CHAPTER 19

X-rays, computed axial tomography and endoscopy

The physical properties of electromagnetic radiation can be used as diagnostic tools

Introduction

As discussed in Chapter 18, sound waves can be used to form images for diagnostic purposes. In this chapter, the use of electromagnetic radiation (EMR) for medical imaging is studied. The chapter will discuss the use of X-rays in the form of plain X-ray films, as well as in computed axial tomography. The use of visible light in endoscopies will also be examined.

19.1 The nature of X-rays

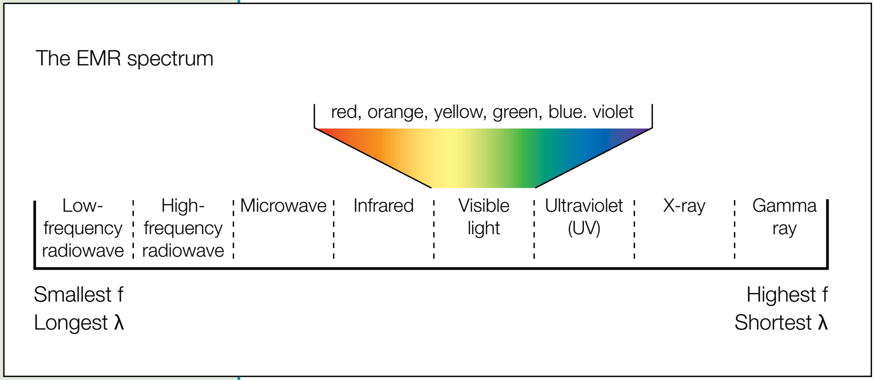
■ *Compare the differences between 'soft' and 'hard' X-rays*

X-rays are high-frequency EMR. They are between gamma rays and UV rays in the EMR spectrum, which is shown in Figure 19.1. X-rays are very energetic as a result of their high frequency ($E = hf$) and are therefore also very penetrative.

There are two types of X-rays: hard X-rays and soft X-rays. **Hard X-rays** are those that have higher frequencies. As a result, they are able to produce high-resolution pictures and are therefore preferred for medical imaging.

NOTE: A high-frequency wave, due to minimal diffraction, will enable the differentiation of two very closely placed points, allowing their visualisation, and hence increasing the resolution of the image. This property is common to all EMR. For instance, a purple-light microscope can resolve smaller objects compared to normal light microscopy due to the higher frequency of the purple light.

Figure 19.1 The EMR spectrum



Soft X-rays, on the other hand, are X-rays that have lower frequencies. Lower frequencies result in lower penetration power, which makes the soft X-rays unable to penetrate through the body tissues to reach the X-ray films to produce an image. (See later this section for the formation of X-ray images). Furthermore, lower frequencies also lead to lower resolution. Consequently, soft X-rays are not useful for medical imaging.

19.2 The production of X-rays for medical imaging

■ *Describe how X-rays are currently produced*

X-rays used for medical imaging are produced in a device called an **X-ray tube**. A schematic drawing of an X-ray tube is shown in Figure 19.2.

In the X-ray tube, X-rays are produced in two ways.

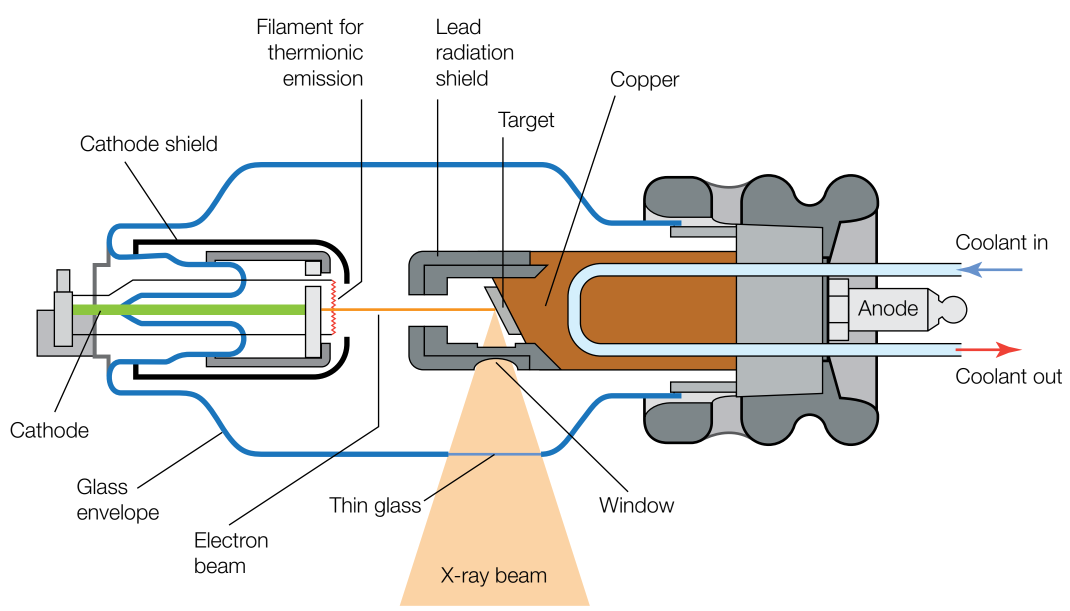


Figure 19.2 An X-ray tube is used to produce X-rays for diagnostic purposes

The bremsstrahlung (braking) radiation

The majority of the X-rays produced by the X-ray tube are derived from the deceleration of the electrons as they hit the anode (more correctly, as they are bent around the nucleus of the target atoms).

Electrons are first produced at the cathode via thermionic emission. The thermionic emission is used to free the electrons from the surface of the cathode so that they can be easily accelerated towards the anode by the high voltage applied across the two electrodes. The fast-moving electrons are then decelerated as they collide with the anode. As a consequence of the collisions, the electrons lose proportions of their kinetic energy, which are converted into mainly heat energy (98%–99%) and X-rays (1%–2%)—the law of conservation of energy. The X-rays produced in this way are given the name **bremsstrahlung (braking) radiation**. The frequency of the X-ray produced relates directly to the energy of the X-ray. The bremsstrahlung radiation has a continuous spectrum of frequencies as a result of variations in the kinetic energy the electrons possess as well as the proportions that are converted into X-rays. The maximum frequency, and hence energy, of the X-rays produced depends on the size of the voltage supplied to the X-ray tube.

A graph can be used to demonstrate a spectrum of X-rays produced using an X-ray tube (see Fig. 19.3).

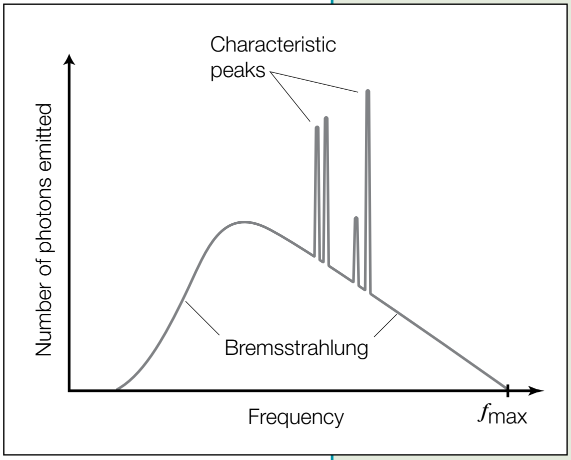


Figure 19.3 Spectrum of X-rays produced by an X-ray tube: the continuous part of the line represents bremsstrahlung radiation; whereas the spikes represent characteristic X-rays

The characteristic radiation

Characteristic radiation or X-rays are produced via a different mechanism. When electrons from the cathode reach the anode, they may strike the inner electrons of the atoms and knock them away from their usual positions. This process leaves vacancies in the lower energy shells that are in turn filled by the electrons falling from outer energy shells and, in so doing, emitting energy in the form of X-rays (only for large atoms). Distinguishing them from the braking radiation, these X-rays are characteristic of the metal used for the anode. In other words, different materials used for the anode will produce different characteristic X-rays. These are seen as spikes on the X-ray spectrum, as illustrated in Figure 19.3.

The features of an anode

The anode is the target that the electrons strike and decelerate. During the deceleration process, huge amounts of heat are produced. The features adopted by the anode design are all aimed at withstanding the heat as well as dissipating the heat quickly and efficiently.

- First, tungsten metal is used as the material for the anode target. This is because tungsten has the highest melting point among all metals and this is essential for withstanding the heat.
- The tungsten metal is placed at an angle to the incoming electrons in order to increase the surface area that will be interacting with these electrons. Consequently, the heat is allowed to be distributed over a larger area, which in turn decreases the amount of heat experienced per unit area of the tungsten metal. This prevents melting of the metal.
- The tungsten metal rotates at a speed of 3600 revolutions per minute so that different parts of the tungsten metal are exposed to the incoming electrons at different times. This allows the heat to be distributed evenly throughout the entire tungsten metal.
- Last, the tungsten metal is mounted on a piece of copper to help conduct the heat away from the tungsten metal. Furthermore, a coolant, often oil, is made to circulate through the anode to help carry away the excessive heat.

Overall this method of production of X-rays is extremely inefficient as the majority of the electrons' kinetic energy is converted into heat and only a very small amount is used to produce X-rays. The huge amount of heat can cause the entire X-ray tube to melt down; therefore, the cooling system of the anode needs to be operating efficiently at all times.

19.3 Using X-rays for medical imaging: the principle

The first step in X-ray imaging is to produce the X-rays using an X-ray tube. This happens when the radiographer turns on the X-ray machine after the patient is positioned in a particular posture depending on the organ or the system being examined. In order to produce good-quality X-ray images, the X-ray beam produced needs to be narrow and this is achieved by using a lead collimator. Furthermore, because soft X-rays only produce low-resolution images and have poor penetration power, they are not useful for medical imaging and are filtered out after their production. This also reduces the amount of X-rays the body is exposed to. The soft X-rays can be filtered using a thin sheet of aluminium while the hard X-rays penetrate through it to image the body.

The principle of the image formation is that as the X-rays pass through the body, they are attenuated (absorbed) by the tissues in the body differently. Some tissues—for example, the bones—attenuate X-rays more than other tissues—for example, muscle and fat—whereas air minimally attenuates X-rays. The consequence is that different amounts of X-rays pass through the body, with a pattern determined by the nature of the tissue structures encountered, to reach the X-ray film. The arriving X-rays expose the film, similar to casting a shadow. X-rays that have been attenuated the most will not expose much of the film, leaving the film whitish when developed. On the other hand, X-rays that are minimally attenuated will expose the film maximally, making the film appear dark. Of course, there will be all shades of grey in between: for example, bone will appear whitish on a plain X-ray picture, air in the lungs will appear dark, and fat and soft tissues will appear grey. These are shown in Figures 19.4 and 19.5 (overleaf). The organ or system to be examined should be placed as close as possible to the film so that the image produced will have a sharp edge and minimal magnification.

An X-ray machine

ANALOGY: The way X-rays are used to produce images is very similar to the way light casts shadows (except X-rays can penetrate through flesh, whereas light cannot). If an object blocks out light completely, a definitive shadow is produced. If, on the other hand, an object only blocks out a proportion of the light, a grey shadow is created.

ANALOGY: The way X-ray images are displayed using X-ray films is similar to the negatives of normal photos. Maximum exposures to light will turn the films dark, whereas non-exposure to light leaves the films white (clear).

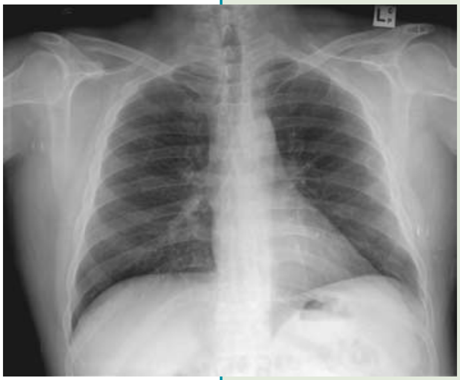


Figure 19.4
A typical chest X-ray

In recent years, X-ray films have been less frequently used as they have gradually been replaced by computer technologies. Today, in most metropolitan hospitals, instead of displaying the image of a body part by exposing an X-ray film, the image data can now be collected using a computer system and the same image is recreated and displayed on the screen. This system makes the viewing of the images more convenient and enables the adjustment of contrast while viewing, as well as avoiding the need to store hard copies of X-rays films, which can take up a lot of space.

19.4 The clinical uses of X-ray imaging

Viewing the skeletal system

Because bones attenuate X-rays well, they create sharp shadows on X-rays films. Recall that with a conventional X-ray film (also known as a plain X-ray film), bones appear white. Also, the high frequency of the X-rays will result in a high-resolution image. A plain X-ray film of the bones can show a high level of structural details of the bones that no other medical imaging can achieve. It is therefore the investigation of choice for assessing bone diseases or problems.

Common bone pathologies diagnosed by X-rays are fractures (see Fig. 19.5 overleaf), dislocations and tumours of the bone. Plain X-ray films are also useful for assessing joint pathologies, such as osteoarthritis, a condition that involves

Figure 19.5 An X-ray film of the ankle bones, showing a fracture in the tibia and fibula

wearing-out of the cartilages that line the articulating bones, leaving a bare bone-to-bone contact. Cartilages do not attenuate X-rays well, and therefore are not seen on X-ray films. Thus a normal joint will appear to have a 'gap' (where the cartilages exist) between the articulating bones on X-ray films. In osteoarthritis, this 'gap' is reduced (due to the loss of the lining cartilages). The articulating bones also look frail. See Figures 19.6 (a) and (b)

An extension of using X-rays for bone imaging is the imaging of teeth, which have a similar composition to bones. X-ray images of teeth can be useful for assessing the growth of wisdom teeth in adolescents to determine whether they are growing in the correct orientation or if they will require surgical intervention.

Figure 19.6 (a) An X-ray film of a normal joint

Figure 19.6 (b) An X-ray film of a joint with osteoarthritis

Gathering X-ray images

SECONDARY SOURCE INVESTIGATION

PHYSICS SKILLS

12.3A, B, D
13.1C, E

■ *Gather information to observe at least one image of a fracture on an X-ray film and X-ray images of other body parts*

You must search for X-ray images that show fractures. After acquiring a few X-ray images that show fractures, think about the following points.

- What are the sources of these X-ray images?
- What purposes do these images serve? Is it possible to identify the clinical scenario that is associated with each of the X-ray images?
- What are the features that would help to identify these images as plain X-ray films? Describe the colour, resolution and contrast of these images.
- What bones are shown in each of these images?
- Where is the fracture in each of the images? Try to describe it.
- You may wish to search for the following terms to increase your knowledge of fractures: 'transverse fractures', 'oblique fractures', 'spiral fracture', 'segmental fractures', 'comminuted fractures', 'buckle fractures' and 'greenstick fractures'. Also look up 'displaced' and 'rotated fractures'. Do any of these terms apply to the fractures shown in the films?

Chest examination

The other very common use of X-ray imaging is for the examination of the lungs and heart. Many patients presenting to the emergency department have a chest X-ray.

The lungs are filled with air, which minimally attenuates X-rays, consequently they form a good contrast with the surrounding tissues. The heart, which is positioned in between the lungs, will also have its shadow outlined by the lungs.

A normal chest film is shown in Figure 19.7 (a). You can see a clear lung field as the X-rays pass through the air in the lungs with minimal attenuation. Small markings in the lung field are the bronchi and arteries in the lungs and are normal. The heart shadow is seen between the lungs. Many problems will show up clearly on a chest film as they often disrupt the normal aeration of the lungs. These problems include infection in the lungs (pneumonia), lung cancer, lung abscess, lung collapse, and many more. An example is shown in Figure 19.7 (b). The heart shadow will allow its size and orientation to be assessed, which may be used as screening criteria for certain cardiac diseases.

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A simple atlas of the human chest

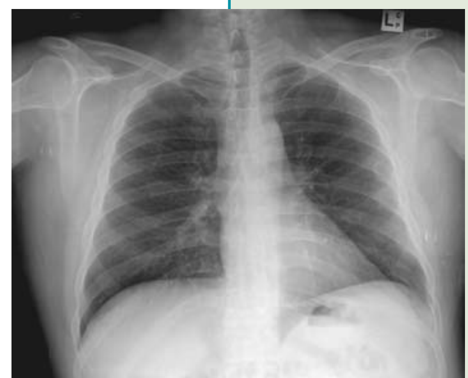


Figure 19.7 (a) A normal chest X-ray film showing clear lung fields

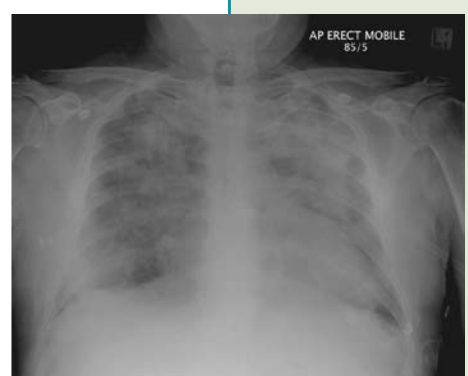


Figure 19.7 (b) A chest X-ray film that shows diffuse pulmonary pathology

Stones

Some stones are calcified, which means they contain calcium. This allows them to attenuate X-rays similar to bones so that they will appear whitish on X-ray films. These stones are termed radiopaque. Examples include calcified kidney stones or gallstones. However, some stones are not calcified, and hence may be missed if only plain films are ordered. These include a great proportion of gallstones and some kidney stones; they are termed radiolucent.

The digestive system

The digestive system, including the stomach and bowel, is not usually seen on plain X-ray films due to the poor contrast between soft tissues. However, sometimes the bowel can be visualised using X-rays—for example, when the bowel is blocked due to certain pathologies, air accumulates inside the bowel, which enables a contrast between the bowel and the rest of the abdominal content and hence its visualisation. This is the basis by which bowel obstruction can be diagnosed using a plain abdominal X-ray film. This is shown in Figure 19.8.

Figure 19.8 (a) A plain abdominal X-ray film showing the normal appearance of intra-abdominal organs

Figure 19.8 (b) A plain abdominal X-ray film showing bowel obstruction; note the air accumulated inside the (small) bowel

SR

A simple atlas of the human abdomen

Figure 19.9 An X-ray contrast material outlining the gastrointestinal tract

The bowel can be visualised better using a contrast medium, one that has the ability to attenuate X-rays. A common example is barium sulphate. This is taken orally by the patient, and it passes through the gastrointestinal tract. As it attenuates X-rays, it makes the bowel radiopaque (which will appear whitish) and allows its visualisation. This method of imaging can be used to assess swallowing, the anatomy of the oesophagus (food pipe), stomach and small intestine (see Fig. 19.9). Nevertheless, contrast X-ray images of the gastrointestinal tract are now largely replaced by computed axial tomography (discussed later in this chapter).

Arterial blood flow

Blood flow through an artery can also be studied using X-ray imaging after introducing an iodine-based contrast into the artery. Such an image technique provides information about blockages or dissection of an artery.

A FURTHER NOTE ON GATHERING: You must search for X-ray images of other body parts. Some examples are provided in this section. When viewing these images, try to recognise the features that identify them as X-ray films. Think about why these body parts show up on X-ray films. What pathologies are shown in each of these images?

Advantages of X-ray imaging

- X-ray imaging is one of the cheapest imaging methods available at a hospital, therefore is often ordered as the first line of investigation to establish an initial diagnosis.
- X-rays are able to produce high-resolution images of bones and tissues that contain air due to their high frequency. X-ray films are the investigation of choice for detecting bone and lung problems. (These organs cannot be visualised using ultrasound.)

Disadvantages of X-ray imaging

- X-rays are harmful as they cause ionisation and damage to body tissues. Nevertheless, the amount of X-rays used for a plain X-ray film is minimal and health side effects are also minimal if they are irregularly used. However, X-rays should not be used for pregnant women as the growing foetus is more susceptible to even a trace amount of ionising radiation.
- The main limitation of X-ray imaging is its poor ability to differentiate between different types of soft tissues. All soft tissues, including muscles, tendons and skin, attenuate X-rays to a similar extent. When viewed using X-rays, they will all appear grey, and hence cannot be differentiated.
- X-ray imaging only produces two-dimensional images, which may make interpretation of certain pathologies difficult. For instance, when a round lesion is seen in a chest film, it is difficult to ascertain whether the round lesion is in front of or inside the lung. Fortunately this problem may be solved by taking X-ray pictures from different angles, such as from the side.

Computed axial tomography

19.5

As mentioned already, the main limitation of X-ray imaging is its lack of ability to differentiate between different types of soft tissues. Therefore, clinically, it is difficult or nearly impossible to distinguish between adjacent soft tissue organs—such as the muscles from the skin, the liver from the stomach, or the bowel from the bladder—as they all have very similar attenuation to the X-rays. To help overcome this problem, an imaging technique known as **computed axial tomography** (CAT or CT) was developed. The basic principle of a CT scan is to use a computer to reanalyse the attenuated X-rays as they pass through the body and use this data to electronically reconstruct the images of the target organ. Since CT relies on computer reconstructions, it is far more sensitive in distinguishing small differences in the attenuation of the X-rays as they pass through the body. This allows differentiation of different types of soft tissue organs. CT reproduces the images of the body organ using slices that orientate either horizontally or vertically.

The functional principle of CT scans

19.6

■ *Explain how a computed axial tomography (CAT) scan is produced*

A photograph of a typical CT machine is shown in Figure 19.10 (a) and a schematic diagram of the machine is shown in 19.10 (b). The patient who is to have the scan lies on a table and is moved slowly into the gantry. As the section of the body to be scanned passes through the gantry, cross-sectional images (slices) of it will be produced.

The gantry is the doughnut-shaped structure that mounts an X-ray tube. The X-ray tube produces a beam of X-rays that pass through the body and attenuate as they encounter different types of tissues. Finally, the attenuated X-rays arrive at the detector on the other side of the gantry, which measures the intensity of the arriving X-rays. From this, the level of the attenuation of the X-rays can be calculated and the data is fed to the computer for analysis. In a first generation CT machine, the X-ray tube is made to rotate one degree at a time with a corresponding movement of the detector to the opposite direction, and the same process is repeated until the entire 180 degrees are completed. See Figure 19.10 (b). Every time the X-ray tube rotates, the X-rays will pass through the body at a slightly different orientation; this is essential for generating all the necessary data for the image reconstruction of the slice of the body (section) being scanned.

Figure 19.10 (a)
A CT machine

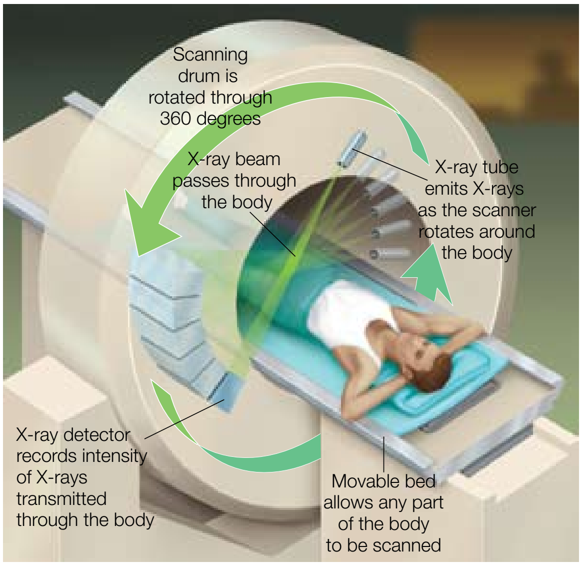


Figure 19.10 (b)
A schematic drawing of a CT machine

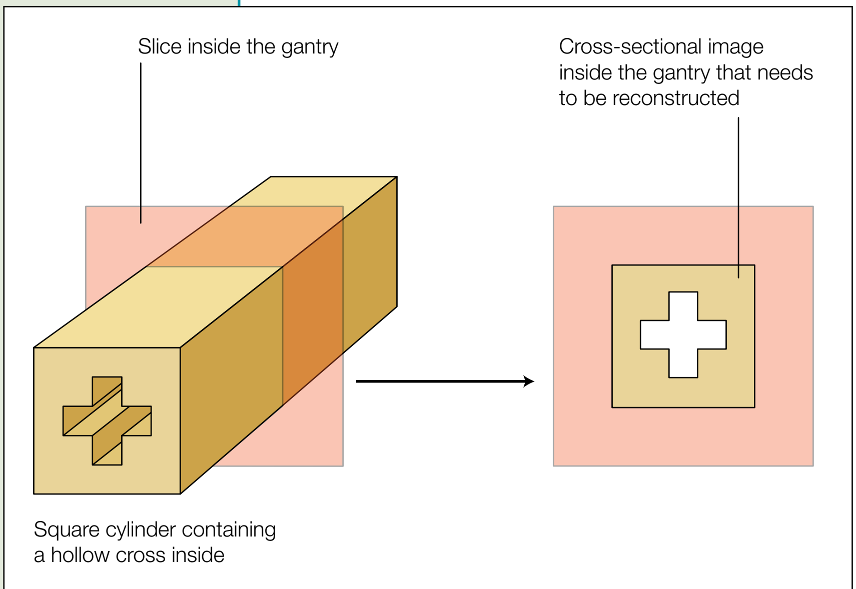


Figure 19.11 A square cylinder containing a hollow cross

As the patient is moved progressively through the gantry, many other slice images of the body section are created.

In order to understand how a CT scan is able to reconstruct a slice image of the body from the X-ray attenuation data collected by the detector, one may consider a simple scenario as shown in Figure 19.11. Figure 19.11 shows a square cylinder that has a hollow cross inside. Imagine if this square cylinder were placed inside the gantry: the CT would have to reconstruct the cross-sectional image of this square cylinder for the slice that is inside the gantry—a two-dimensional cross.

Inside the gantry, X-rays are made to pass through the body slice being scanned from different angles (the entire 180 degrees). When these X-rays are detected and analysed, they will all be resolved into two vector components, one coming vertically down and the other horizontally across. For the cylinder, assume the X-rays will be analysed in five vertical columns and five horizontal rows (this is grossly simplified). Because the solid parts of the cylinder will attenuate X-rays more than the hollow cross and the X-rays coming down vertically through column 1 and 5 will not encounter any hollow parts, these two columns will have the maximum attenuation and will be assigned the value ‘5’. On the other hand, the X-rays that pass through the middle (column 3) will encounter the greatest number of hollow parts (3 parts) therefore will be attenuated the least. This column is assigned with an attenuation value of ‘2’ (5 minus 3). A similar principle can be used for the X-rays passing through column 2 and 4: both will be assigned with a value of ‘4’. The same process will apply for the X-rays passing through the horizontal rows. These are summarised in Figure 19.12 (a). The next step is to add up the values of the X-ray attenuation so that each little square will have a number that is the sum of the values assigned to the vertical column and the horizontal row that make up this square. This is shown in Figure 19.12 (b). Note that the little squares represent the pixels of CT images, which are the smallest image-forming units. A typical CT will have 512 × 512 pixels for each image. Finally, colours are assigned to these squares. In this case, if black

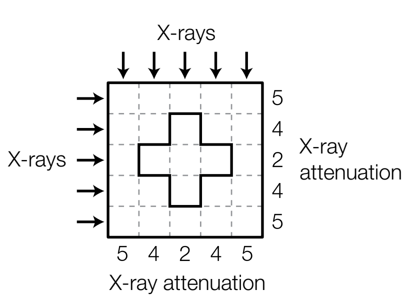


Figure 19.12 (a) The resolved X-rays passing vertically down and horizontally across the square cylinder and are analysed in five columns and five rows

10	9	7	9	10	5
9	8	6	8	9	4
7	6	4	6	7	2
9	8	6	8	9	4
10	9	7	9	10	5
5	4	2	4	5	

Figure 19.12 (b) The values of the columns and rows are added to give each little square a sum value

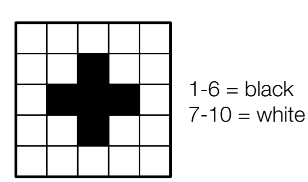


Figure 19.12 (c) Colours are assigned; the hollow cross is reconstructed

is to represent hollowness, then the squares with the value of '1' through to '6' are made black; whereas those with the value of '7' through to '10' are made white to represent the solid part. The result is that a two-dimensional hollow cross is reconstructed, as shown in Figure 19.12 (c).

A real organ will have a more complicated shape compared to the hollow cross, therefore more pixels (more columns and rows) are required. Although the above example illustrates the principle of reconstructing a cross-sectional image by the computer, reconstructing images of real body organs requires more data to be processed. Furthermore, a typical CT scan will produce hundreds of slices, again indicating that the volume of the data needed to be processed by the computer is enormous.

Frequently, CT cross-sectional images are interpreted by a radiologist (a doctor who specialises in reading medical images) who has an extensive knowledge of the anatomy of the body and is able to mentally reconstruct a three-dimensional representation of the body parts. Occasionally, in order to assist the doctor in making more accurate assessment of the anatomy of the body, these horizontal slices may also be added vertically by the computer to electronically recreate three-dimensional images. One example is shown in Figure 19.13. This imaging technique is useful for assessing complex pathologies such as fractures of the facial bones, for which a good reconstruction is based on an accurate knowledge of the pattern of the damage.

Figure 19.13 A three-dimensional CT image

The use of a radio-contrast medium

Radio-contrast materials, like those used for plain X-ray films, can also be used for CT scans to enhance the contrast between tissues, enabling certain organs to be visualised more precisely than without the use of the contrast. Examples include visualising a brain tumour or visualising lymph nodes inside the abdomen.

The modern CT machines

For first generation CT machines, as described above, the image formation process was extremely slow. This is because the X-ray tube needed to rotate one degree at a time and pause after each rotation to emit and detect the X-rays. The speed of the machine was further limited by the speed the computer was able to analyse the data and reconstruct the images. Modern CT machines are much faster. Most hospitals use third generation CT machines, which employ an X-ray tube that emits a fan-shaped X-ray beam. Such a beam will pass through a wider sector of the body and hence enable fewer rotations of the X-ray tube to complete the scan. Sixty-four detectors are placed on the opposite side of the gantry to receive this fan-shaped X-ray beam simultaneously. Furthermore, the gantry also has 64 arrays of these detectors in the longitudinal axis so that 64 slices of the body section can be reconstructed simultaneously with one pass of the X-rays. (The X-rays therefore also have to fan out in the longitudinal axis, hence making more of a cone shape.) The development of fast computer systems enabled more voluminous data handling and more rapid data processing so that the speed

A contrast CT image of the abdomen: note that the bowel lights up as it contains contrast material

of image reconstruction was also greatly enhanced. Modern CT scans are so fast that the patient can be moved through the gantry in a stepless, smooth motion and the images are produced at the same time without any delay.

19.7

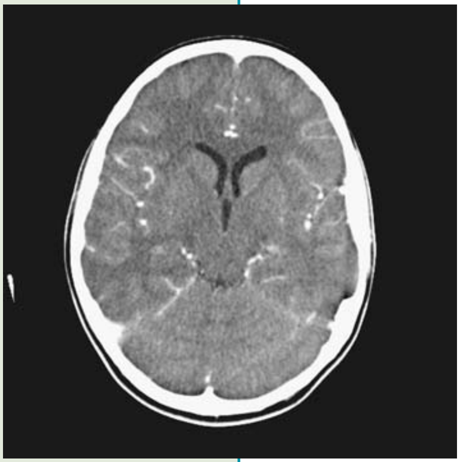
SR

A simple atlas of the human brain

The clinical uses of CT scans

- ***Describe circumstances where a CAT scan would be a superior diagnostic tool compared to either X-rays or ultrasound***

CT scans are used in a variety of clinical settings to visualise diseased body parts. Indeed, with the appropriate use of a radio-contrast medium, CT scans can help to diagnose almost all problems. CT scans are commonly used for scanning the following.



A horizontal slice CT image of a normal brain

Brain

A CT scan, unlike a plain X-ray film, is good for visualising both the skull bone and the brain itself. The brain and its structure can be visualised well by CT because its computer system is able to analyse the small differences in the attenuation of the X-rays as they pass through brain substances. These differences are otherwise too small to be differentiated on a plain X-ray film.

CT scans are used for diagnosing strokes (when the brain is injured by having been deprived of blood flow or by a haemorrhage from a blood vessel that supplies the brain). It is also good for detecting brain abscesses and brain tumours.

Recall that the adult brain cannot be visualised using ultrasound. This is because at the bone and tissue interface, significant amounts of ultrasound waves are reflected, leaving only a small proportion to reach the brain.

A horizontal slice CT image showing bleeding compressing the brain (arrow)

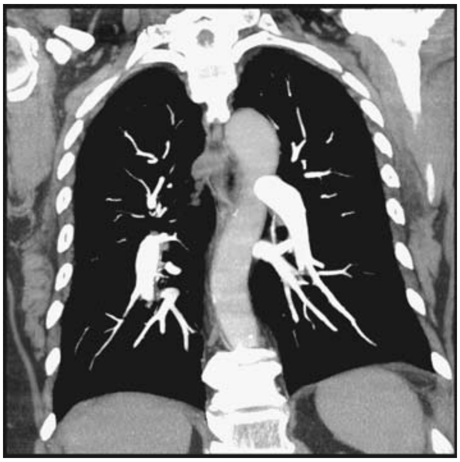
Lungs

Although plain X-ray films are adequate (in most cases) in diagnosing simple lung problems, more subtle lung problems are better assessed using CT scans. Examples of these include pulmonary fibrosis (scarring of the lungs) and lung malignancies. Also, CT scans are more accurate in measuring the size of any abnormal fluid collections around the lungs (pulmonary effusion) compared to the plain X-ray films. This is important as it guides treatment.

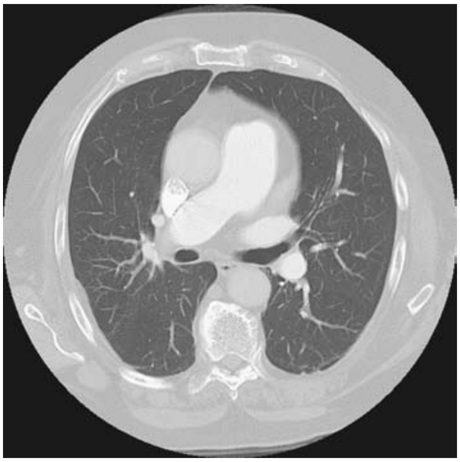
Ultrasound cannot be used to assess lung problems. Why is that? (See Chapter 18.)

Abdominal organs

CT scans are frequently used for examining the digestive system, including the oesophagus, stomach, small bowel, large bowel, liver, gall bladder, spleen, pancreas, kidneys, bladder, and so on. The use of the contrast material is not essential as the computer can easily analyse small differences in the attenuation of the X-rays as they pass through various organs. Nevertheless, the use

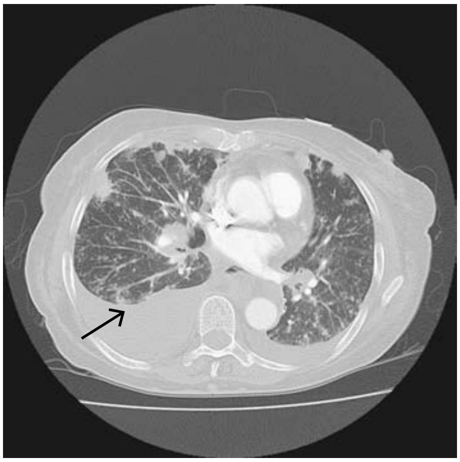


A coronal section of a normal chest



A cross-section of a normal chest

A coronal section of an abnormal chest



A cross-section of an abnormal chest showing fluids collecting around both lungs

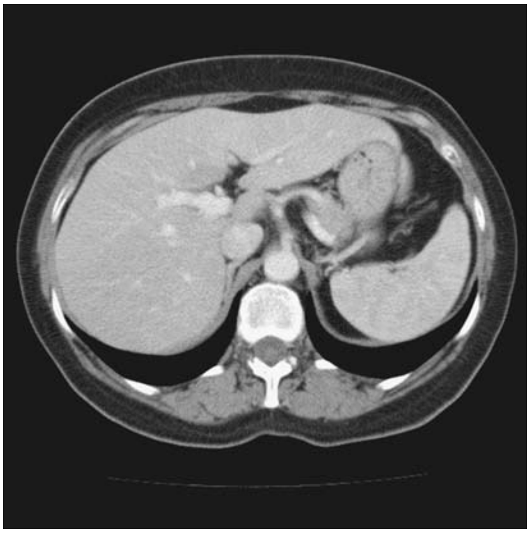
of contrast will further enhance the view of certain organs or certain diseases. Some of the common intra-abdominal illnesses that can be diagnosed quite accurately using CT are malignancies, diverticulitis (a condition that involves infection of abnormal pockets protruding from the wall of the large bowel), appendicitis, pancreatitis (inflammation of the pancreas), and many more. Due to the ability to differentiate soft tissues and the high level of detail CT images can provide, they have replaced plain X-ray imaging for diagnosing almost all gastrointestinal pathologies.

Soft tissues

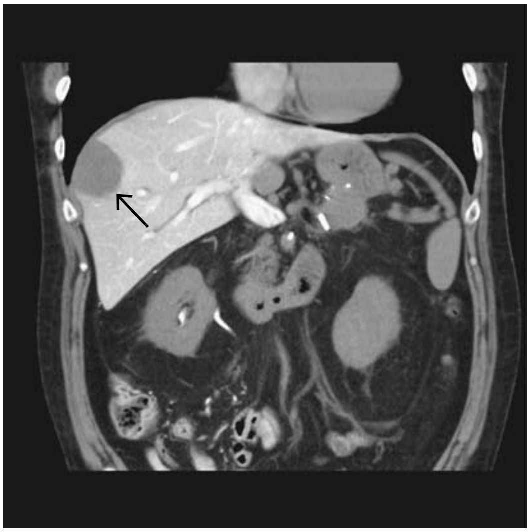
CT scans may be used to detect muscle tears as well as tendon or ligament ruptures. Recall that soft tissues cannot be visualised using plain X-ray films, due to their inability to detect small differences in the attenuation of the X-rays.

Although ultrasound is able to visualise soft tissues, they produce low-resolution images that can make the interpretation of the images a challenging task. Nevertheless, ultrasound is cheap and does not expose the patient to the harm of X-rays. They are suitable for diagnosing soft tissues that are superficial and do not have complex structural details. For deeper and more complicated soft tissue injuries, CT scans are a little more superior. However, as discussed in Chapter 21, magnetic resonance imaging is the investigation of choice for soft tissue injuries.

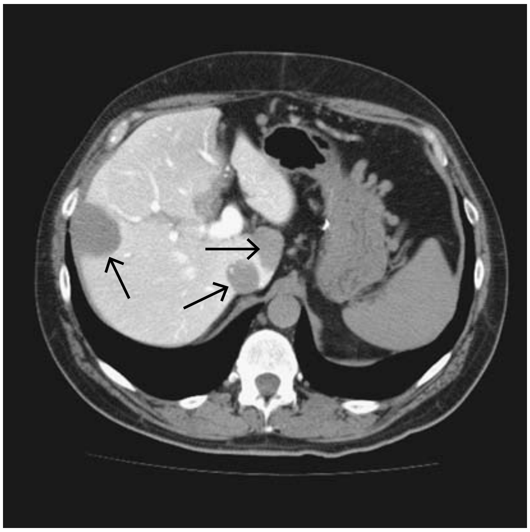
A coronal section of a normal abdomen



A cross-section of a normal abdomen



A coronal section of the abdomen showing a tumour in the liver (arrow)



A cross-section of the abdomen, showing three tumours in the liver (arrows)

The uses of CTs are vast and CT scans are now employed in many hospitals as the preliminary imaging technique to establish a diagnosis. The only exception is when the diagnosis can be established accurately either using ultrasound scans or plain X-ray films, which are cheaper and safer to use.

Evaluation of the use of CT scans

- Because they can differentiate between different types of organs and tissues, CT scans are used as a standard diagnostic tool to establish an initial diagnosis for almost all body systems.
- CT scans are more expensive compared to ultrasound scans and plain X-ray films, thus a cost-effective consideration needs to be employed when using them. Nevertheless, CT scans are still considerably cheaper compared to other imaging methods discussed later.
- A CT scan exposes the patient to more X-rays (approximately 40 times) compared to a plain X-ray film, and thus is more likely to do harm. CT scans are absolutely not advised for pregnant women and should not be repeated too often.

Observing and comparing CT scans

- ***Gather secondary information to observe a CAT scan image and compare the information provided by CAT scans to that provided by an X-ray image for the same body part***

You are asked to compare images of a body part produced by a CT scan to that produced by (plain) X-ray imaging. Besides comparing images provided in this text, you may also obtain your own images. Ask your GP whether you can see plain X-ray films and CT scans performed for the same body part (same disease). Your relatives may also have had both of the scans done for a particular body part (disease).

After obtaining these images, compare and comment on the following:

- Features of each type of images: their colour, resolution and contrast.
- X-rays produce two-dimensional images of a body part, whereas CT produces many slices (cross-sectional images) of the same body part. Which image type is easier to interpret? What pathologies (if any) are shown in these images?
- Summarise how you can recognise an image as a CT image or a plain X-ray image. A table may be used.

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H12.3 A, B
H12.4 F
H14.1A, C, E, G, H

19.8 Endoscopy

Endoscopy is a medical imaging technique that involves the insertion of an optical fibre camera through either a natural orifice or a surgically created opening to examine the interior of a body part. The greatest advantage of endoscopy is that it offers a direct view of the interior of the body parts without the need to surgically expose them (cutting the body parts open). Simple procedures (commonly called key-hole surgeries) can be carried out at the same time as the viewing, so endoscopy differs from other imaging methods as it is both diagnostic and therapeutic. In order to understand how endoscopes work, some basic properties of light need to be discussed.

Refraction

Refraction is a wave property. Although refraction applies to all waves, it will only be discussed for light (EMRs) in this section.

SR

Simulation: Reflection and refraction

Definition

Refraction occurs when light travels from one medium to another and the change in its speed as it is doing so is accompanied by a change in its direction.

The law of refraction: qualitative

Qualitatively, the law that governs the refraction of light may be summarised as:

When light travels from a less dense medium to a denser medium or when its speed reduces as it passes from one medium to another, its pathway bends towards the normal. See Figure 19.14 (a).

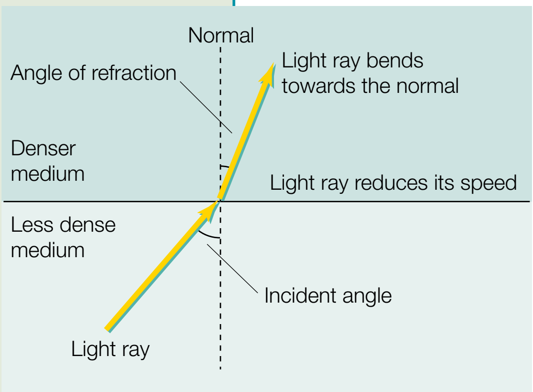


Figure 19.14 (a) Refraction of light: when light travels from a less dense medium to a denser medium or when its speed reduces, it bends towards the normal

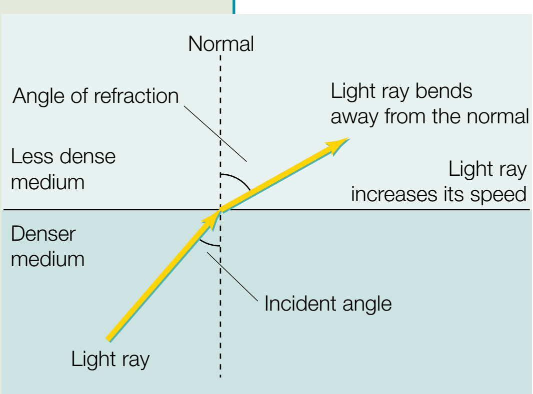


Figure 19.14 (b) Refraction of light: when light travels from a denser medium to a less dense medium or when its speed increases, it bends away from the normal

When light travels from a denser medium to a less dense medium or when its speed increases as it passes from one medium to another, its pathway bends away from the normal. See Figure 19.14 (b).

NOTE: Both the incident angle and the angle of refraction are measured from the normal, not from the interface between the two media.

Importantly it is not the change in density of the media that determines the direction of bend of the wave; rather, it is the change in speed of the wave. This is evident when one studies the refraction of a sound wave, which bends away from the normal when it travels from a less dense to a denser medium because its speed increases!

Critical angle

As light travels from a denser to a less dense medium, its speed increases and subsequently bends away from the normal. Recall from the Preliminary Course that the ratio of the sine value of the size of the incident angle to the sine value of the angle of refraction is a constant (termed the refractive index). Consequently, when the size of the incident angle is increased, there will be an accompanying increase in the size of the angle of refraction. The angle of refraction will eventually reach 90° as the incident angle continues to increase in size. At this point the incident angle is referred to as the **critical angle**. This is illustrated in Figure 19.15.

Definition

The **critical angle** is the size of the incident angle such that when refraction occurs, the angle of refraction is 90° to the normal.

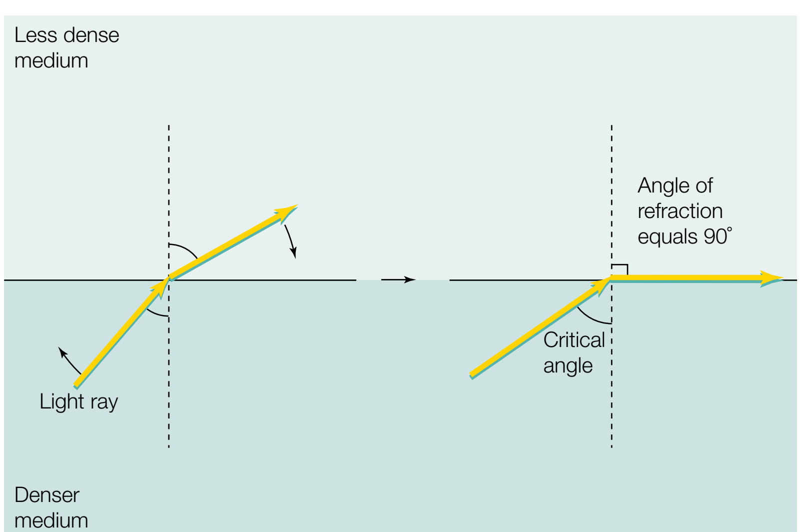


Figure 19.15 Critical angle

Total internal reflection

Following from the previous section, if the incident angle is to increase further, the angle of refraction will increase beyond 90º, that is, beyond the interface between the two media such that the light now reflects back into the first medium and total internal reflection is said to have occurred. This is shown in Figure 19.16.

SR

Animation: Total internal reflection

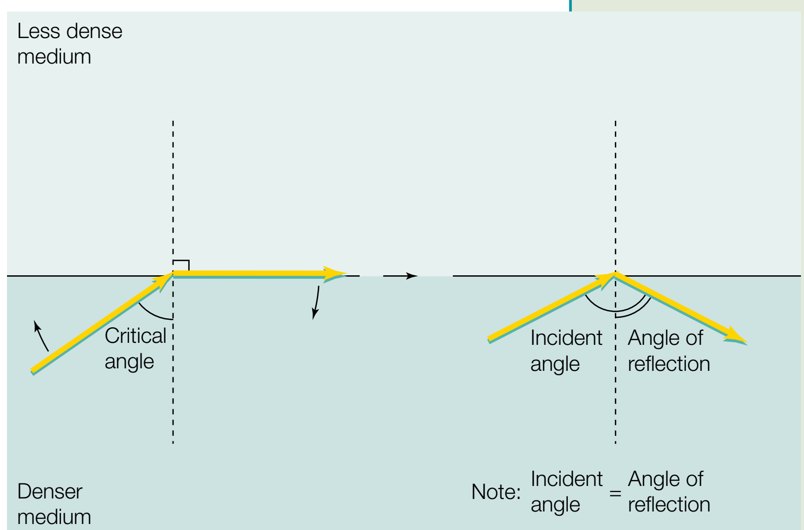
Definition

Total internal reflection occurs when the incident angle is greater than the critical angle such that the angle of refraction now exceeds 90º. As a consequence, no light will enter the second medium and all are reflected at the boundary back into the first medium.

Although total internal reflection is unusual, as the reflection is caused by a non-reflective surface and arises as a consequence of the initial refraction, it still obeys the law of reflection:

1. the incident angle equals the angle of reflection
2. the incident wave and the reflected wave both lie in the same plane.

Figure 19.16 Total internal reflection



Optical fibres

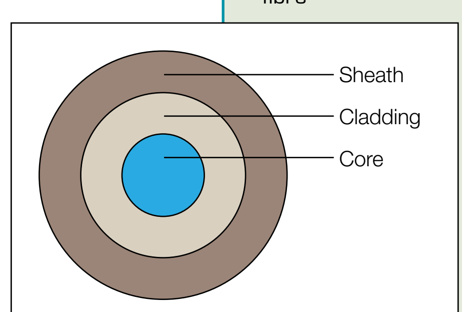
19.9

■ *Explain how an endoscope works in relation to total internal reflection*

One of the most useful applications of total internal reflection is optical fibres. Optical fibres are used in many areas, such as in telecommunications (cable Internet), and importantly for medical imaging. They form the essential components of an endoscope.

A typical optical fibre consists of a core, a cladding and a sheath arranged concentrically (with the core as the innermost structure) as shown in Figure 19.17 (a). A longitudinal view of the optical fibre is also shown, Figure 19.17 (b). The way the optical fibre operates is that the core is made to be denser compared to the cladding (more correctly a higher refractive index) and is engineered so that when light enters the core, it will always undergo total internal reflection. (The core and cladding are engineered to have a very small critical angle.) This allows the light to be bounced inside the core and it consequently propagates from one end of the fibre to the other. This

Figure 19.17 (a) A cross-sectional view of an optical fibre



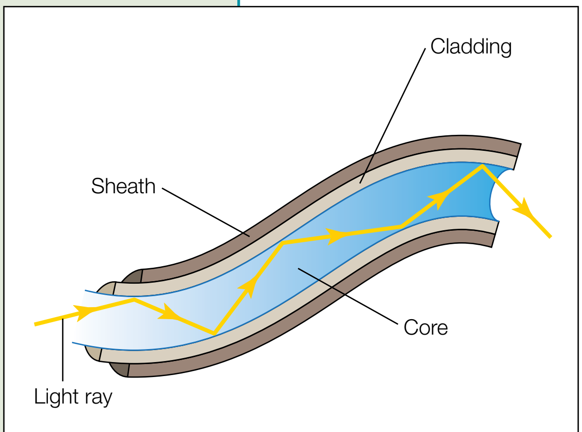


Figure 19.17 (b) A longitudinal section of the optical fibre showing the propagation of light by total internal reflection

is shown in Figure 19.17 (b). The sheath shields off light in order to minimise the entry of light from the external environment, which may lead to interference.

Importantly, the transmitted light carries information. If flashes of light are used and a light flash is interpreted at the receiving end as a '1', and no flash is interpreted as a '0', then digital data is transmitted. This forms the basis of cable internet. For digital data transmission, infrared is often used.

Continuous (analogue) visible light may also be transmitted. This transmits visual images that can be either viewed directly or be displayed on TV (like a video camera). This forms the essential part of an endoscope.

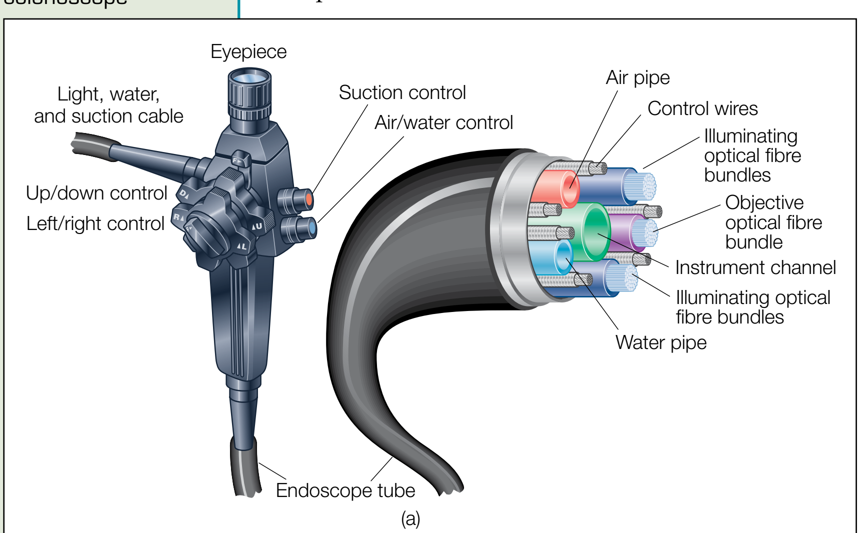
19.10 Endoscopes

- ***Explain how an endoscope works in relation to total internal reflection***
- ***Discuss differences between the role of coherent and incoherent bundles of fibres in an endoscope***

There are many different types of endoscopes with different uses. Different endoscopes have different designs. A typical endoscope, used for examining the large bowel lumen (colonoscope), is described here to illustrate the basic structure and principle of an endoscope.

A typical colonoscope consists of a pair of **illuminating optical fibre bundles**, a single **objective optical fibre bundle**, an air and water channel and an instrument channel. All are enclosed in a shaft (tube), made from plastic, that contains a metal frame. The shaft is strong but at the same time flexible due to the metal frame, and the plastic makes it resistant to bowel secretions. The length of the shaft may be 1–2 m. The length of the shaft will depend on the endoscope's purpose. A controller is attached to one end of the shaft (the proximal end), which is held by the doctor. The controller allows the doctor to manipulate the shaft so that it is able to be bent as it passes through the large bowel. The controller also controls water and air that pass through the scope, and contains an opening for the instrument channel. All are shown in Figure 19.18. The free end (the distal end) is inserted into the target organ to conduct the examination, in this case, the anus.

Figure 19.18 A typical colonoscope



The illuminating optical fibre bundle: Incoherent bundle

The illuminating optical fibre bundles transmit light from an exterior source into the organ being examined. These bundles are classified as incoherent bundles.

Definition

An **incoherent bundle** is one in which individual optical fibres are randomly placed alongside each other so that the fibres are not in the same relative positions at the ends.

A schematic drawing of an incoherent bundle is shown in Figure 19.19. The consequence of the fibres not being in the same relative positions at the two ends is that light patterns entering one end of the bundle will be distorted as they arrive at the other end. However this will not matter for illumination as its sole purpose is to carry light into the interior of the organ. Hence, whether the light pattern is distorted or not will not affect the outcome.

Usually an incoherent bundle contains up to hundreds of individual fibres and the fibres are thick in order to maximise the transmission of light. Incoherent bundles are also cheaper to manufacture.

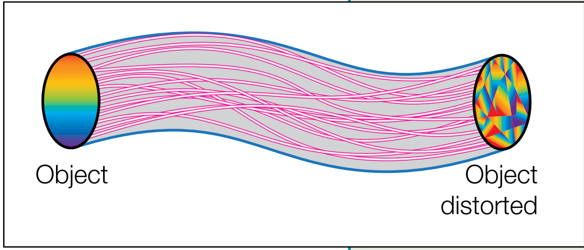


Figure 19.19 An incoherent bundle

The objective optical fibre bundle: Coherent bundle

The purpose of the objective optical fibre bundle is to carry back the visual images of the organ's interior to the doctor or the video monitor for viewing. Such a bundle is classified as a coherent bundle. Lenses are placed at the ends of the bundle to produce focused images. A schematic drawing of a coherent bundle is shown in Figure 19.20.

Definition

A **coherent bundle** is one in which the individual optical fibres are kept parallel to each other throughout their length, so that they are in the same relative positions at the ends.

The importance of coherence for the objective bundle is that the light beams that are carrying back the visual images need to be kept in the same relative positions when travelling through the individual fibres, so that images will not be distorted when reaching the observer. If an incoherent bundle is used in this case, the images will be 'jumbled' so that they cannot be interpreted. Compare Figure 19.20 to Figure 19.19.

The fibres for a coherent bundle are thin and thousands of fibres are included in a bundle in order to improve the resolution of the images produced. A coherent bundle is more expensive than an incoherent bundle as a result of higher technical difficulty in manufacturing.

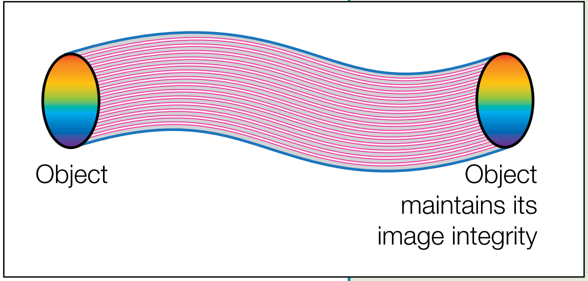


Figure 19.20 A coherent bundle

Air and water channel

The air channel, as its name suggests, provides a passage through which air can be pumped into the organ to cause inflation so that the organ can be examined more easily. Water can be pumped through the same or a separate channel to gently flush the organ lumen to help with the examination. It can also be used to wash the objective lens when it fogs up.

Instrument channel

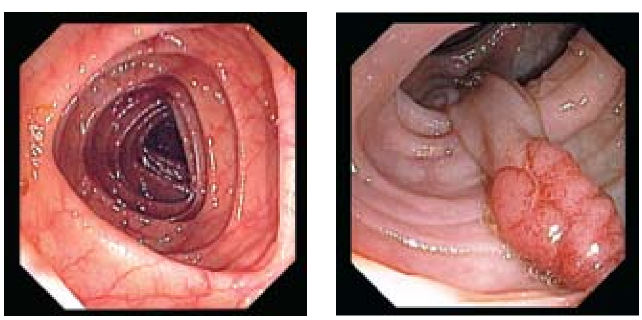
The instrument channel can be used to insert various instruments to perform small operations while the endoscope is inside the organ. The instruments include forceps, biopsy scissors, diathermy, and others. Biopsy of tissue samples, resection of small polyps and using diathermy to stop bleeding can all be performed easily.

19.11 The uses of endoscopes

- ***Explain how an endoscope is used in:***
  - ***observing internal organs***
  - ***obtaining tissue samples of internal organs for further testing***

Depending on the particular use of the endoscope, the structure of the endoscope can be quite different. For instance, an arthroscope (an endoscope that is used to view the inside of a joint) does not have an instrument channel so instruments, if needed, have to be inserted through another surgical incision into the joint. Also, an arthroscope has a rigid shaft with a much smaller diameter.

Some common endoscopes used clinically are described below.



Colonoscope, images showing the lumen of a normal large bowel (left) and abnormal (right) the lumen of the large bowel showing a polyp (abnormal growth)

SR

Video: colonoscopy

Colonoscopes

A colonoscope is used to examine the lumen of the large bowel. The patient is given a light sedation so that he or she remains comfortable during the examination. The scope is then passed slowly through the anus and is advanced until the junction between the large bowel and small bowel is reached. The scope can be used to view pathologies such as tumours and polyps of the large bowel, as well as inflammation of the bowel wall in certain diseases. Biopsies of tissues to further confirm a particular diagnosis are frequently performed.

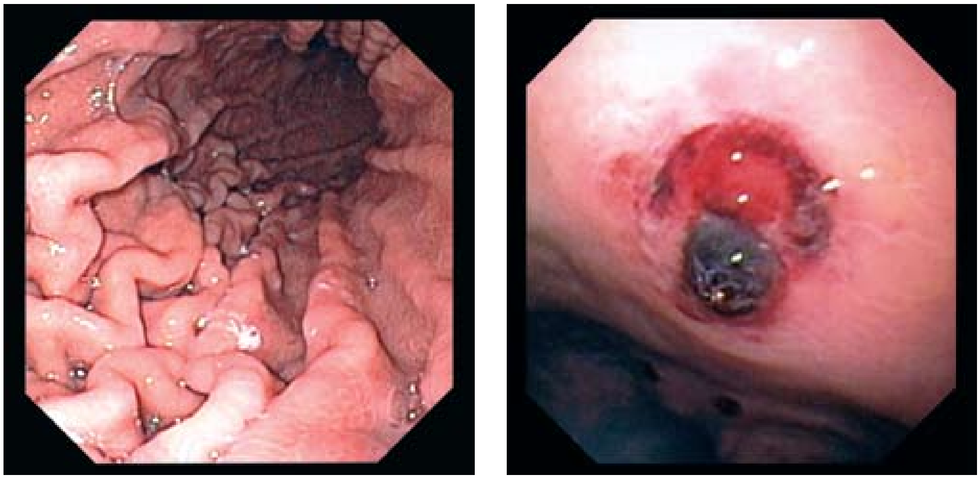
An arthroscope

SR

Video: arthroscope

Arthroscopes

An arthroscope is inserted via a small surgical incision into the joint after the patient has been given a general anaesthetic or sedation. The scope can view joint pathologies such as arthritis, torn ligaments or tendons. If extra surgical portals are created, instruments can be inserted to perform arthroscopic surgeries. A common procedure is the repair of ligaments.



Gastroscope showing normal (left) and abnormal (right) digestive tract (ulcer)

Gastroscopes

A gastroscope is structurally similar to a colonoscope. After sedating the patient, the scope is passed into the patient's mouth. It then passes down the oesophagus to reach the stomach, the duodenum and sometimes early parts of the small bowel. The scope can diagnose tumours and polyps, ulcers and bleeding spots within the lumen of the oesophagus, the stomach and early parts of the small bowel. Biopsies are often taken to confirm the diagnosis. Other endoscopic procedures include ceasing acute bleeding from a peptic ulcer by injecting chemicals down the scope, and resection of polyps.

SR

Video: gastroscope

Laparoscopes

A laparoscope is a rigid and short endoscope that is inserted into the patient's abdomen via a small incision through the umbilicus (the belly button) under general anaesthetic. Unlike a gastroscope or a colonoscope, which only examines the luminal aspect of the bowel, a laparoscope visualises the exterior aspect of the bowel as well as other abdominal organs such as the liver, the gall bladder, the spleen and any other organs that are outside the actual gastrointestinal tract.

Instrument channels are created separately via further incisions through the abdominal wall. Elaborate equipment is available to carry out many different types of operations. These range from small and common operations, such as the removal of the gall bladder (for gallstones) or the appendix (appendicitis) to large operations such as the removal of the stomach and the large bowel (when they are affected by cancer). These operations are conventionally known as **key-hole surgeries**.

SR

Video: laparoscopic surgery

Cystoscopes

A cystoscope is much smaller than other types of endoscopes. The scope is passed through the urethra to reach the bladder and the ureters to diagnose and treat diseases of the urinary tract. Examples include tumours, polyps and stones.

Bronchoscopes

A bronchoscope is passed through the trachea to reach the large then small bronchi. It is the investigation of choice for diagnosing lung cancer as well as obscure infections of the lungs. Again, biopsies and interventional procedures can be done.

Observing endoscope images

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H12.3A, B

■ *Gather secondary information to observe internal organs from images produced by an endoscope*

The materials included in this section give you an opportunity to appreciate the images of the internal body parts provided by various endoscopes. You may wish to collect more images. Also note that endoscopic examinations can be recorded as videos.

How do the endoscopic images differ from images produced by other imaging methods, such as ultrasound, X-rays or CT? Are the endoscopic images easier or more difficult to interpret?

Evaluation of the uses of endoscopes

The invention of endoscopes has revolutionised medical practice. The fact that endoscopes allow a direct view of internal body organs as well as enabling tissue biopsies makes them accurate and reliable imaging methods. Now, although a provisional diagnosis may be made based on CT scans, the final diagnosis or the extent of the disease is often determined after carrying out an endoscopic examination. For instance, bowel cancer may be diagnosed by CT imaging, but in order to determine the pathological nature of the cancer and its spread, a colonoscopy is required.

Endoscopes are considered as only minimally invasive as they are inserted either through natural orifices or small surgical incisions. Before endoscopes were invented, a laparotomy (a vertical cut through the midline of the abdomen to open up the abdominal cavity) may have been performed to establish a diagnosis. Even more important is the invention of endoscopic surgeries. More operations are now done endoscopically. A common example is the removal of a gall bladder (for gallstones) using a laparoscope and associated instruments. The major advantage of a laparoscopic surgery is the lower level of post-operative pain as well as a quicker recovery time. For instance, a patient undergoing a laparoscopic removal of the gall bladder can usually be discharged from the hospital in two to three days with minimal pain and may resume normal daily activities within weeks. For a patient who undergoes a conventional open gall bladder removal (where there will be a large cut under the right ribcage), the hospital stay will be a week and it takes a few months before the patient can return to his or her full functional capacity. Shorter hospital stays and returning to work sooner help to reduce the cost of the disease to an individual and to society.

However, the invasiveness (even minimally) of endoscopes is a downside. Performing an endoscopic examination is classified as a medical procedure rather than imaging as it carries specific risks and the patient needs to consent. For instance, when performing a colonoscope, there is a risk that the bowel may be perforated by the scope, in which case the patient may require an urgent open surgery to repair the perforation.

Lastly, because endoscopes have to be operated by doctors, the cost of endoscopy largely depends on the fees charged by the doctor and can be variable. The results of endoscopic examinations are also largely operator dependent.

Transfer of light by optical fibres

FIRST-HAND INVESTIGATION

PFAs

H3, H5

PHYSICS SKILLS

12.1A, B, D
12.2B

TR

Risk assessment matrix

■ *Perform a first-hand investigation to demonstrate the transfer of light by optical fibres*

The theory of the transmission of light by optical fibres has been described. You are required to perform an experiment to demonstrate the transfer of light by optical fibres. The procedure, safety precautions and some points for discussion are described here.

Aim

To demonstrate the transfer of light by optical fibres.

Equipment and materials

A light source, a ray box, an optical fibre bundle, some paper.

Procedure

1. Obtain a bundle of optical fibres; this may be provided by the teacher (school), or found in old toys or optical fibre cables that are no longer in use.
2. Observe and describe the optical fibre bundle; are the fibres made from plastics or glass? Measure the length of bundle.
3. Obtain a light source; this can be a light bulb placed inside a ray box.
4. Secure the optical fibre bundle onto the light source; this can be done with tapes.
5. Close the room curtains, turn off the room lights and switch on the light source. Ensure no light escapes where the bundle joins the light source.
6. Demonstrate the transfer of light by viewing the light coming through the other end of the bundle. This can be assisted by placing a piece of paper (preferably black) at the end of the bundle.
7. Bend the bundle to various angles to assess whether bending affects the transmission of the light.
8. Coherence of the bundle may be checked. If a particular light pattern can be created at the ray box (for example, a circle or a square shape), see if the same pattern is recreated at the receiving end—on the piece of paper.

Safety precautions

1. Optical fibre bundles that are made from glass may be sharp and may also break. Take care when handling them.
2. Do not look straight into the light source, whether at the ray box or at the receiving end. Intense light may damage the eyes.
3. Ensure careful handling of the electrical appliances. Do not handle them with wet hands.
4. If laser is to be used as a light source, careful supervision is required. No students are allowed to handle the laser source.

Points for discussion

1. If both plastic and glass optic fibres are to be used in the class, describe their differences in appearance and the ability to transfer light.
2. Does the bending of the bundle affect the transmission of light? If so, at what angle?
3. Are the fibres coherent or incoherent?
4. Describe qualitatively the resolution of the image produced on the receiving paper.

CHAPTER REVISION QUESTIONS

1. (a) What is the EMR spectrum?
   (b) What is the position of X-rays in this spectrum?
2. (a) Define 'hard' and 'soft' X-rays.
   (b) Which type of X-rays are best used for medical imaging and why?
3. Describe how X-rays are produced for medical imaging.
4. What is the principle behind using X-rays to produce images of body parts?
5. Bob was a high school student who had a fall when he was playing basketball. He went to his GP pointing to a painful elbow. His GP performed a quick examination and sent him to have a plain X-ray of the elbow.
   (a) What was the purpose of ordering the X-ray?
   (b) Why didn't the GP order an ultrasound of the elbow?
6. A 40-year-old woman presents to the emergency department with high fever, severe shortness of breath and chest pain. A plain X-ray film of the chest is ordered. What information maybe obtained with such an investigation?
7. Describe two advantages and two disadvantages of X-ray imaging.
8. CT scans also use X-rays to produce images of the body parts; however, they are superior to plain X-rays films. Why?
9. Describe in detail how CT scans are able to use X-rays to produce slice images of the body parts.
10. David presented to his GP with intermittent headaches that had lasted for over a year. His GP ordered a CT scan of the brain (head).
    (a) Name one problem of the brain that can be revealed by a CT scan.
    (b) Why would a CT scan be better than X-ray imaging in detecting brain diseases?
    (c) Could ultrasound be used to try to reveal the brain problem in this case?
11. CT scans have almost replaced X-ray imaging for diagnosing abdominal illnesses.
    (a) What makes CT scans superior to X-ray imaging in detecting abdominal illnesses?
    (b) Can ultrasound be used for diagnosing abdominal illnesses?
12. (a) Describe briefly two other clinical uses of CT scans.
    (b) Describe one disadvantage of CT scans.
13. (a) Describe the law of refraction of light.
    (b) Define the term 'critical angle'
    (c) Define 'total internal reflection'.
14. Describe in detail how the property of 'total internal reflection' helps the transmission of light through optical fibres.
15. Compare the differences between a coherent and incoherent optical fibre bundle.
16. John was a 60-year-old man who was provisionally diagnosed to have colon cancer based on the images provided by an abdominal CT scan. The doctor advised him to have a colonoscopy.
    (a) What was the purpose of performing a colonoscopy?

(b) What is the role of the water and air channel in a colonoscope?
(c) What is the role of the instrument channel in a colonoscope?

17. Name two types of endoscope (other than colonoscope). For each, describe:
(a) how the scope is inserted into the body
(b) what organs or body systems the scope is able to view
(c) what pathologies can be detected using the scope

18. (a) When doctors propose a 'key-hole surgery to remove the gall bladder', what do they actually mean?
(b) What are the advantages of performing key-hole surgeries for certain illnesses compared to the conventional open surgeries?

19. Describe one disadvantage of using endoscopes.

SR

Answers to chapter revision questions