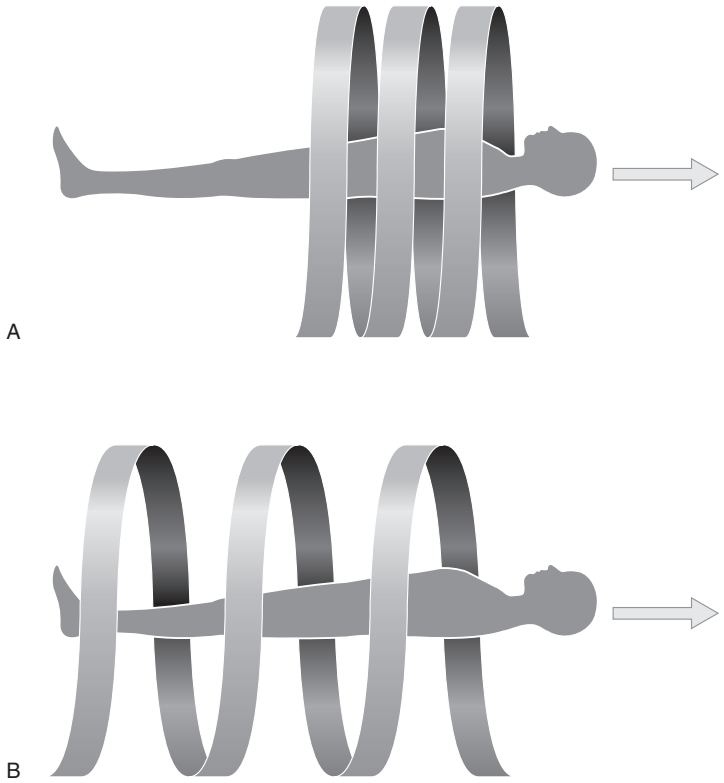


Fig. 1.6 ***(A)*** *Pitch is low. The table moves less for each tube revolution. The image is sharper.* ***(B)*** *Pitch is high. The table moves further for each revolution so the resulting image is more blurred. The helix is stretched.*

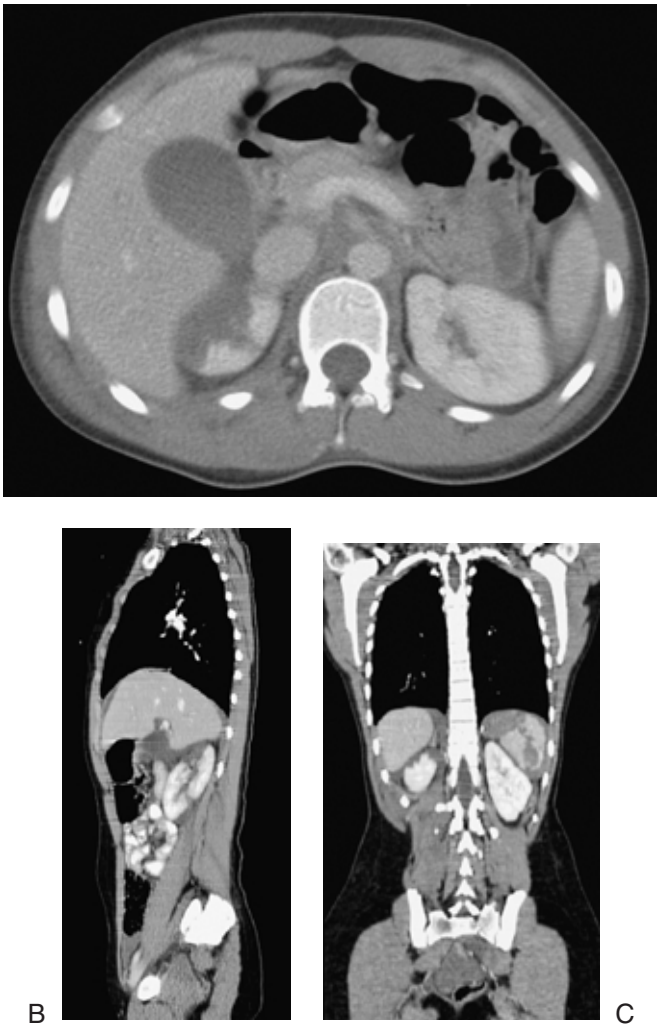
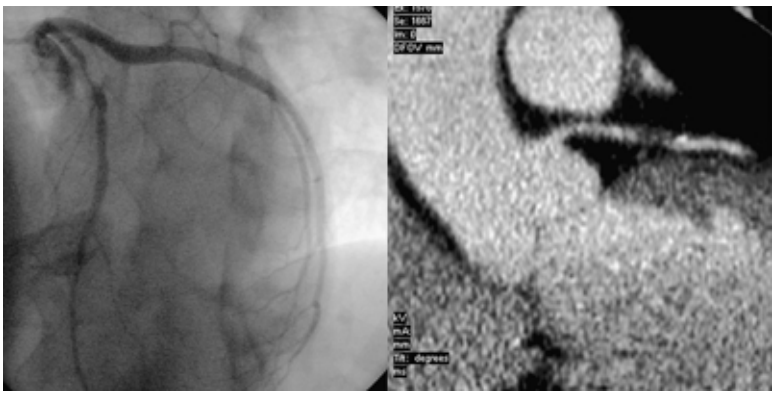


Fig. 1.7 *The three images demonstrate a haemoperitoneum, shattered right kidney and a lacerated spleen in axial* ***(A)****, sagittal* ***(B)*** *and coronal* ***(C)*** *planes.*

- **Three-dimensional imaging** – using reconstructed computer data enables the external and internal structure of organs to be viewed. The data can be projected as a three-dimensional model to display spatial information or surface characteristics (volume and surface rendering) (see Fig. 2.10). This is becoming increasingly useful for patients unable to have invasive endoscopy.
- **CT angiography (CTA)** – following intravenous contrast enhancement, images are acquired in the arterial phase and then reconstructed and displayed in either a 2D or 3D format. This technique is commonly used for imaging the aorta, renal and cerebral arteries. In addition there is increasing interest in the use of CTA to image the coronary and peripheral vessels (Fig. 1.8).



A B

Fig 1.8 *The image on the right is a two-dimensional 'angiogram' derived from a three-dimensional reconstruction, showing a small left anterior descending artery with a severe proximal stenosis. The image on the left is a comparative image from the invasive traditional coronary angiogram of the same patient, confirming the lesion.*

Contrast media

Contrast between the tissues of the body can be improved by the use of various contrast media. These mostly contain substances with a **high molecular weight** and thus increase the attenuation value of the organ they opacify.

- **Oral contrast** – the bowel is routinely opacified in almost all CT examinations of the abdomen and pelvis because the attenuation value of the bowel is similar to other surrounding structures and therefore pathological processes may be obscured (see Fig. 2.19 – contrast in stomach in upper image). Substances used include dilute barium or iodine-based preparations, which are normally given to the patient to drink 24 hours and 1 hour prior to examination to opacify the distal and proximal gastrointestinal tract respectively.

- **Intravenous contrast** – these are usually iodine-based media. They can be injected to opacify the vascular tree in different **phases**, depending on the rate and volume of contrast injection and the timing of image acquisition. **Arterial** opacification is maximal at approximately 20 seconds with **venous** enhancement rising to a peak after approximately 70 seconds. The level of intravascular enhancement then declines as the contrast equilibrates with the tissues of the body before being excreted by the kidneys into the ureters and bladder.

  These different phases of enhancement are used to image various organs depending on the indication for the CT examination. Spiral scanners, because of their speed, are able to acquire images during each phase of enhancement, thus increasing the information obtained from the study. For example, when imaging the pancreas for a suspected tumour, thin sections are initially acquired during the arterial phase to best demonstrate the tumour and also to diagnose any arterial involvement of the tumour. A second scan during the portal venous enhancement phase is then performed to optimally demonstrate any liver metastases and tumour invasion into venous structures (see Fig. 2.19).

  The high density of contrast can be utilized to display only the blood vessel lumen when reconstructing axial data with a maximum intensity projection (MIP). This is used to look for vascular disease.

- **Air** – can also be used as a negative contrast agent, for example in imaging of the large bowel in CT colonography (see Fig. 2.21).

Dual-modality imaging

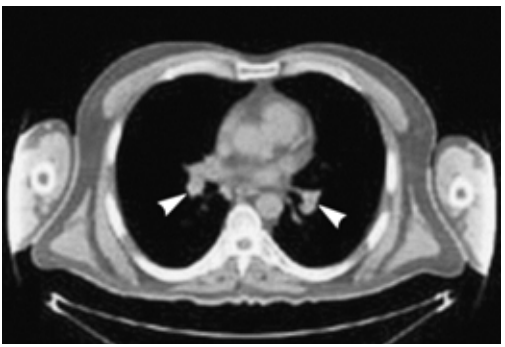
Positron emission tomography (PET)/CT

PET allows the detection of glucose uptake in tissues. The radiopharmaceutical utilized is 18-FDG (18-fluorodeoxy-D-glucose). The technique has particular use

in the detection of malignant and inflammatory lesions where glucose uptake is increased.

PET and CT imaging can be performed in the same machine, thus providing superimposed CT and PET images of pathology in a single examination. This results in a complementary, overlapping display of anatomical and functional/metabolic information, which can be used in the accurate and efficient diagnosis and follow-up of cancer patients (Fig. 1.9).

A



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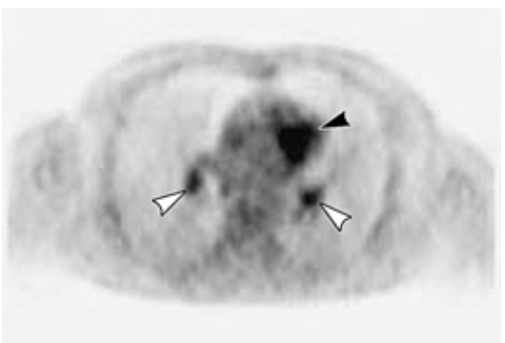


Fig. 1.9 ***(A)*** *CT of thorax showing soft tissue masses (lymphadenopathy – white arrowheads) adjacent to the pulmonary vessels.* ***(B)*** *PET scan at the same axial level showing increased metabolic activity (white arrowheads). Note high metabolic activity within the left ventricle (black arrowhead).*

Continued

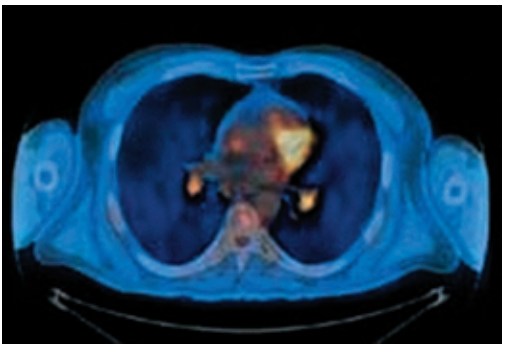
C 

Fig. 1.9 *cont'd.* ***(C)*** *PET/CT fused image correlating increased metabolic activity within lymph node masses implying pathological enlargement. Courtesy: Nuclear Medicine, University Hospital, Zurich, Switzerland.*

Advantages and disadvantages of CT

Advantages

- CT is readily available in most hospitals.
- It is an increasingly rapid imaging modality with excellent image resolution, enabling faster and more accurate diagnostic evaluation of patients over a wide spectrum of clinical indications.
- The data acquired in one scan can subsequently be manipulated to provide multiplanar and 3D reconstructions.

Disadvantages

- **Radiation** – although CT scans account for only 4% of X-ray examinations, they contribute to more than 20% of the radiation dose to the population by 'medical X-rays'. For typical doses of common radiological examinations, see Table 1.1.

Advantages and disadvantages of CT

Table 1.1 Radiation doses (mSv – millisieverts) (from Royal College of Radiologists 2003 Making the best use of a department of clinical radiology. Guidelines for doctors, 5th edn. Royal College of Radiologists, London)

Diagnostic procedure	*Typical effective dose (mSv)*	*Equiv. no. of CXR*	*Approx. equiv. period of background radiation*
CXR	0.02	1	3 days
CT head	2.0	100	10 months
CT chest	8	400	3.6 years
CT abdomen/pelvis	10	500	4.5 years

UK average background radiation = 2.2 mSv per year; regional averages range from 1.5 to 7.5 mSv per year.

- **Artefacts** – an artefact is a feature or appearance that is seen on an image, which does not actually exist. They occur in all imaging modalities and are often unavoidable. Recognizing the presence of artefacts is important in order to avoid confusion with pathology. However, with the increasing speed of image acquisition in a single breath hold by the most modern scanners, many artefacts are being minimized or eliminated. Types of artefact include:
  1. *motion* – from patient movement during a scan, commonly due to breathing
  2. *streak (beam hardening)* – dark 'streaks' behind high-density objects, e.g. dental amalgam and metallic joint replacements
  3. *partial voluming* – different tissue densities within a *single* voxel lead to 'averaging' of data. For example, a small black object within a larger white space would look like a shade of grey.
- Relatively poor tissue contrast when compared to MRI can be a problem, despite the use of oral and IV contrast. This may occur in thin adults and children due to the lack of intra-abdominal fat separating the various tissue planes.
- CT has a relatively high cost and limited portability.
- There can be contrast media-related complications, including allergic reactions and renal toxicity.