CHAPTER 33

Medical Physics

INTRODUCTION 33.1

Discoveries in physics have played a major role in the development of medicine, especially those branches of medicine that are concerned with the use of radiant energy and nuclear isotopes in the diagnosis and treatment of disease. Improvements in microscopy techniques, such as the higher resolution of electron based microscopes, have resulted directly from the practical applications of theoretical discoveries in quantum physics.

Ever since the Nobel prize-winning discovery of the X-ray by Bavarian physicist Wilhelm Conrad Roentgen in 1895, when he produced the first X-ray of his wife's hand, diagnostic radiology or medical imaging has improved in its ability to photograph and record the internal anatomy and physiology of the human body and those of other animals. Diagnostic radiology is the imaging and analysis of both the normal anatomy and physiology of the body as well as possible abnormal effects due to disease or injury. It is usually carried out using X-ray radiographs, tomographs or computerised axial tomographs (CT scans), but other diagnostic techniques such as ultrasonics, magnetic resonance imaging (MRI), or positron emission tomography (PET) are becoming widespread.

The radiologist uses direct observation of the image obtained or extra detail can be sought with the use of various contrast media that are administered to the patient just before the radiology. Examples include upper gastrointestinal examinations (GI series), intravenous pyelograms (IVP) for the kidney and bladder, barium enemas for colon examinations, arthrograms for skeletal joints and myelograms or angiograms for the spinal cord and blood lymph vessels. These procedures allow the radiologist to record movements of organ systems internally as the contrast material flows through them in real time. The image is viewed directly on a radiation-sensitive screen (fluoroscopy), computer monitor or by recording onto videotape.

Australia possesses many nuclear medicine departments in hospitals and private facilities that use a range of medical radioactive isotopes. These isotopes are produced mainly by neutron bombardment in reactors such as at the Australian Nuclear Science and Technology Organisation (ANSTO) at Lucas Heights in Sydney. The cyclotron particle accelerator device is also used to produce short-lived isotopes, at places such as the National Medical Cyclotron (NMC) at ANSTO and the Cyclotron and PET Centre at Melbourne University's Austin Hospital and School of Physics. These facilities provide isotopes for therapeutic radiology, which is the treatment of malignant disease with ionising radiation in conjunction with drug therapy, hyperthermia and psychological counselling.

Medical physicists are those specialists who work with radiologists, oncologists, physiologists and radiographers in providing numerous practical applications of physics in the medical sciences. The understanding of basic physical principles is a necessary prerequisite for all these fields of study. In this chapter let us briefly examine the underlying principles of these diagnostic and therapeutic tools. You may need to revise previous chapters on optics, electromagnetism, quantum physics and nuclear physics.

33.2 MICROSCOPY TECHNIQUES

A microscope's resolution, or ability to distinguish small detail in a specimen, is limited by the wavelength of the light used to illuminate the specimen. In an electron microscope (EM) a beam of electrons accelerated by a high voltage (50 kV) is used instead of visible light. The de Broglie wavelength of these electrons is about 100 000 times shorter than that of light photons and so an electron microscope greatly increases the possible resolving power. Modern **transmission electron microscopes** (TEM) can resolve details down to about 0.2 nm, compared with the best optical microscopes, which resolve down to about 200 nm, with magnifications up to ten million times. The limitation for the TEM is the ability of the electrostatic and magnetic lenses to maintain good focusing. Electron microscopes need the electron beam travelling through a vacuum in order to prevent scattering by air molecules. (See Figure 33.1.) The first types were built in the 1930s.

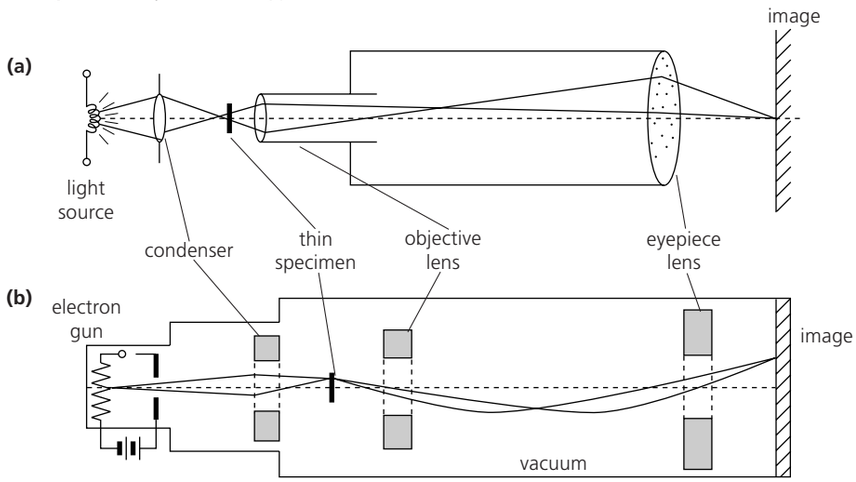


Figure 33.1
Comparison of a light microscope **(a)** with an electron microscope **(b)**.

A newer instrument is called a **scanning electron microscope** (SEM) and uses a well focused beam of electrons to scan the surface of a specimen. The first practical SEM was built in 1970 by the British-born American physicist Albert Victor Crewe. The instrument is capable of producing three-dimensional images and is not really a microscope at all. The spot beam is scanned backward and forward across a specimen by the scanning magnetic field. The incident electrons cause the ejection of secondary electrons with energies typically of a few electron-volts, which are collected to form a cathode ray tube (CRT) control grid current, as shown in Figure 33.2. The sweep or timebase of the CRT is in synchronisation with

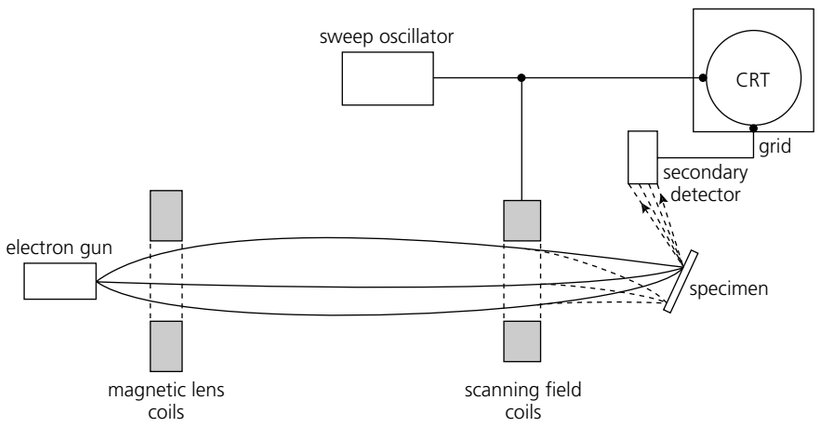
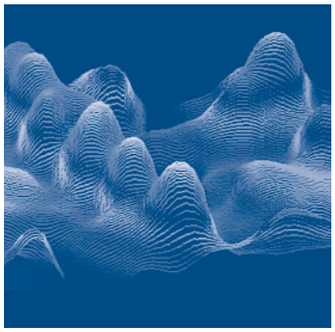


Figure 33.2
Scanning electron microscope.

the scanning beam, and the variations in electron collector current control the CRT sweep beam brightness. The specimen is usually placed at between 30° and 60° to the incident electron beam to improve secondary ejected electron current. The resolution of an SEM is less than for a TEM, with useful magnifications extending to about 50 000 times. With an SEM, thin slices of specimen are not needed as with a TEM, with even whole living specimens able to be observed. In certain circumstances, X-rays produced due to electron collisions can be used to obtain an elemental analysis of the specimen as well. The instrument is then referred to as an **electron probe microanalyser**.

In 1986 the Nobel prize for physics was shared between Ernst Ruska, for his design of the first TEM in the 1930s, and Gerd Bennig and Heinrich Rohrer of the IBM research laboratory in Zurich, Switzerland, for designing a new kind of SEM called the **scanning tunnelling microscope** (STM). The device relies on the quantum tunnelling effect between a scanning metal tip probe and the surface of the specimen. As the probe is moved over the surface, the flow of tunnelling electrons is kept constant by varying the height of the probe above the specimen's surface. These fluctuations in height are used to produce topographical line scans from which 3D images can be constructed. Superconducting magnetic levitation principles are used to control the height of the probe. Bennig and Rohrer were able to obtain 10 angstrom separations with their first designs. Photo 33.1 is an STM image of the oblique surface of a crystal of tantalum diselenide obtained by Professor Dan Haneman at the University of New South Wales, showing the outer electron charge contours of the lattice array of atoms.

Photo 33.1
A scanning tunnelling micrograph.



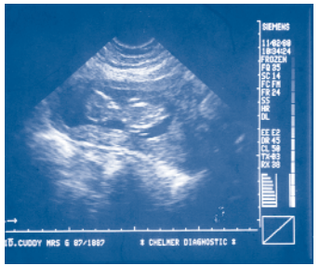
The most recent variation of the scanning probe microscope is called the **atomic force microscope** (AFM). The atomic force microscope does not use a tunnelling current, so the sample does not need to be able to conduct electricity. As the probe in an AFM moves over the surface of a sample, the electrons in the metal probe are repelled by the electron clouds of the atoms in the sample. As the probe moves along over the sample surface, the AFM adjusts the height of the probe to keep the force on the probe constant. An electronic sensing mechanism records the up-and-down movements of the probe, and feeds the data into a computer, which then constructs a three-dimensional image of the surface of the sample.

ULTRASOUND 33.3

Sound waves above the human audible frequency range, usually 20 kHz, are called **ultrasonic waves**. Modern ultrasonic generators can produce frequencies up to several gigahertz by transforming alternating voltages or currents into mechanical oscillations, through the use of **piezoelectric** crystals.

Ultrasonic waves have long been used by living organisms, such as bats and dolphins, for echo location, and similar sonar devices are used for underwater detection and communication by submariners and boaties. In physics and engineering, ultrasonics can be used in determining properties of matter, such as compressibility and elasticity, or for fault detection in industrial materials, such as sheet metal or cast components. High vibration rates caused by ultrasonic blasting is used to clean jewellery, produce photographic emulsions and even to homogenise milk. Ultrasonics in the gigahertz range can be used to produce an ultrasonic microscope able to resolve detail to about one micron.

Photo 33.2
Foetal ultrasound image.



In the medical field, ultrasound is used as a therapeutic tool to repair damaged tissue or to treat conditions such as bursitis, arthritis or muscular damage. These applications require the ultrasound probe to produce localised heating or diathermy as a result of tissue resistance to the transmission of the waves.

Ultrasound has been used to great advantage in destroying embedded kidney stones, reducing them to small fragments that can be easily removed by catheter or passed in the urine. As a diagnostic tool, ultrasound is often more revealing than X-rays in showing the subtle density differences in cancerous tissues. It is nowadays used widely to produce foetal images from the uterus. (See Photo 33.2.) Foetal ultrasound examination was first used by Dr Ian Donald of Glasgow, Scotland, in the early 1950s. The piezoelectric crystal is housed in

a hand-held transducer unit pressed against the skin, using a surface gel, over the organ or part of the body being imaged. A narrow fan-shaped beam of 5 MHz ultrasound waves penetrates the surface and is partially scattered and absorbed. Reflected waves received by the transducer unit are again converted to electrical signals and sent to a computer for conversion to a two-dimensional video image in real time. Pure fluids in the body reflect very little sound, so a fluid image is black on the ultrasound scan. The ability of tissues to reflect sound waves to various degrees is called the tissue **echogenicity**. Tissues such as fatty masses and liver tissue image as white or light grey because of their high reflectivity, whereas tissues such as breast lymphoma image as dark grey because of their low reflectivity. Using high intensity, very fine ultrasonic beams, a surgeon can produce an ultrasonic scalpel for very delicate surgery in areas such as the brain or internal structure of the ear.

Doppler ultrasonography uses the Doppler effect of wavelength changes between the incident and back scattered waves to provide images of moving fluids within the body, such as blood flow (Figure 33.3). Blood cells travelling toward the transducer will cause reflected ultrasound waves of shorter wavelength than the incident waves. Again, a computer is necessary to convert the reflected wave energy into a comprehensible video image.

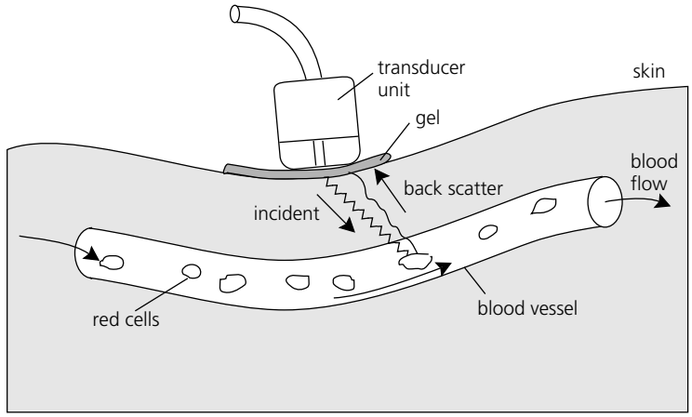


Figure 33.3
Doppler ultrasonography.

Colour Doppler allows the imaging to quickly indicate direction of blood flow. Blood flowing toward the transducer is coloured red, and blood flowing away is coloured blue. The colours are superimposed on the cross-sectional image, which gives the direction of blood flow. This technique is very useful in echocardiography studies and in identifying small blood vessels such as calf veins and kidney arteries.

Radiologists today have a wide variety of ultrasound probes. Those used for imaging body cavities and organs are called intercavitary scanners, such as are used for transvaginal scanning in the early stages of pregnancy up to about 12 weeks, and transrectal probes used for prostate gland examination. High-frequency and ultra-high-frequency (20 MHz) probes are now being developed for musculoskeletal applications and in the treatment of various skin disorders. The greatest advantages of ultrasound in medicine are its lack of ionising radiation, relatively low cost and ease of portability. Despite the possible destructive effects of ultrasound, medical imaging is now regarded as quite safe.

33.4 MEDICAL ISOTOPES AND RADIATION

The history of nuclear medicine is closely interwoven with major discoveries in physics and chemistry. Radioisotope production techniques developed rapidly during the 1970s and 1980s. Today, the use of these isotopes has been combined with various imaging techniques and computer data analysis to become a powerful medical diagnostic tool.

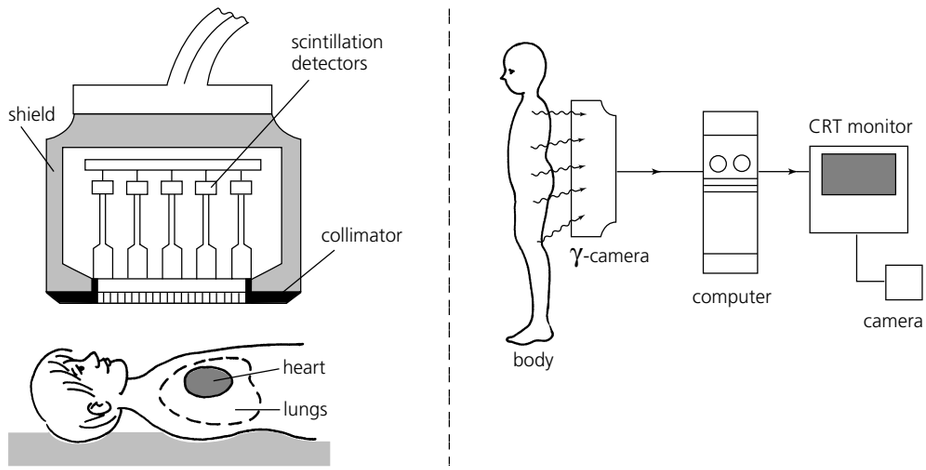
Scintigraphy refers to the use of gamma (γ) radiation to form images following injection of a suitable **radiopharmaceutical** compound. The radio part refers to a radionuclide, which

is the radiation emitter, such as the widely used technetium (^{99m}Tc), while the pharmaceutical part refers to the compound to which the radiation emitter is bound or attached, and which is injected into the body to be observed and analysed. The radioisotope technetium-99m is an isotope of the artificially produced element technetium and it has almost ideal features for nuclear medicine studies:

- It has a 6 hour half-life, which is long enough to adequately examine metabolic processes yet is short enough to minimise radiation dose to the patient.
- It decays by gamma rays and low energy electrons only.
- The low energy gamma rays escape the human body easily and are accurately detected by an external gamma camera.
- The chemistry of technetium is very versatile and it can be tagged onto a range of biomolecules that concentrate in different organ groups of the body.

Once the radiopharmaceutical compound is absorbed by organs or regions of the body, the gamma rays are imaged using an external gamma camera, which converts the absorbed energy of the radiation into an electrical signal for recording via a process called **scintillation**. When a gamma photon strikes a crystal of sodium iodide that has been doped with a small amount of thallium, the energy is absorbed and re-liberated by the crystal as a photon of visible light. This light is detected by a photovoltaic cell and converted into an electrical impulse that can be amplified and recorded. The gamma camera used in medical scintigraphy measures the radiation emitted by each spot in the body through the use of a multi-channel collimator. The camera contains numerous scintillation detectors corresponding to collimated channels. The outputs of the detectors are computer-combined into a single colour-enhanced image on a monitor screen. The gamma camera itself is housed inside a lead shield to protect the sensitive detectors from background radiation. A typical nuclear medicine camera is the General Electric 'Starcam 3000', or the General Electric 400 ACT or the Marconi Irix. (See Figure 33.4.)

Figure 33.4
Scintigraphy using a gamma camera.



The metastable atom ^{99m}Tc, in passing from the high energy state to the low energy state, releases a gamma photon with energy 140 keV. This makes it very suitable for use in imaging. Technetium-99 has a half-life of about 6 hours and is very versatile. If injected into the bloodstream together with a tin compound, for instance, it attaches to the red blood cells and can be used as a blood flow **tracer**. If administered as the compound ^{99m}Tc-methylene phosphorate, it is taken up by bone and can be used to detect early osteomyelitis much faster than the wait needed for early calcium deposition to be shown on X-ray images. As well as the technetium, other widely used diagnostic medical radioisotopes are gallium-67 (^{67}Ga), thallium-201 (^{201}Tl), iodine-123 (^{123}I) and indium-111 (^{111}In). Some therapeutic radioisotopes used in nuclear medicine include iodine-131 (^{131}I), phosphorus-32 (^{32}P) and strontium-89 (^{89}Sr). (See Table 33.1.)

Table 33.1 MEDICAL RADIOISOTOPES

ISOTOPE	HALF-LIFE	PRODUCTION	EMISSION (keV)	CLINICAL APPLICATIONS
^{99m}Tc	6 h	reactor	γ (140)	cerebral blood flow coronary artery disease oncology and renal function
^{67}Ga	78 h	cyclotron	γ (185)	lymph node cancer, infection
^{201}Tl	72 h	cyclotron	γ (168) X (83)	coronary artery disease oncology
^{18}F	2 h	cyclotron	γ (511)	glucose metabolism — neurology cardiology, oncology
^{131}I	8 d	reactor	γ (364) β (606)	hyperthyroidism and thyroid cancer
^{123}I	13 h	cyclotron	γ (159)	thyroid and kidney studies
^{111}In	67 h	cyclotron	γ (245)	protein, cells and antibody studies
^{32}p	14.3 d	reactor	β (1710)	blood disorders

Technetium has become the most widely used radionuclide for diagnostic nuclear medicine. It is formed from the decay of a parent radionuclide, molybdenum-99, which, through this parent–daughter process, can be provided in a convenient, readily available and mobile form, the technetium generator. Table 33.2 shows the available technetium-labelled compounds and their uses.

Table 33.2

RADIOPHARMACEUTICAL	SHORT FORM	CLINICAL USE
Technetium sulfur colloid	99mTcS/C	reticulo-endothelial system (liver, spleen and bone marrow scan)
Technetium macro aggregated albumin	99mTcMAA	pulmonary blood flow (lung scan)
Technetium diethylene triamino penta acetic acid	99mTcDTPA	renal blood flow, function and excretion (kidney scan)
Technetium methylene diphosphonate	99mTcMDP	skeletal studies (bone scan)
Sodium pertechnetate	$Na_2$99mTcO_4	thyroid, salivary gland and gastric scans
99mTc red blood cells	99mTcRBC	cardiac function and blood pool scans
99mTc Sestamibi 99mTc Tetrofosmin	99mTcMIBI 99mTcTETRO	myocardial perfusion (heart muscle blood flow)
99mTc hexa methylene propylene amine oxime	99mTc HMPAO	brain scan and scans for infection

As can be seen from Table 33.1, the production of radioisotopes in Australia is both nuclear reactor and accelerator cyclotron based. Today, cyclotrons are the preferred method and a lot of research is currently being done to investigate the cyclotron production of technetium in Australia. Presently the technetium-99 and iodine-131 are produced at the Australian Nuclear Science and Technology Organisation (ANSTO) HIFAR reactor at Lucas Heights, Sydney.

Other reactor radioisotopes currently produced include:

- Cobalt-60: used for external beam radiotherapy.
- Iridium-192: supplied in wire form for use as an internal radiotherapy source.
- Iron-59: used in ferrokinetic studies of iron metabolism in the spleen.
- Selenium-75: used in the form of seleno-methionine to study the production of digestive enzymes.
- Ytterbium-169: used for cerebrospinal fluid studies in the brain.

ANSTO's National Medical Cyclotron facility (NMC) produces thallium-201 and gallium-67 for both myocardial (heart) and tumour studies at Australian hospitals. Australia's second medical cyclotron is housed at Melbourne's Austin Hospital, in the Cyclotron and PET Centre, which primarily produces positron emitting radioisotopes for positron emission tomography (PET). This is discussed in Section 33.5.

Other cyclotron produced radioisotopes include:

- Rubidium-81: as a gas source, this isotope can produce images of lung ventilation conditions such as asthma.
- Carbon-11 and nitrogen-13: used to study brain physiology and pathology, especially in conditions such as epilepsy and dementia.

In Australia, the National Health and Medical Research Council (NHMRC) maintains the standards for radiation protection. Radiation hazards occur to the body as a result of damage to cells caused by ionising radiation. This damage, as a result of the formation of chemically active ions inside the cells, can take various forms but usually involves a combination of temporary cell division inhibition, or genetic chromosome damage leading to mutations or even cell death. Those cells mostly at risk are the actively dividing ones, such as bone marrow, lymph glands or the gonads. The degree of damage varies according to radiation dose and dose rate, the irradiated volume of tissue and the type and duration of radiation.

Recall from Chapter 28 that the units for **absorbed dose** of radiation refer to the energy absorbed in a given mass of body tissue as a result of ionising radiation. The SI unit is the joules per kilogram (J kg^{-1}) and is referred to as the **gray (Gy)**, where 1 Gy = 1.0 J kg^{-1}.

Table 33.3 WEIGHTING FACTORS — DOSE EQUIVALENT

TYPE OF RADIATION	DOSE EQUIVALENT
Photons (X-rays and γ-rays)	1.0
Electrons (β particles)	1.0–2.0
Neutrons (fast or thermal)	5–20 depending on energy
Protons	5–10
Alpha particles	20
Heavy ions	20

Dose equivalent is a refined unit that takes into account the fact that some types of radiation can produce more damage in tissues than others, even though the absorbed dose is the same. This leads to the use of weighting factors for the different types of radiation, as shown in Table 33.3. The SI unit for dose equivalent is the joules per kilogram (J kg^{-1}) or the **sievert (Sv)**, where 1 Sv = 1.0 J kg^{-1} = (weighting factor) $\times$ absorbed dose.

Table 33.4 lists some typical absorbed doses administered to an adult patient for common X-ray procedures, and Table 33.5 lists the total body dose equivalent administered to an adult patient for some common nuclear medicine studies. The total average intake from natural background radioactivity is 1–2 mSv per year. The highest known level of background radiation is in the Kerala and Madras regions of India where a population of over 100 000 people receives an annual dose rate that averages 13 mSv. The dose from a normal X-ray is about 25 μSv, while the dose from a typical dental X-ray to the cheek is about 1.0 mSv. It is estimated that if 100 people are exposed to 1.0 Sv of radiation, then 5 of these people will

develop a fatal cancer. A dose of 5–6 Sv over a short period of time leads to acute radiation sickness and death as a result of damage to bone marrow, the gastrointestinal system and the central nervous system.

Table 33.4 TYPICAL RADIATION DOSES ADMINISTERED TO ADULTS (X-RAY UNITS = mGy)

PROCEDURE	SKIN	BONE MARROW	OVARY
Abdomen AP	4.9	0.48	0.84
Chest AP	0.2	0.042	0.002
Pelvis AP	4.0	0.53	0.75
Kidneys IVP	5.2	0.47	0.53
Lumbar spine (lateral)	20.7	0.79	1.36

Table 33.5 TOTAL BODY DOSE EQUIVALENT USED IN SOME NUCLEAR MEDICINE PROCEDURES

NUCLEAR MEDICINE PROCEDURE	TOTAL BODY DOSE EQUIVALENT (mSv)
Thyroid scan ^{99m}Tc	1.16
Bone scan ^{99m}Tc.MDP	5.2
Lung scan ^{99m}Tc.MAA	1.8
Gallium scan ^{67}Ga	20.3

Radiation therapy

In medical terms, radiation therapy is the technique used to deliver a lethal radiation dose to a specific organ or site in the body while keeping the dose to surrounding tissues to a minimum. The most common methods involve using internal radioisotopes that target specific sites or external rotation techniques that allow concentration of radiation beams to very localised sites. Examples of isotopes used for these therapeutic purposes are cobalt-60 and caesium-137. The commonest use of therapeutic radioisotopes is in the treatment of cancerous tumours. The chances of recovery from the different forms of cancer are variable, depending on factors such as early detection. Lung and bowel cancers have the lowest survival rate, even following treatment. The methods of treating cancer involve a combination of surgery, chemotherapy (chemically based therapy), and radiation therapy. In radiation therapy the usual method is to give a total dose of about 120 mSv, split into a series of smaller doses of about 12 mSv over a span of 20 days. A newer technique involves delivering doses to specific targets, using radioactive elements that chemically bind to the DNA of the cancer cells. This method is highly localised and thus much more efficient.

In all forms of radiography and nuclear medicine, the protection of patients and staff is very important. In the techniques of diagnostic and therapeutic radiology the 'ALARA' principle is used. The probability of damage by all justifiable exposure to radiation is kept *A*s *L*ow *A*s is *R*easonably *A*chievable, which includes keeping doses to individuals, number of people exposed, and likelihood of others exposed, as low as possible. Staff are required to wear radiation monitors called thermoluminescent dosimeters (TLDs) in order to be checked monthly for exposure. Most operators return a 'below detectable limit' or BDL reading, but a high exposure might be 200 μSv for the month. These devices were discussed in Chapter 28. In Australia, radiation protection regulations are based on the International Commission on Radiological Protection (ICRP) guidelines, which provide a maximum permissible dose for occupational exposure of 20 mSv a year averaged over five years (total 100 mSv) with a maximum of 50 mSv in any one year. For public exposure the maximum dose is 1.0 mSv a year averaged over five years (total 5.0 mSv).

Hadron therapy

The term **hadron therapy** was first used in the early 1990s to describe radiation therapy using beams of heavy charged and uncharged particles such as protons, neutrons and heavy positive ions of carbon, neon and silicon. The name distinguishes this form of radiation therapy from its counterparts using X-rays (photons) and high energy electron beams (leptons) in the naming conventions of the standard model. One of the major problems with the therapy is the high cost of treatment machine facilities, which require cyclotrons and synchrotrons. However, in the small number of major centres of hadron therapy in the world, such as in the USA, Japan, Switzerland and Germany, clinical applications are showing excellent results.

The main advantage of hadron therapy over conventional radiation therapy that aims to kill tumour cells with beams of ionising radiation is that the hadron beams provide much better (higher) dose distributions to the tumour itself while limiting the doses to surrounding healthy tissue. This results from the way hadron beams are absorbed at the microscopic level within the tumour tissue. Generally speaking the neutron, proton or ion beams produce a greater number of secondary charged particle interactions along the beam path at the target site in the tissue. This means that they produce high energy depositions or high linear energy transfer (LET) characteristics in a very small area of tissue.

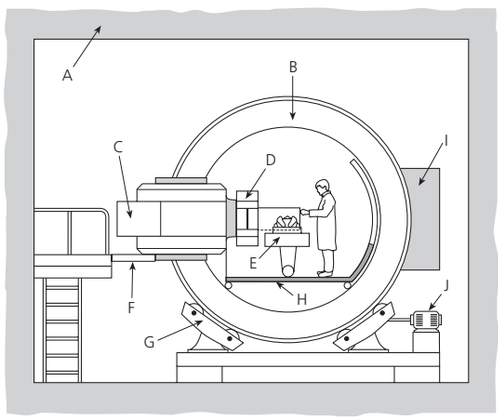
This is significant at the cellular level because it allows the energy to be directed at the cell's DNA double helix. In simple terms the hadron beams are much better at targeting and ionising the actual DNA, whereas both electrons and X-rays are quite poor at targeting such a small area. The biological DNA is the controlling centre of the tumour cell, so destroying the DNA kills the cells very effectively and leads to elimination of the cancer.

A second advantage with High LET radiation beam therapy is that cells irradiated by this method show far less tendency to change their cell division cycles, so far fewer cells are prone to therapy resistance as is often the case with electron or X-ray therapy.

A third advantage relates to the fact that typical cancer tumours are poorly supplied with blood vessels, and tumour tissues are therefore low in oxygen content ('hypoxic' conditions). Such tissues are resistant to conventional X-rays but can be destroyed more effectively by hadron beams. Since normal tissues surrounding the tumour are well oxygenated, irradiation with hadrons will kill more tumour cells than X-ray irradiation will.

The first use of neutrons in the treatment of cancer patients was in the USA at the University of California, Berkeley Cyclotron Laboratory in 1938. This cyclotron machine designed by E. O. Lawrence used a 16 MeV deuteron beam smashing into a thick beryllium target. The neutron beam itself had a mean energy of about 7.0 MeV. Today the most advanced neutron therapy accelerator is housed at the Wayne State University Gerhenshon Radiation Oncology Centre and uses a 48.5 MeV deuteron superconducting cyclotron coupled with multileaf collimators. The facility uses a single shielded room with the accelerator and its internal beryllium target mounted on a ring gantry that can be rotated 360 degrees around the patient; total mass is about 60 tonnes. (Refer to Figure 33.5.)

Figure 33.5
Neutron therapy superconducting cyclotron.



A: room shielding
B: ring supports
C: superconducting cyclotron
D: multileaf collimator
E: patient table
F: service platform
G: roller assembly
H: moving floor
I: counterweight
J: drive motor

Proton beam therapy has been used since about 1961 and heavy ion (^{12}C) beam therapy has been used since 1975 at various centres around the world. Proton therapy tends to be the treatment of choice for paediatric cancers, as the risk of secondary radiation-induced cancer as a result of the treatment is far lower. Proton therapy may involve either 'proton radiosurgery', as used on brain lesions, or 'proton precision radiation therapy', used on the brain stem and spinal cord structures as well as prostate and cervical cancers. At present there are twenty active proton therapy centres in the world, twelve neutron and three heavy ion centres. Some of the new centres being planned will combine both proton and heavy ion machines. It is anticipated that in the next ten years hadron therapy will become a familiar tool in the armoury of oncology treatment around the world.

Activity 33.1 RADIATION THERAPIES COMPARED

Use the material presented in this chapter, as well as Internet research, to compare and contrast the techniques of hadron, photon and lepton therapies in modern medicine. Outline what each contains, as well as the advantages and disadvantages of these methods. Present your report in such way as to convince the reader that more is available than just X-rays.

33.5 MEDICAL IMAGING TECHNIQUES

— X-rays and tomography

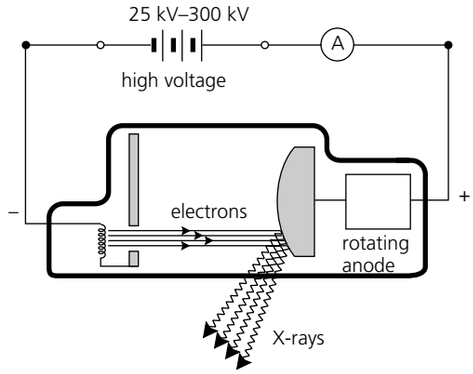
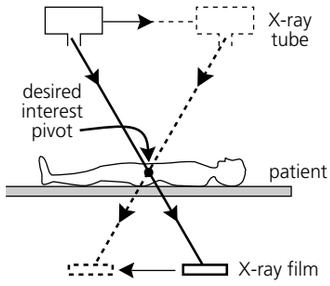


Figure 33.6
Basic X-ray tube apparatus.

X-rays are a form of EM radiation, as discussed in Chapter 28, with frequencies and energies much higher than those of visible light. X-rays are produced in an X-ray tube by focusing an electron beam onto a tungsten target. They are then able to be focused and pass through a patient's body and onto X-ray film, producing an image (Figure 33.6). The image is processed in much the same way as normal photographic film. As the X-rays pass through the body tissues they are absorbed by different amounts, resulting in a variation of densities on the final exposed and processed X-ray film. Five different densities are recognised by radiologists. Densities 1–5 in order are:
Density 1 — Air/gas: black; for example, lung, bowel, stomach
Density 2 — Fatty tissue: dark grey; for example, subcutaneous tissue layer or peritoneal fat
Density 3 — Soft tissue/water: light grey; for example, solid organs, heart, blood vessels, muscles
Density 4 — Bone tissue: off-white; for example, humerus bone
Density 5 — Contrast material/metal: bright white; for example, metal staples or pins holding a fracture.

Organs are best seen with conventional X-ray film if they sit beside tissue of different density. For example, the right heart border is usually seen very well because it sits against air-filled lungs. Similarly, the psoas muscle is usually seen very well in abdominal X-rays because of the lower density fat tissue lying beside it. In the procedure called an intravenous pyelogram (IVP), or X-ray of the kidneys and bladder, a non-ionic iodine solution called Ioversol is injected into the patient's bloodstream to act as a contrast medium. This allows greater differentiation of the various tissues.

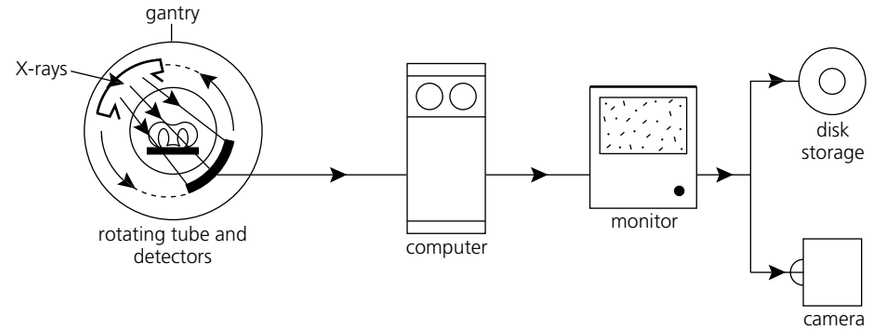
Figure 33.7
Conventional tomography.



Sectional radiography or conventional **tomography** (from the Greek *tomos* meaning 'slice') is used if the organ or structure being examined is obscured by overlying tissue as, for example, in radiography of the kidneys that are being obscured by bowel loops. In this process the X-ray tube and detecting film move about a pivot set at the desired plane of interest (Figure 33.7). Organs or structures above and below that being imaged are blurred by the motion of the X-ray tube. This technique is used today in conjunction with cross-sectional imaging techniques such as ultrasound and the newer CT or MRI scans. We will now take a look at these.

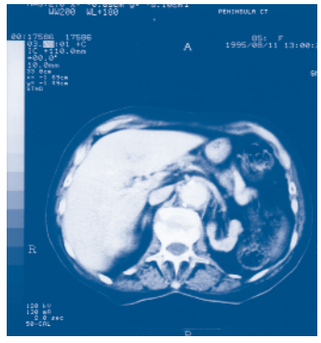
Computed tomography (CT)

Figure 33.8
Computed tomography (CT).



What used to be called the computed axial scanner (CAT) or body scanner was invented in 1972 by the British electronics engineer Godfrey Hounsfield, at the central research labs of EMI Ltd., reportedly with money made from sales of the company's Beatles records! The devices were in general use by 1979. A modern computed tomography scanner or **CT scanner**, such as the General Electric 'Pace', produces cross-sectional images with the use of X-rays. The patient passes through a gantry that rotates around the body at the level of interest (Figure 33.8). Information from the X-ray detectors is analysed by computer software and displayed as an image. These images are photographed to produce a series of slices through the body. Similar density differences are found in CT images as with conventional X-ray film but with much greater density control made available by the computer. Much greater differentiation is possible between solid organs as well as between organs and processes such as tumour or fluid collections. CT scans are also very sensitive to contrast material and minute amounts of calcium.

Photo 33.3
Typical CT scan of a body trunk.



Intravenous contrast material is used with CT scans for reasons such as differentiating normal blood vessels from abnormal masses, such as lymph nodes. Contrast material also makes tissue abnormalities more apparent. Oral contrast medium is used for abdomen CT scans to allow the distinction to be made between normal bowel loops and abnormal masses or fluid collections.

The computer software driving the CT scanners allows fine manipulation of the densities to display various tissues of the body where required. This is called altering the window settings and is especially used to view lung tissue and liver tissue in chest or abdominal CT scans. Photo 33.3 shows a typical body trunk CT scan.

Recently, CT scanners that allow continuous collection of data as a patient passes through the CT gantry have been developed. The tube and detectors rotate continuously around the body from head to toe in a spiral pattern. This is called a 'helical scan'. The software that operates the CT scanners is very complex but the major advantages of helical CT scanning are as follows:

- Increased speed of examination, a big advantage as patients undergoing CT scanning need to be kept very still.
- Rapid examination at optimal levels of intravenous contrast medium concentrations.
- Images can be retrospectively constructed from the computer data.
- High quality 3D images are possible.

Despite the tremendous complexity of CT scanners, they still involve the use of ionising radiation and cannot image many fine details in soft tissues. CT scans are also usually limited to transverse (head to toe) or axial (across the body) planes. For these reasons the technique known as magnetic resonance imaging is now becoming more widespread.

Magnetic resonance imaging (MRI)

Magnetic resonance imaging (MRI) has become accepted over the past ten years as a very powerful diagnostic imaging tool. The first MRI scanner was tested on 2 July 1977 by Brooklyn, NY medical researcher Ray Damadian, as a diagnostic tool that did not subject patients to X-rays. Britain introduced the technique in about 1974 and the scanner's commercial sale was approved in the USA in 1984. MRI uses the magnetic properties of the hydrogen atom to produce images, and as hydrogen is present in many biological compounds that make up the body tissues, many diagnostic applications of MRI have been developed.

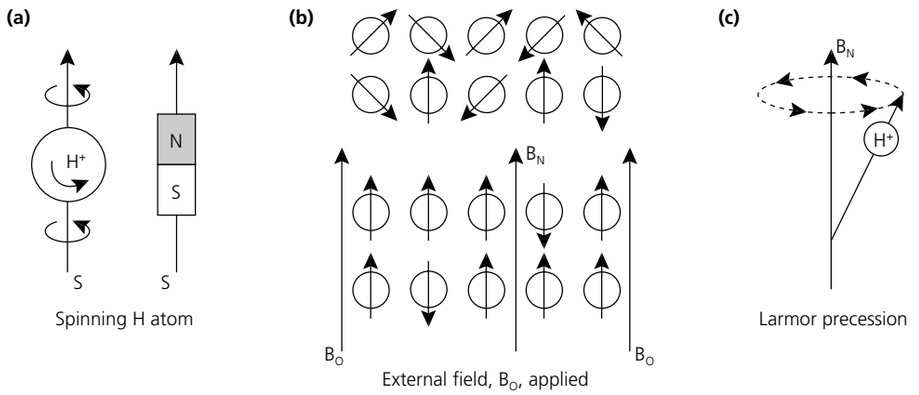


Figure 33.9
Magnetic resonance.

The single proton in the nucleus of a hydrogen atom may be thought of as a small spinning bar magnet with a north and south pole. (See Figure 33.9**(a)**.) If a very strong external magnetic field is applied to tissues containing hydrogen atoms, they will mostly align themselves in the direction of this applied field, rather than remaining randomly aligned (Figure 33.9**(b)**). Although now aligned in the direction of the applied field (B_0), the hydrogen nuclei do not remain motionless, but spin around the line of the field in a precessional motion, as shown in Figure 33.9**(c)**. The frequency of precession is an inherent property of the hydrogen atom in a magnetic field and is known as the **Larmor frequency**. The Larmor frequency changes in proportion to the magnetic field strength but is within the radio frequency range around 10 MHz. Hence the hydrogen atoms are radiating radio frequency (RF) energy.

A second magnetic field is now applied at right angles to the original external field. This second magnetic field is at the same frequency as the Larmor frequency and is called the RF pulse. It is applied by an electromagnetic RF coil (Figure 33.10). This RF pulse now causes the net magnetisation vector of the hydrogen atoms to turn toward a direction that is at right angles to the original external magnetic field. Thus, the applied RF pulse has added energy to the atoms. When it is switched off again the atoms relax in various ways, the net magnetisation vector returns to its original direction and in doing so emits an RF signal that is received

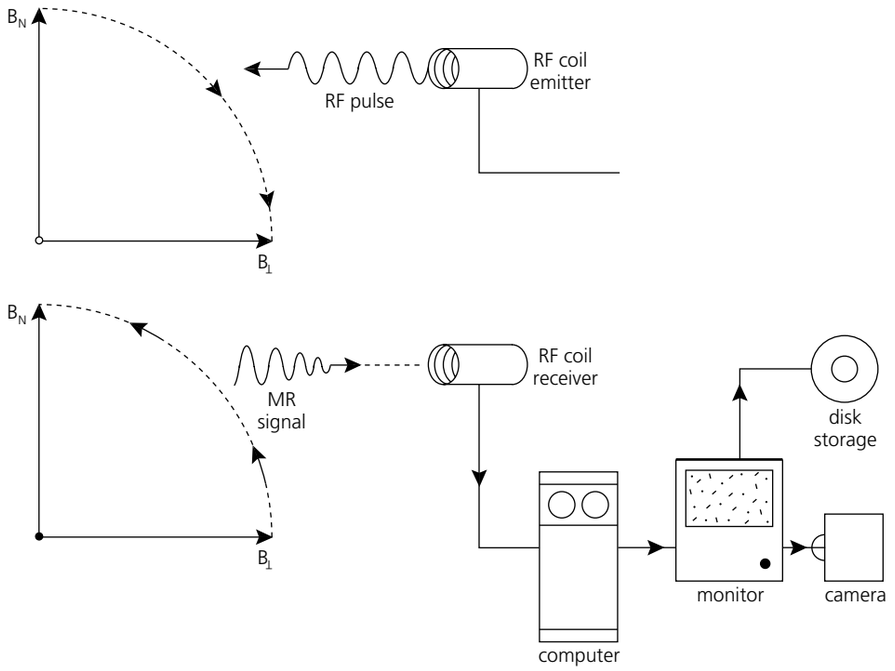


Figure 33.10
Generation of the MR signal.

by the RF coil. The signal induces small currents in the RF coil that are called the MR signal. It is these signals that are analysed by the computer software to produce an image.

The MRI image is surprisingly similar to a CT image but, of course, has not been produced with X-rays. Photo 33.4 shows a typical head scan MRI image with all the soft tissue detail. CT scans depend on tissue density, and ultrasound scans depend on echogenicity, but much of the complexity of the MRI image is due to a variation of properties such as proton density, chemical environment, magnetic susceptibility and the relaxation time of the hydrogen atom in various biological compounds. Radiologists can alter the duration and amplitude of the applied RF pulse to provide different types of images designed to clarify anatomy details or pathology details.

Photo 33.4
MRI brain scan.

The main advantages of MRI as an imaging diagnostic tool are that it allows:

- excellent soft tissue contrast
- imaging in any plane, being especially useful in scans of the musculoskeletal system
- no use of ionising radiation.

MRI is the radiologist's choice for most spine and brain disorders, but it has not replaced CT, ultrasound or endoscopy as the choice for thoracic and abdominal disorders. Unfortunately MRI is very expensive, with running and maintenance costs very high, and the instrumentation is obviously not very portable. The applications of MRI are being developed rapidly, with certain paramagnetic contrast materials that increase soft tissue detail even further being developed.

Further developments

The gamma camera as used in tomography produces only a two-dimensional image. In a technique known as **single photon emission computed tomography** (SPECT), the gamma camera moves around the body as with CT scans, but the computer is programmed to analyse data coming from a single depth within the patient. Cross-sectional scans, similar to those produced by plain tomography, are obtained. The main applications of SPECT are in bone scanning, thallium-201 cardiac scanning and in cerebral or brain studies in which colour-enhanced cross-sectional images are obtained using radioactive iodine-123 as the γ emitter attached to a variety of tracer compounds, such as amphetamines.

Radioisotopes such as nitrogen-13 and oxygen-15 produce positrons that are very short-lived. As they are emitted from the nucleus, they collide with an orbital electron in adjacent atoms and are annihilated, producing energy in the form of two γ photons travelling in opposite directions. A technique called **positron emission tomography** (PET) uses a circular array of detectors around a patient to search for these γ pairs at coincident times. A target molecule, such as glucose, is tagged with the positron emitter, such as nitrogen-13. The tagged solution is injected into the patient's bloodstream. The data from this process are again computer processed to produce a colour-enhanced image. A PET scan can be done quite quickly so that it can provide information on rapidly changing internal processes, such as brain activity. It has had good success in the study of epilepsy, locating quickly the deep-seated focal point of the epileptic activity in the brain. The radionuclides used for PET scans are very short-lived, ^{15}O — 2 minutes, ^{13}N — 10 minutes, ^{18}F — 2 hours, and thus must be produced by a cyclotron at the hospital site. At present, PET studies in Australia are carried out primarily at the Austin Hospital PET Centre in Melbourne.

The biochemical properties of the commonly used positron emitting radioisotopes are generally superior to those of the single γ emitters for functional medical imaging because the elements used are in fact the principal elements of the human body. Several positron emitting isotopes are now produced in Australian cyclotrons. Glucose metabolism images taken using radioactive glucose (^{18}F-fluoro-2-deoxy-D-glucose or FDG) provide unique clinical information in cardiology, neurology, oncology and psychiatry. PET will also have a major role in biomedical research with its ability to radiolabel compounds enabling in situ studies of biochemical processes.

— Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***1** Describe how you would explain the difference between medical physics and nuclear medicine.

***2** Calculate the de Broglie wavelength of electrons accelerated by a potential difference of 55 kV in an electron microscope.

***3** What device takes the place of optical lenses within an electron microscope in order to focus the electron beam?

***4** Explain why a technician producing a specimen for scanning electron microscopy does not need to produce a thin cross-section.

***5** Place the following names into chronological order of their medical physics discoveries. Briefly outline the contribution made by each person: Ray Damadian, Ernst Ruska, Wilhelm Roentgen, Heinrich Rohrer, Ian Donald, Godfrey Hounsfield.

***6** Outline the differences between the echogenicity of normal fatty tissue and abnormal lymphoma tissue in the body. What imaging technique makes use of these differences?

***7** Define these terms associated with diagnostic ultrasound: piezoelectric, Doppler ultrasonography, echocardiography and intercavitary scanning.

***8** Make a list of the radioisotopes typically used in the clinical applications and diagnosis of coronary heart disease and cardiology. What radiation is emitted and how are the radioisotopes originally produced?

***9** A person is given a technetium-99 lung scan. How does the total body dose equivalent in this hospital procedure compare with that of a person who does not require this procedure? To what form of radiation is the scanned patient subjected?

***10** A radiographer refers to a typical density 5 area on an X-ray plain film. What object or part of the body is it likely to be?

***11** Explain how a CT scan differs from a plain X-ray image. Imagine you were trying to explain the procedure to an elderly family relative in order to allay their fears.

***12** Magnetic resonance imaging in medical physics or radiology depends on what type of energy emitted by the hydrogen atom?

****13** Patient A reports to a hospital with an acute kidney disorder and patient B reports with suspected damage to the nerve spinal cord at the base of the brain. Predict which mode of diagnostic imaging a consultant radiologist might order for each patient. Explain your reasons.

****14** Using sketches, outline the differences between an X-ray tube and a computed tomography scanner.

****15** Use Table 33.4 to determine which X-ray procedure to the body produces, on average, the highest and the lowest dosage rates. Explain why this might be so.

****16** Write a short report on diagnostic medical imaging techniques that allow monitoring of moving fluids in the body.

Extension — complex, challenging and novel

*****17** Ionising radiation interacts with body tissues basically by destroying cell components. Explain why the weighting factor for alpha particles might be much higher than for protons or electrons. Refer to Table 33.3.

*****18** Compile a report on one of the following medical topics **(a)** to **(e)**. You should include the following sections in your report, where appropriate to the topic:

- Overview of the ailment (who gets it and why)
- Physics principles underlying the procedure
- Dangers associated with the procedure
- Success rates and future possibilities.

(a) Breast cancer is second only to lung cancer as a cause of death from cancer among women in Australia. Women have a 1 in 10 chance of developing it during their lifetime. Radiation therapy achieves success in about 50% of cases. Discuss.

(b) X-rays can be used to treat malignant melanomas although surgical removal is the treatment of choice. Discuss the difference.

(c) Laser treatment seems to be effective in repairing detached retinas, removing portwine birthmarks and tattoos. Discuss.

(d) Fluoroscopes were used in suburban shoe stores throughout Australia in the 1950s to get X-ray images of feet in shoes. In retrospect, this was a dangerous procedure. Why?

(e) The following conditions often require the use of radiation therapy. Research and report on: prostate, bladder and testicular cancers; Hodgkin's disease; uterine, ovarian and cervical cancers; carcinoma of the lung; Ewing's sarcoma.

****19** Read the following material from information available on the website of the Austin Medical Centre in Melbourne, and complete the questions following. You may also need to refer to other tables in the chapter.

All radiology (X-ray) and nuclear medicine tests involve the administration of radiation. Whether this is by way of an X-ray tube or radioactive material is of no consequence; it is still radiation. The levels of radiation exposure, however, differ between the two. The following table [Table 33.6] compares the effective dose from a range of radiological and nuclear medicine tests with the equivalent number of chest X-rays. There is also a column listing the length of time one would need be exposed to natural background radiation to receive the same exposure.

Table 33.6

NUCLEAR MEDICINE INVESTIGATION	EFFECTIVE DOSE (mSv)	EQUIVALENT NUMBER OF CHEST X-RAYS (mSv)	EQUIVALENT PERIOD OF NATURAL RADIATION
Radiography (normal X-rays)			
Extremities (e.g. knee)	0.01	5	1.5 days
Chest	0.02	1	3 days
Skull	0.1	5	2 weeks
Cervical Spine	0.1	5	2 weeks
Thoracic Spine	1.0	50	6 months
Lumber Spine	2.4	120	14 months
Hip	0.3	15	2 months
Pelvis	1.0	50	6 months
Abdomen	1.5	75	9 months
Biliary Tract	1.3	65	7 months
Intravenous Pyelogram	4.6	230	2.5 years
CT examinations (X-ray scans)			
Brain	2.0	100	1 year
Cervical spine	3.0	150	1.5 years
Thoracic spine	6.0	300	3 years
Chest	8.0	400	4 years
Abdomen	8.0	400	4 years
Lumber spine	3.5	175	1.8 years
Pelvis	7.0	350	3.5 years
Nuclear medicine — 99mTc			
Bone imaging	3.6	180	1.8 years
Cerebral perfusion (blood flow)	4.5	225	2.3 years
Lung perfusion	1.0	50	6 months
Myocardial perfusion	5.0	250	2.5 years
Thyroid imaging	1.0	50	6 months
DTPA renogram (kidneys)	1.6	80	10 months
DMSA renal	0.4	20	8 weeks
Hepatobiliary	2.3	115	14 months
Liver sulfur colloid	0.7	35	4 months
Gastric emptying	0.3	15	2 months

Questions

1 What does the term mSv mean in the column heading for 'effective dose'?

2 You have a typical X-ray for a broken arm and your mate says that you received some dangerous levels of radiation. How would you respond to his worries?

3 Why would you think that CT scans to parts of the body are much higher in effective dose than normal radiographs?

4 Give a reason for the increased dose to the lumbar rather than the thoracic spinal column.

5 A patient requires investigation of her heart blood flow patterns. Which would be the technique of least effective dose for the patient — technetium gamma scan or CT scan? What other factors do you think the specialist might consider, especially if it were for a possible heart-attack victim?

6 Find out the meaning of the terms hepatobiliary, DTPA and DMSA, used in the table.

7 From the table calculate an average effective dose from natural radiation causes per year.