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Radiation Protection in Hospitals

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RADIATION PROTECTION IN HOSPITALS

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PREFACE

This book has evolved over many years of lecturing on the topic of radiation protection to a wide spectrum of hospital personnel. The level and emphasis of teaching varies with the audience but various aspects of radiation are common and relevant to the many different professions within a hospital environment. The book has thus been structured to cater for readers with different backgrounds, training and needs by providing both an elementary radiation physics text in Part I and an advanced, comprehensive Part II containing important reference material relating to specific medical applications of x-rays and of radioactivity. Each of the introductory chapter sections in Part II briefly describes the particular therapy or diagnostic field before concentrating on aspects of radiation protection.

Health and safety are the most important aspects of any working environment and this book's main aim is to instil the universal principles of good radiation protection practice into the reader, rather than to catalogue current specific radiation protection rules in any one particular country. It should nevertheless help readers to understand their own national legal requirements; such requirements vary between countries and even between states in the USA. It also aims to assist those responsible for providing local radiation protection rules in individual hospital departments, laboratories, wards and operating theatres involved with radiation. One further objective is to provide information for teachers of nursing and radiography students and for those taking the Part I examination for the Fellowship of the Royal College of Radiologists. As the material in the book has been used in World Health Organisation and International Atomic Energy Agency seminars and workshops throughout the world, it can also provide a useful reference work for hospitals in developing countries.

Many of the chapters contain common section headings for ease of reference and to enable aspects of radiation protection to be more easily compared in the various diagnostic and therapeutic fields (e.g. shielding barriers, nursing procedures, radiation sources). I have always found visual aids to be of great help when teaching, and this is reflected by the number of illustrations and specially drawn cartoons included in the text. Historical material is also used to aid understanding.

CHAPTER 1

ATOMS, RADIOACTIVITY AND X-RAYS

1.1 THE BOHR ATOM

When the periodic table was constructed in 1870 by Mendeleef, the *elements* were arranged according to their *atomic weights* and the smallest indivisible particle of an element was considered to be an *atom*. This situation altered in 1913 when the Danish physicist Niels Bohr described his simple model of an atom consisting of a central *nucleus* around which small negatively charged particles known as *electrons* rotated. The electrons rotated around the nucleus in fixed orbits, rather similar to the planets rotating around the sun. There is a maximum number of electrons that can be accommodated in each shell. For example, in the shell closest to the nucleus, the K shell, the maximum is two electrons and in the next shell, the L shell, the maximum is eight (figure 1.1). The lightest atom is hydrogen with one orbital electron and the next lightest is helium with two orbital electrons, thus completing the innermost shell. For a heavier atom such as oxygen with its eight orbital electrons, the K shell contains two electrons and the L shell six. Table 1.1 lists the first eighteen elements in the periodic table where the serial numbers 1–18, usually denoted by the symbol *Z*, are the *atomic numbers* of the atoms (see §1.3). Using these shell limits, one can see that neon (${}_{10}\text{Ne}$) will have two full shells and sodium (${}_{11}\text{Na}$) will have one electron in the third shell. For an

Table 1.1 Elements of the periodic table with atomic numbers $N = 1-18$.

Outermost electronic shell	Groups according to the number of electrons in the outer shell							
	I	II	III	IV	V	VI	VII	VIII
1 K shell	${}_1\text{H}$							${}_2\text{He}$
2 L shell	${}_3\text{Li}$	${}_4\text{Be}$	${}_5\text{B}$	${}_6\text{C}$	${}_7\text{N}$	${}_8\text{O}$	${}_9\text{F}$	${}_{10}\text{Ne}$
3 M shell	${}_{11}\text{Na}$	${}_{12}\text{Mg}$	${}_{13}\text{Al}$	${}_{14}\text{Si}$	${}_{15}\text{P}$	${}_{16}\text{S}$	${}_{17}\text{Cl}$	${}_{18}\text{Ar}$

PART I

- 1 ATOMS, RADIOACTIVITY AND X-RAYS
- 2 RADIATION RISK
- 3 RADIATION ABSORPTION AND ATTENUATION
- 4 RADIATION MEASUREMENT
- 5 RADIATION SHIELDING
- 6 CLASSIFICATION OF RADIATION WORKERS

electrically neutral atom, the atomic number will equal the number of orbital electrons: for hydrogen $Z = 1$, for helium $Z = 2$ and for oxygen $Z = 8$.

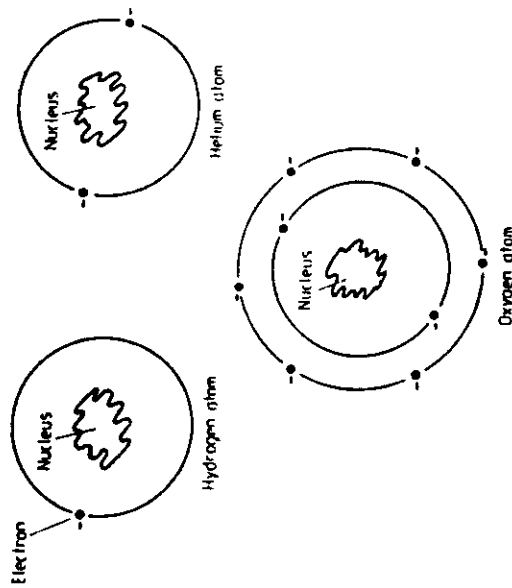


Figure 1.1 Schematic diagrams of the Bohr atom representation of electrons orbiting the nuclei of hydrogen, helium and oxygen.

1.2 THE NUCLEUS

In the Bohr model of the atom the *nucleus* represents almost all the atom's mass and, whereas the orbital electrons carry a negative charge (the reason for the minus signs in figure 1.1), the nucleus carries a positive charge. Under normal conditions the number of net positive charges on the nucleus equals the number of net negative charges on the electrons and thus the atom is electrically neutral. An increase of one in the atomic number Z in such an atom therefore means the addition of one positive charge to the nucleus and also one extra orbital electron. The positive charge in a nucleus is carried by particles known as *protons*, which have an electric charge equal in magnitude but opposite in sign to the electron, although the mass of a proton is 1836 times as large as the mass of an electron. The nucleus also contains particles called *neutrons* with no electric charge but a mass approximately equal to that of a proton.

$$\text{Electron mass} = 9 \times 10^{-31} \text{ g}$$

$$\text{Proton mass} = 1.64 \times 10^{-24} \text{ g.}$$

An atom with one proton in the nucleus is therefore an atom of hydrogen, one with two protons and two neutrons in the nucleus an atom of helium, and one with eight protons and eight neutrons in the nucleus an atom of

oxygen. However, the number of protons in the nucleus does not always equal the number of neutrons, for example, an atom of uranium has 92 protons and 146 neutrons in the nucleus (figure 1.2).

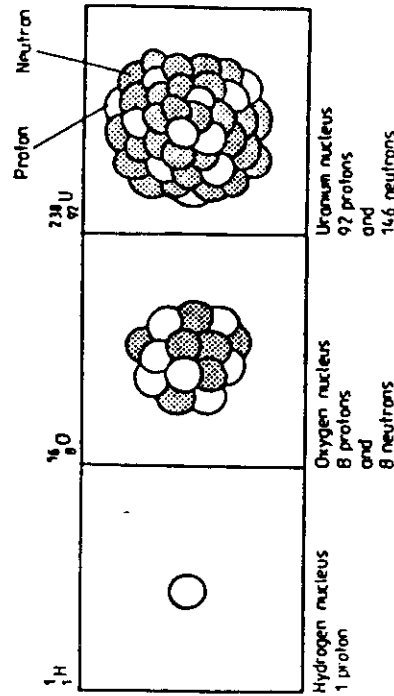


Figure 1.2 Schematic diagrams of the nuclei of hydrogen, oxygen and uranium.

1.3 ISOTOPES

The total number of protons and neutrons in a nucleus of an atom is called the *mass number* A and atoms with a particular mass number and atomic number are called *nuclides*. Hence the atom with eight protons and eight neutrons in a nucleus is a nuclide of oxygen with atomic number $Z = 8$, neutron number $N = 8$ and a mass number $A = 16$. This information is expressed using the symbolism

$$\begin{matrix} \text{Mass Number} & \text{Nuclide} \\ \text{Atomic Number} & \end{matrix} \quad {}^{16}_{8}\text{O}$$

for the oxygen nuclide. Nuclides with the same atomic number, Z , but different mass numbers, A , are known as *isotopes*. There are, for example, three isotopes of hydrogen with mass numbers one, two and three, and all with the same atomic number, $Z = 1$. The nuclear state of some isotopes is unstable and these are the *radioactive isotopes*, also termed *radioisotopes* or *radionuclides*.

1.4 PARTICLES

The Bohr model of the atom is a very simplified view of nuclear and atomic structure and there are many more elementary particles than just the proton, the electron and the neutron. For example, the *positron*, which is a particle with the same mass as an electron but with a positive rather than a negative

charge; several types of *meson*, such as the mu and the pi mesons, which can be produced by the interaction of very high energy particles with matter and have a mass between some 200 and 300 times that of the electron.

1.5 RADIOACTIVITY

Of the three isotopes of hydrogen, ${}^1\text{H}$, ${}^2\text{H}$, ${}^3\text{H}$, only two isotopes, normal hydrogen ${}^1\text{H}$ and deuterium ${}^2\text{H}$, are stable. The other, tritium ${}^3\text{H}$, is radioactive. Water (H_2O) with deuterium atoms in place of normal hydrogen is known as *heavy water*. The radioactive isotope of hydrogen is artificially produced using a nuclear reaction, although it was not the first radioactive material to be discovered. The initial discovery in March 1896 in Paris was of naturally occurring radioactivity. This was made by Henri Becquerel (1857–1908) who had been studying the luminescence of uranium salts by ordinary light to try to find if ordinary fluorescent or phosphorescent substances might produce rays similar to x-rays. He placed uranium mineral crusts on photographic plates wrapped in light-tight black paper which were then exposed to sunlight and developed. However, in February 1896 due to poor weather and lack of sunshine Becquerel put his prepared photographic plates in a drawer and then developed them for some unknown reason on 1 March without having exposed them to sunlight. To his surprise silhouetted images of the crust shapes appeared on the developed plates and he rightly concluded that neither sunlight, fluorescence nor phosphorescence were necessary to produce this effect. Radioactivity had thus been discovered and several explanations were originally proposed for this new phenomenon (including the incorrect one that radioactive substances were storerooms for certain forms of extra-terrestrial energy).

1.6 RADIUM

It was Becquerel's discovery of radioactivity that led Pierre (1859–1906) and Marie Curie (1867–1934) to announce the discovery of radium on 26 December 1898 (figure 1.3). The Curies had a more suitable radiation measuring device than a photographic plate—an electrometer equipped with an ionisation chamber—and they demonstrated that the intensity of the radiation was proportional to the amount of uranium. Many substances were studied and it was eventually found that the uranium mineral pitchblende showed a higher radiation intensity than could be explained simply by the presence of radioactive uranium and thorium compounds. This was followed by the discovery of the radioactive element polonium, $Z = 84$, associated with the bismuth extract of the ore and finally, radium, $Z = 88$,

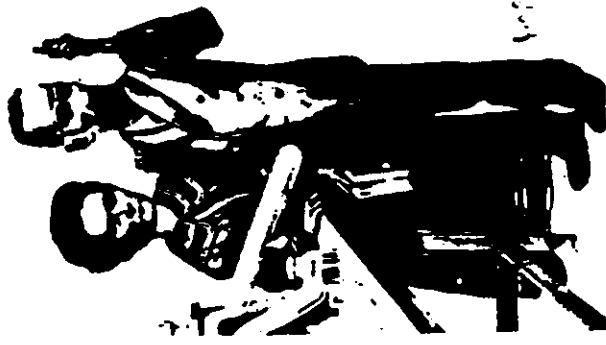


Figure 1.3 Pierre and Marie Curie from a cartoon entitled 'Radium' which appeared in the 22 December 1904 issue of the magazine *Vanity Fair*. It should be noted that this is a cartoon and it is NOT good radiation protection practice to pick up radioactive sources in your fingers. (Illustration by courtesy of the Wellcome Trustees.)

associated with the barium extract. However, although a knowledge of the new element, radium, had been gained, it was an immense problem to refine it from pitchblende ore in any quantity and in 1902 it was still considered an achievement to obtain a yield of 260 mg of radium bromide per ton of ore. However, such processing problems are now only a historical memory and today radium itself is little used in medicine, having been replaced by the artificially produced radionuclides: caesium-137, cobalt-60, iridium-192 and gold-198.

1.7 ALPHA, BETA AND GAMMA RAYS

Early experiments with radioactive substances showed that they contained radiation components with different penetration powers. *Alpha* (α) rays were the least penetrating and were completely absorbed by a few centimetres of air or by a very thin sheet of metal, *beta* (β) rays were absorbed by about 1 mm of lead and *gamma* (γ) rays, the most penetrating, were capable of passing through some 10 cm of lead (figure 1.4). Another

difference was that only the alpha and beta rays could be deflected by a magnetic field. The nature of the three radiations was obviously different and it was shown that alpha rays are the nuclei of helium atoms, that is two protons plus two neutrons. Thus they are four times the mass and twice the positive charge of a proton. Beta rays are electrons and gamma rays are photons of electromagnetic radiation. The latter are not particles like the other two forms of radiation.

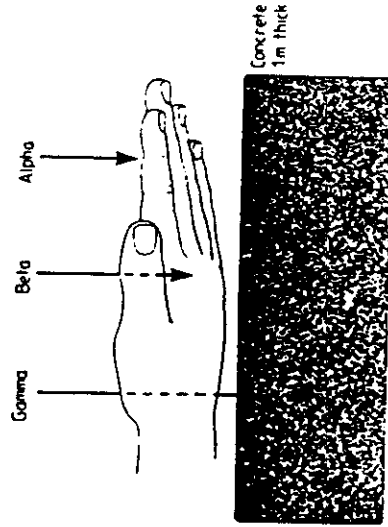


Figure 1.4 The penetrating power of radiation: alpha rays will just penetrate the surface of the skin; beta rays can pass through 1–2 cm of human tissue; gamma rays are very penetrating and can pass right through the human body but would be almost completely absorbed by 1 m of concrete. (Illustration based on one published by the IAEA in their booklet *Radiation—A Fact of Life*.)

1.8 ELECTROMAGNETIC SPECTRUM

The electromagnetic spectrum includes all types of electromagnetic radiation, from very long wavelength radiowaves to very short wavelength cosmic rays. Wavelength is inversely proportional to energy in the electromagnetic spectrum. For the ionising radiations used in medicine, the higher the energy the greater the penetrating power, although it should be remembered that not all electromagnetic radiations are ionising—only x-, gamma and cosmic rays. Moreover, the term *photon* is used when discussing x- and gamma rays, both forms of electromagnetic radiation, since a beam of radiation delivers its energy as a series of individual energy ‘packages’, known as photons.

1.9 IONISATION AND EXCITATION

Alpha, beta, gamma and x-rays are termed *ionising* radiations and the process of ionisation is caused by the interaction of radiation with the orbital electrons of the atoms in the irradiated material. One of the processes by which the α , β , γ or x-rays expend their energy is by ejecting orbital electrons which produces a negatively charged ejected electron and an ionised atom. This must now have a net positive charge since there are more protons in its nucleus than orbital electrons. The electron and the ionised atom are called an *ion pair* and the ionised atom will eventually recombine with another electron.

When beams of alpha and beta rays interact with the orbital electrons, ionisation does not always occur. Instead, the energy transferred to the electrons may simply excite them to a higher energy level rather than eject them. This process is called *excitation*. Another effect with alpha and beta charged particles can occur when the particles are deflected by the nucleus and slowed down very rapidly in the absorbing material. Then they emit energy in the form of x-rays known as *bremsstrahlung*, or braking radiation, but this is only important in practice for beta particles and materials with high atomic numbers.

1.10 RADIOACTIVE DECAY

Radioactivity is spontaneous disintegration in the nucleus of an atom to form a nuclide of a different atomic number, Z . This disintegration is associated with the emission of alpha or beta particles and gamma rays from the nucleus. In many cases the decay also involves a change in the mass number. Figure 1.5, as an example of alpha decay, shows the ^{238}U nucleus

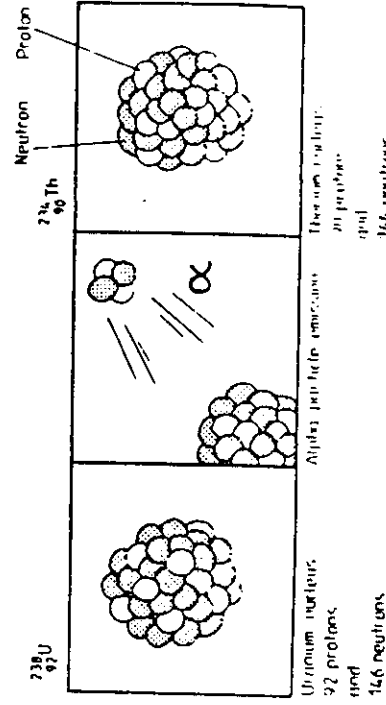
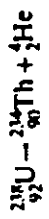
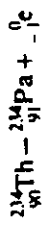


Figure 1.5 Schematic diagram of the radioactive alpha decay of a ^{238}U nucleus to a ^{234}Th nucleus.

disintegrating to form ^{234}Th and this process can be written in the form of an equation with the alpha particle described as a helium nucleus.



It will be noticed that the mass and atomic numbers balance on both sides of the equation. Figure 1.6 is an example of decay by beta emission and shows the ^{234}Th nucleus disintegrating to form ^{234}Pa



where the beta particle is written as an electron and the mass and atomic numbers again balance. As the mass numbers (234) have remained constant one of the neutrons in the thorium nucleus has therefore effectively been changed into a proton as the beta particle was emitted.

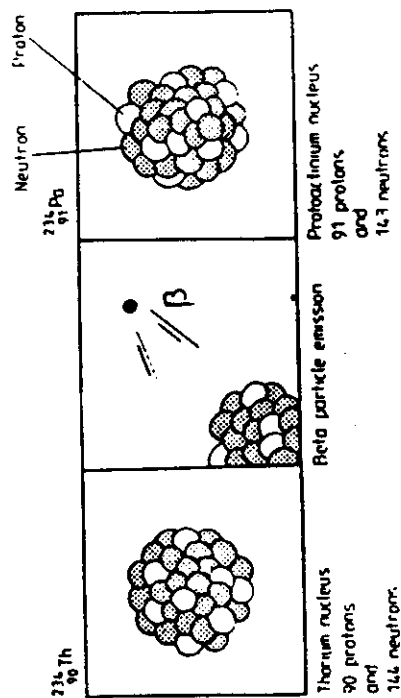


Figure 1.6 Schematic diagram of the radioactive beta decay of a ^{234}Th nucleus to a ^{234}Pa nucleus.

In the above examples, the decay product of ^{238}U is itself radioactive, and ^{234}Pa , the decay product of ^{234}Th is also unstable. These radioactive isotopes are part of a *radioactive series*, in this instance the uranium-238 series of which radium-226 is also a member. Radium decays by alpha emission to the gas radon-222; there are 13 members of this radioactive series which eventually stabilises with an isotope of lead, ^{206}Pb . There are only four naturally occurring radioactive series and the decay processes of artificially produced radioactive isotopes used in medicine are not part of these series.

1.11 RADIOACTIVE HALF-LIFE

For a given amount of radioactive material, the time for half the atoms to disintegrate is called the *half-life*, sometimes denoted by $t_{1/2}$ (figure 1.7).

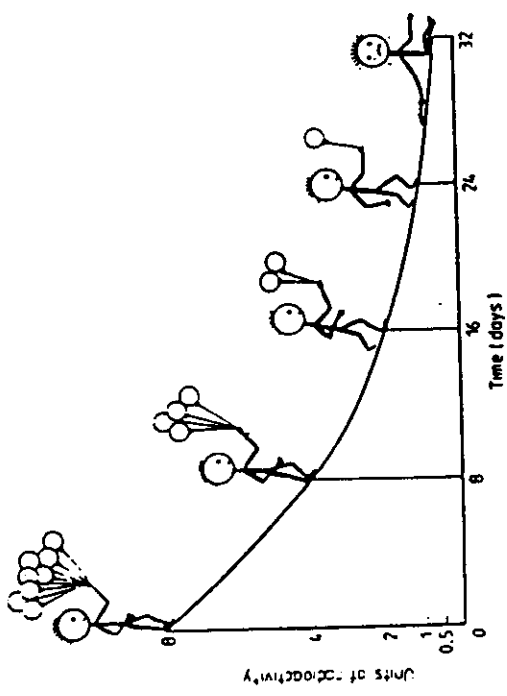


Figure 1.7 Schematic diagram of the radioactive decay of an isotope with a half-life of eight days. The arbitrary units of radioactivity are given on the vertical scale of the graph and are also represented by the number of balloons. After four half-lives (32 days) the amount of radioactivity remaining has considerably reduced.

Thus the time taken for 1600 atoms of a radioactive isotope to decay to 800 atoms is $t_{1/2}$, for continued decay to 400 atoms a further $t_{1/2}$ Half-lives (table 1.2) can vary from parts of a second to thousands of years. For example, ^{226}Ra , used for many years in the therapeutic treatment of cancer, has $t_{1/2} = 1620$ years whereas $^{99\text{m}}\text{Tc}$, now used in nuclear medicine to diagnose abnormalities in the brain, liver and bone, has a half-life of only six hours. The major gamma ray energies differ with different radioactive isotopes. Consequently radiation protection facilities have to be designed

Table 1.2 Half-lives and gamma ray energies of some of the radioactive isotopes used in medicine.

Radionuclide and mass no	Major gamma ray energy (MeV)	Half-life
Radium-226	0.029–2.43	1620 years
Cesium-137	0.662	30 years
Cobalt-60	1.17, 1.33	5.3 years
Iridium-192	0.296–0.613	74 days
Iodine-131	0.364, 0.637	8 days
Gold-198	0.411	2.7 days
Technetium-99m	0.140	6 hours

accordingly, taking into account the gamma energy as well as the initial amount of radioactivity, the half-life and the physical state—solid, liquid or gas.

1.12 X-RAYS

X-rays were discovered in Würzburg, Germany on 8 November 1895 by Wilhelm Röntgen (1845–1923) when he was investigating the phenomenon of the passage of an electrical discharge from an induction coil through a partially evacuated glass tube. Although the tube was covered in black paper and the whole room was in complete darkness, he observed that a paper screen covered with a fluorescent material became illuminated. These strange new rays were also found to penetrate other objects, such as a wooden plank, a thick book and metal sheets. X-rays had been discovered and the first public announcement was made that year in December under the title 'On a new kind of ray'. Generally, this discovery was received with acclaim and headlines appeared entitled 'Illuminated tissue', 'Electrical photography through solid bodies' and other such unusual descriptions, though at least one magazine remarked on the 'revolting indecency of seeing other people's bones'. X-ray pictures of hands, purses, Egyptian mummies and small animals were soon taken for demonstration purposes in many countries (figure 1.8).



Figure 1.8 An early demonstration x-ray picture: an American frog exhibited at the 1898 Röntgen Society Presidential Conversation in London and later published in the *Archives of the Roentgen Ray*.

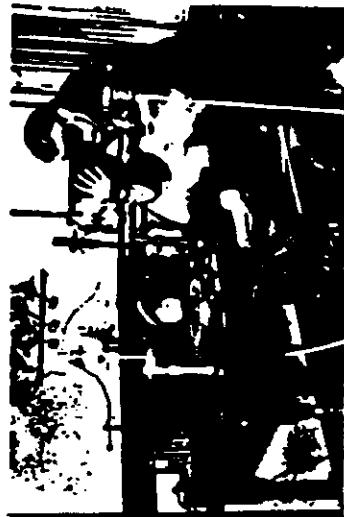
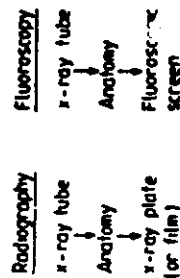


Figure 1.9 Diagnostic x-ray apparatus in New York, 1896. The arrangement is for both radiography and fluoroscopy.

Immediately after the discovery of x-rays, attempts at radiation protection procedures were virtually non-existent because the harmful effects of ionising radiation had not been realised. Figures 1.9 and 1.10 show early diagnostic and therapeutic x-ray apparatus without any protective shielding surrounding the x-ray tubes, or any method of collimating the x-ray beam

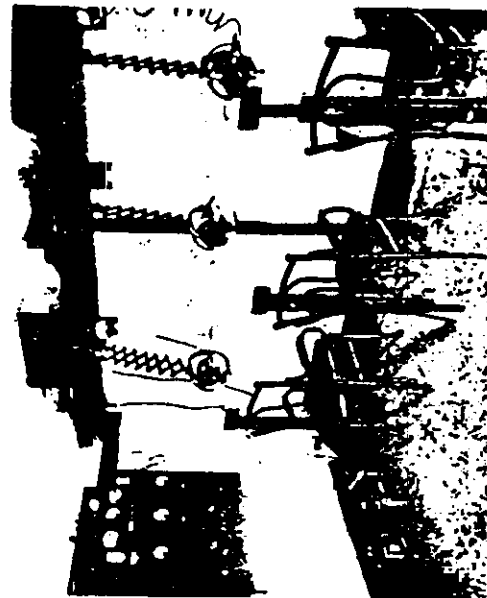


Figure 1.10 Therapy apparatus in The London Hospital, 1913.

CHAPTER 2

RADIATION RISK

towards the area of interest. Radiography and fluoroscopy are taking place simultaneously but neither man is wearing any protective lead apron. Protection during therapy was no better than during diagnosis and in figure 1.10 the treatment chairs are so close together that if three patients were being treated simultaneously they would be likely to receive radiation from all three x-ray tubes.

Radium sources were also used, around 1903, to try to obtain diagnostic images of hands and small animals such as mice. However, with the high energy of radium gamma rays (see table 1.2) compared with the low energy of x-rays at that time (some 50 keV) no contrast was obtained and bone and soft tissue images were unobtainable. The dangerous habit of placing one's hand on a radium source for long periods of time was thus avoided.

2.1 EARLY HISTORY

When the initial discoveries of x-rays, radioactivity and radium were made it was not immediately realised that they could have a harmful effect. This was partly because of their latent effect but even so, some of the radiation injuries of the early pioneers were initially attributed to agents, such as electrical effects, ultraviolet and platinum particles from x-ray tubes. It can be seen in figures 1.9 and 1.10 that x-ray apparatus at the start of this century was often unprotected by any lead shielding: figure 4.2 shows that the x-ray output was often measured as an erythema dose by self-exposure of the physician's skin. Furthermore, the hand was frequently used as a test object for demonstration purposes by x-ray engineers. These factors led to cases of radiation dermatitis and chronic ulceration, eventually resulting in radiation induced cancers. In many instances the pioneer radiologists and x-ray technicians had to submit to amputation of all or part of a hand as a curative measure, although this was often too late.

The first recorded case of radiation-induced cancer was demonstrated in October 1902 at the Hamburg Medical Society. 'This unfortunate patient was an employee in a factory making roentgen tubes. In 1898 he used his right hand as a test object. Two years later an ulcer developed in the radiated area which was diagnosed as carcinoma. Amputation of the arm was done in 1902. Two years later there was recurrence in the axilla and the death resulted in 1906. Although he was the first actually to develop roentgen cancer, many other workers, mostly physicians, who had been exposed about the same time or even earlier, developed carcinoma during the next few years. By 1911 a monograph on the subject detailed 54 cases from European and American clinics.' Early treatments also contained elements of risk to the patient since the effects of radiation were not fully understood and one example is that of a five year old girl treated in December 1896 in Vienna, only 13 months after the discovery of x-rays. The treatment was given for hirsuties and an artificial alopecia was produced over the whole of the back which had been exposed to x-rays two hours per day for some 16 days. The hair started to fall out after 12 days and after total epilation a violent dermatitis set in which

healed only very slowly. The doctor in charge remarked that 'this accident was full of instruction' and in future he reduced the exposure to ten minutes duration. This case marked the beginning of radiotherapy.

As well as the epiloatory effect of x-rays, in March 1896 Thomas Edison, the foremost American inventor of his era and responsible for both the electric light bulb and the phonograph, reported that his eyes were sore after experimenting with x-rays. Indeed, his laboratory was involved in an attempt to produce room lighting by means of an x-ray tube. This had calcium tungstate fused into the glass walls of the tube to produce a fluorescent lamp of several candle power. However, once the harmful effects of radiation had become obvious in terms of the ulceration suffered by one of his assistants, Edison concluded that 'it would not do, and would not be a very popular kind of light, so I dropped it'.

Radium burns as well as x-ray burns were also noted: for example, both Pierre Curie and Henri Becquerel suffered radium burns on their hands and fingertips where they had handled radium sources. Indeed, it was an accidental burn received by Becquerel in April 1901 that led to radium therapy being proposed. Becquerel had carried in his shirt pocket for six hours a tube of radium loaned to him by the Curies and ten days later a burn was noticed. This was recognised as identical with x-ray dermatitis and radium was used therapeutically at St Louis Hospital, Paris, for the treatment of lupus and other dermatological conditions. Later, in Becquerel's 1903 Nobel lecture, he remarked that the use of radium was being explored for the treatment of cancer.

As well as the medical and technical pioneers some of the patients treated with x-rays or radium for benign conditions also eventually suffered from radiation-induced cancers. A series of these case histories was collected by Sir Stanford Cade in the *British Journal of Radiology* (30 393-402) in 1957. The latent periods between irradiation and diagnosis of the induced cancer vary widely in the literature and have been reported as long as 56 years, although the mean value for the Cade data is 30 years. Many of the documented cases referred to irradiation for cosmetic purposes by a 'beauty specialist' or a 'commercial firm' and cosmetic preparations containing radium were widely available (figure 2.1). Indeed, tubes and pots of radium paste continue to be found in old houses and antique shops from time to time, as do other rather alarming items: for example, a radium impregnated electric blanket and several soda syphon bulbs containing the gaseous daughter product of radium, radon. Radon, also known as radium emanation, was recommended as a health cure for inhalation and closed chambers were built, known as 'Emanatoriums' or 'Inhalatoriums'. In addition, radon was prescribed for gout and rheumatism in drinking water. Other unusual remedies included injections of vaseline impregnated with radon (1909) and radioactive mud used in the form of poultices (1913). Some of the early experiments (1900-1910) were also highly undesirable from the protec-



Figure 2.1 Radium ointments: No 1 is described as 'for all septic conditions' and No 2 as 'for all skin infections'. Thorium A, also a radioactive isotope, was in 'dols' rub cream'; boxes of 'radium vitae face powder' were also on sale. (Courtesy: National Radiological Protection Board, Harwell.)

tion point of view, such as the burning of radium bromide in a bunsen flame merely to determine the colour, carmine, and a study of the effect radium had on cholera germs and the bacilli of tuberculosis, diphtheria and typhus. In the latter, '5 cc of a very poisonous broth was injected under the skin of both ears of a rabbit and one ear exposed to uranium rays—no inflammation occurred in the treated ear'.

2.2 OCCUPATIONAL HAZARDS

2.2.1 Uranium miners

The earliest known cases of cancer induced by radioactivity were well before Becquerel's discovery in 1896 and were found in the Erzgebirge (Ore Mountains) which separate Saxony from Bohemia, in the uranium mines of Joachimsthal (Jáchymov) and Schneeberg. As long ago as the sixteenth century, Paracelsus (1493-1541) described the occupational diseases of the ore miners and included a disease which killed in the prime of life. It was not until three centuries later that this locally known *bergkrankheit* (mountain sickness) was identified as cancer of the lung and attributed to working in a high atmospheric radon environment. The estimated number of miners' deaths from lung cancer was 400 at Schneeberg during the period 1869-1939. At Jáchymov the 336 deaths attributed to lung cancer from

1875–1939, represented some 43% of all deaths for that period at the Jáchymov mine. (This was the mine from which the Curies obtained their pitchblende ore.) Mortality statistics are also available from other uranium mines: for example in Colorado, USA, 22 deaths from lung cancer were observed from 1950–65, whereas only six deaths were expected from a knowledge of mortality patterns among the general population with the same age and sex distribution.

2.2.2 *Watch dial painters*

Another occupational radiation hazard which has been well documented was the ingestion of radium salts during the period 1916–24, when girls painting watch dials with luminous paint developed the habit of pointing the brush between their lips. Many of them regularly ingested small amounts of radium over a considerable period of their working lives. This hazard was observed in two factories, one in New Jersey and the other in Connecticut, and this habit was prohibited in the United States in 1924. The early deaths attributed to this radiation hazard were due to aplastic anaemia and necrosis of the jaw, but deaths continued to occur well after 1924. The average cancer induction period for the 14 recorded deaths from osteogenic sarcoma was 23 years; three deaths from cancer of the paranasal sinuses were also recorded 14, 33 and 34 years after exposure.

2.2.3 *Radiologists, radiotherapists and radiumtherapists*

As the pioneers of the initial medical and industrial uses of x-rays were unaware of the radiation hazards, so too were those involved in early medical usage of radium, so much so that many radium skin burns were suffered and, in certain cases, cancers were induced. There have been several studies specifically undertaken to examine the mortality experience of radiologists, radiotherapists and radiumtherapists and other physicians whose work involved the medical applications of x-rays and radioactive materials, such as radium and radon. A major review of the life expectation of British radiologists was made in 1958 and the causes of death during the period 1897–1957 of 1377 male radiologists were studied. It was found, perhaps somewhat surprisingly, since the population included most of the pioneer British radiologists, that for the period 1897–1920† there was no evidence that occupational radiation exposure had caused a detectable non-

†The periods 1897–1920 and 1921–57 were chosen for analysis because the first recommendations of the British X-ray and Radium Protection Committee were issued in July 1921, and from this date it could be expected that radiology was practised under better conditions of radiation protection.

specific shortening of life expectation. For this period there were 302 deaths observed from all causes, whereas the expected number from the general population with a similar age structure was 324. When causes of death due to cancer were separately analysed, there were 55 cancer deaths in the pre-1921 group compared with an expected number of 47.7 from the general population. The post-1920 experience was an observed number of 24 cancer deaths, compared with an expected number of 38.3 from the general population. However, the number of cases of death from cancers of different types were so small that it would only have been possible to detect gross differences in mortality. Nevertheless, from the data available there did not appear to be an excess mortality in the pre-1921 group from skin cancer. No excess mortality from cancer was found in the post-1920 radiologist group, but since the analysis was conducted in 1957, it might have been too early to detect any such excess.

Studies on the mortality experience of American radiologists and physicians are based on larger populations than the British study. These include a review in 1964 of the mortality of 3521 members of the Radiological Society of North America, 6791 from the American College of Physicians and 6027 from the American Academy of Ophthalmology and Otolaryngology. The American studies also grouped their data by time periods and, as with the British data, they found that any patterns of excess mortality or life expectation shortening in later years were disappearing.

2.3 HIROSHIMA AND NAGASAKI

The most extensive study of radiation-induced leukaemia is not for radiologists but for a cohort of 109 000 survivors of the atomic bomb explosions at Hiroshima and Nagasaki. The results can be found in a series of *Life Span Study* reports issued by the Japanese Ministry of Health and Welfare (JNH) in cooperation with the Atomic Bomb Casualty Commission (ABCC) which, since April 1975, has been replaced by the Radiation Effects Research Foundation (RERF). In addition, reports are also to be found in the general literature. Data available in 1972 for the observed and expected deaths from leukaemia for the total cohort are shown in figure 2.2. The follow-up data are analysed in terms of age group at the time of the explosion, and by estimated dose levels in the ranges 0–9, 10–49, 50–99, 100–199 and 200+ cGy†. The risk of leukaemia has decreased since the peak period of 1950–54 when the mortality ratio was 15/0.19 = 79 for the

†A cGy, also known as a rad, is a unit of measurement of absorbed dose. For further explanation see §4.3.

200 + cGy radiation dose group and $5/0.20 = 25$ for the 100–199 cGy dose group. The risk for the more highly irradiated groups (100–199 and 200 + cGy), both for leukaemia and other neoplastic disease, is higher among survivors who were children under ten years old at the time of irradiation. The risk from cancers other than leukaemia increased from about 1960 to 1965 in the groups exposed to 100 cGy or more, but the susceptibility to radiation-induced cancers differed by organ. However, there was a definite association between atom bomb radiation and thyroid, lung and breast cancers, and a possible relation for salivary gland and stomach cancers.

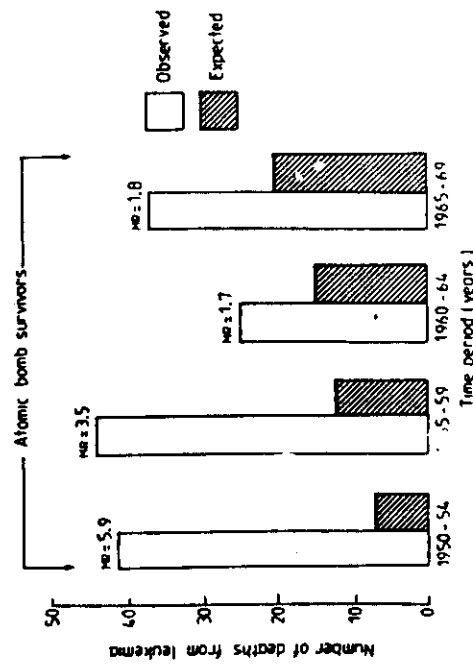


Figure 2.2 Leukemia mortality statistics for Japanese atomic bomb survivors.

$$\text{Mortality ratio (MR)} = \frac{\text{Observed deaths}}{\text{Expected deaths}}$$

2.4 RISK ESTIMATES

Estimating the risk of death per year for an individual from various causes and in various occupational groups is an extremely complex exercise. Methods of stating mortality risks vary and they could be presented in any of the following ways†.

Risk per population sample per year, e.g. for the USA from the 1970 Statistical Abstract of the United States.

Risk of death per year from *heart disease* was 364 out of 100 000 (a probability of $364/100\,000 = 0.00364$).

Risk of death per year from *cancer* was 157 out of 100 000 (a probability of $157/100\,000 = 0.00157$).

Fatal accident frequency rate (FAFR). Defined as the number of fatal accidents in a group of 1000 men in a working lifetime (100 million hours) e.g. for various United Kingdom industries.

Industry	FAFR
Construction	67
Railway shunters	45
Fishing	36
Coal mining	14
Agriculture	10
Metal manufacture and shipbuilding	8
Chemical industry including the Flixborough accident	5
Vehicles	1.3
Clothing and footwear	0.15

Average reduction in lifespan in days, e.g. of one year of working life of a person aged 40 years.

Industry	Lifespan reduction
Deep-sea fishing	31.9
Coal mining	3.6
Oil refinery	2.6
Railways	2.2
Construction	2.1

Comparative risk. The following incur a one in a million risk of death.

650 km air travel
100 km car travel
Smoking three-quarters of a cigarette
1.5 min mountaineering
20 min of life at age 60 years
Use of oral contraceptive pills for 2.5 weeks
Drinking half a bottle of wine

†Data taken from the *IAEA Bulletin*, Vienna, 1980 22 No 5/6. These were adapted from presentations at a symposium on *The Respective Risks of Different Energy Sources*, Paris, January 1980.

Risk of death per person per year for a given activity. These can be compared with the probabilities given above for cancer and for heart disease (which can also be written as 157×10^{-5} and 364×10^{-5}). These may be voluntary, such as cigarette smoking, or involuntary, such as a road accident.

Activity	Mortality risk per person per year ($\times 10^{-5}$)
Smoking 20 cigarettes per day	500
Motor cycling	200
Car racing	120
Drinking one bottle of wine per day	75
Car driving	17
Road accident in the USA	5
Road accident in the UK	4.5
Rock climbing	4
Taking contraceptive pills	2
Floods in the USA	0.22
Tornadoes in mid-West USA	0.22
Earthquakes in California, USA	0.17
Falling aircraft in USA	0.01
Flooding of dykes in Holland	0.01
Bites and stings of snakes etc, UK	0.01
Falling aircraft in the UK	0.002

These statements of mortality risks do not give anything about the acceptability of risk which is fraught with even more problems of specification and agreement than merely factual statements of mortality risks. In medicine, when a life threatening disease such as cancer is present, the benefits of early diagnosis, even if it requires a radiation exposure, and the benefits of radiation therapy, can be relatively easily assessed by the individual and the doctors concerned. This is particularly so when there is a wealth of evidence to show that, in general, a much better prognosis exists the earlier the malignant disease is treated. Good radiation working practices have virtually eliminated major radiation accidents within medicine and nowadays public concern over radiation hazards is directed towards nuclear reactor establishments and nuclear missile sites.

Radiation risks, quoted in a similar manner to those above and those published by the International Atomic Energy Agency (IAEA) are as follows (see §4.5 for an explanation of the radiation measurement units mSv and mrem).

Exposure	Leukemia mortality risk per million population per year
10 mSv (1000 mrem) whole body radiation	1
35 years natural radiation	3.7
35 years within 6 miles of a nuclear power reactor or a military base	3.7

This can be compared with deaths from all the spontaneous leukaemias in the USA of 67 per million (Statistical Abstract USA 1970). The estimated probable dose at the boundary of the nuclear power station was 0.05 mSv (5 mrem) per year and at 6 miles, 0.006 mSv (0.6 mrem) per year, compared with an average natural background radiation level in the United States of 1.05 mSv (105 mrem) per year.

Average reduction in lifespan in days, e.g. of one year of working life of a person aged 40 years.

Occupational exposure	Lifespan reduction
50 mSv (5 rem) per year	1.3 days
5 mSv (0.5 rem) per year	0.1 days

Comparative risk. Incurring a one in a million risk of death:

0.1 mSv (10 mrem) exposure received by living for three years in the vicinity of a nuclear power plant.

In terms of occupational irradiation dose equivalents received by workers in medicine and in the nuclear industry in the United States and the United Kingdom, table 2.1 summarises measured dose equivalents in mSv, where 100 mrem = 1 mSv. These can be related to the risks stated above.

In conclusion, figure 2.3 (from the IAEA's publication, *Radiation—A Fact of Life*) illustrates the points that the major contribution to the average

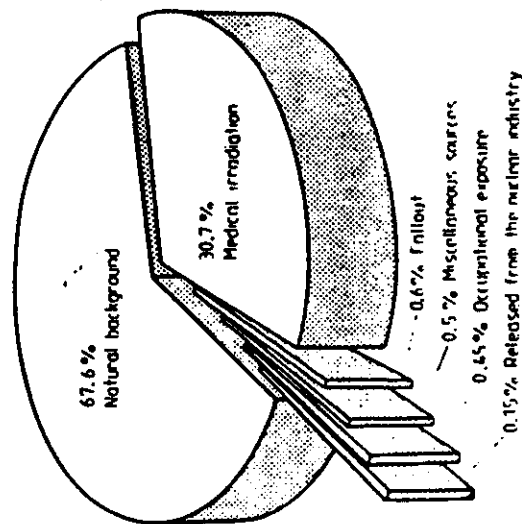


Figure 2.3 Percentage contribution to the overall effective dose

Table 2.1 Occupational radiation dose equivalents. (Data for USA from National Academy of Sciences Report, Washington, 1980 in *IAEA Bulletin* 22 No 5/6 October 1980 M Tubiana p 115. Data for UK in 1975 from *Radiological Protection Bulletin NRPB* No 24, July 1978 *Radiological protection pilot study in medical establishments* B Holliday and J R Gill p 14.)

(a) United States of America

Population	Occupation	Hazards	Average dose equivalent (mSv/year)
200 000	Doctors, technicians	X-rays in medicine	3.0-3.5
200 000	Dentists, technicians	X-rays in dentistry	0.5-1.25
100 000	Doctors, technicians	Handling radioactive isotopes	2.6-5.4
30 000	Personst	Civilian nuclear power plants and reactors	6.0-8.0
35 000	Personst	Naval nuclear propulsion plants e.g. submarines	1.3-3.3
100 000	Personst	Engaged in R and D work with ionising radiation in civilian research centres, universities, etc.	1.3-3.3

(b) United Kingdom

Recorded total dose equivalent for 1975 (mSv)	Number of persons in stated dose equivalent range			
	Diagnostic x-ray departments	Therapy departments	Therapy wards and theatres	Laboratories
0-0.99	230	8	1	3
1.00-1.99	1	23	17	26
2.00-2.99	1	84	33	17
3.00-3.99	0	9	3	4
4.00-4.99	0	7	7	0
5.00-9.99	0	3	6	0
10.00 +	0	0	2†	0

† These people are regarded as occupationally exposed.

‡ Values 11.00 and 13.00 mSv.

dose equivalent is from natural background radiation, the largest man-made contribution is from the medical uses of radiation and that the nuclear power industry is a small contributor to the average radiation dose equivalent. From the same publication comes the comments of the IAEA on risk.

Today we are much more conscious of risks than people were 25 or even 5 years ago. This is partly because of better education, partly because the applications of science and technology have brought with

them new and sometimes imperfectly understood risks, but also partly because of the speed with which news can be brought to our attention. It is not the scale of today's disasters, such as millions of gallons of oil polluting beaches, or hundreds of deaths in a single aviation accident, that makes the difference. After all, in the fourteenth century the Black Death killed some 25 million people in six years and the Great Plague of 1665 wiped out 20% of the population of London. More recently, the influenza pandemic of 1918 killed more than 20 million people.

What does make the difference is the speed with which information about such events is now disseminated around the world. We can learn about them within minutes of their having taken place. However, we must often rely on the interpretations of people who may be thousands of miles from the scene and are just commenting on what they have heard.

Radiation and the risks of radiation command considerable public attention. However, it is not generally realised that safety regulations are much stricter for radioactive materials than for other dangerous substances. For example, nuclear power stations emit radioactive materials; oil- and coal-fired power stations discharge sulphur dioxide (as much as 20 000 to 30 000 tonnes per year from a single large power plant). But in terms of the corresponding lethal doses of these radioactive materials and of sulphur dioxide, the emission limits for nuclear power stations are 100 times lower than they are for oil- and coal-fired stations. This is only one facet of air pollution and air pollution in turn is only one factor to be considered in determining the relative merits of different energy sources. Furthermore, in the case of coal, it has been estimated that in Pennsylvania 30 000 miners died in the mines between 1870 and 1950—an average of about *one man a day for 80 years*. Next to such appalling tolls, the safety history of the nuclear power industry is uniquely encouraging. Radioactive elements gradually lose their radioactivity—and their toxicity—with time. Other non-radioactive materials (for example, arsenic) remain toxic for ever. It has recently been reported by the director of the Mario Negri Research Institute in Milan, that three years after the accidental chemical release in Seveso, Italy, in July 1976, there is still no sign that the toxicity of the dioxin deposited in the region is diminishing. Illustrative examples such as this one demonstrate how radiation risks tend to be viewed separately from other, and sometimes greater, risks.

CHAPTER 3

RADIATION ABSORPTION AND ATTENUATION

3.1 INTERACTION OF X- AND GAMMA RAYS WITH MATTER

There are three main types of interaction between x- or gamma rays and matter: the photoelectric effect, the Compton effect and pair production. These processes are quite complex and are only briefly described below. However, some general statements relating to photon attenuation and scattering can be made with respect to the energy of the incident radiation, the atomic number, Z , of the absorber, the density of the absorber and the thickness of the absorber. The attenuation will increase

- (i) the greater the thickness of the absorbing medium,
- (ii) for a given absorber thickness, the greater the atomic number, Z ,
- (iii) for a given absorber thickness, the greater the density.

These and other factors must be considered when designing radiation shielding.

In the *photoelectric effect* an x- or gamma-ray photon interacts with a bound electron. The photon transfers all its energy to the bound electron, which is then ejected. This *photoelectron* loses its kinetic energy in collisions with other atoms, causing ionisation and excitation as it does so along its path.

Energy of x- or gamma-ray photon = Energy of photoelectron + Energy required to eject the electron from the atom, the *binding energy*.

The binding energy of, for example, the K shell of iodine, is 29 keV. The atom involved in the original interaction is left with a net positive charge, since it is now one electron short. This is an unstable state and the empty orbit may be refilled by another electron from outside the atom. This electron will lose potential energy as it falls into the orbit equivalent to the amount of energy used to remove the electron in the original photon interaction, 29 keV for the iodine K shell. This energy is given out as a single

photon and, since it is characteristic of the orbit refilled, it is called *characteristic radiation*.

In the *Compton effect*, the x- or gamma-ray photon is not absorbed but is only scattered with a reduced energy. The incident photon therefore loses only part of its energy and not all, as in the photoelectric effect. This interaction occurs with electrons which are considered 'free' since Compton scattering occurs when the binding energy is small compared with the energy of the incident photon. The *recoil electron* in this interaction is sometimes termed a Compton electron and its energy is used up in producing ionisation.

Pair production occurs with x- and gamma-ray photons of very high energy, above 1.02 MeV, when there may be interaction between a photon and the very intense electric field of the nucleus. The photon 'disappears', its energy is used to create two particles, an electron and a positron. The electron-positron pair lose their energies along their paths by producing ionisation. Usually, after losing its kinetic energy, the positron will combine with an electron and the two particles disappear. Their equivalent rest mass energy of 1.02 MeV will reappear as radiation in the form of two photons of 0.51 MeV emitted in exactly opposite directions. This is referred to as *annihilation radiation*.

These interaction mechanisms are not equally important at all photon energies or for all absorber atomic numbers, Z —for example, pair production only occurs above a photon energy of 1.02 MeV. For human tissue, with an effective $Z = 7.8$, the photoelectric effect is important up to 50 keV, the Compton effect is important above 30 keV and pair production above 10 MeV. Table 3.1 and figure 3.1 summarise the relative importance of these absorption processes with atomic number and photon energy. Figure 3.1 also indicates the value of Z for human tissue, for lead which is

Table 3.1 Relative importance of absorption processes.

Absorption process	Secondary products of the x-, gamma-ray interaction	Dependence on atomic number, Z	Dependence on x-, gamma-ray photon energy, E
Photoelectric effect	Photoelectron, characteristic radiation	Proportional to Z^4	Proportional to $1/E^3$
Compton effect	Scattered photon of lower energy than the incident photon, recoil electron	Independent of Z	Decreases slowly with increasing E
Pair production	Electron positron pair, annihilation radiation	Proportional to Z	Increases with E : above 1.02 MeV

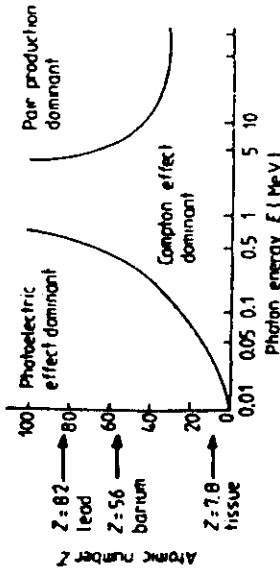


Figure 3.1 Relative importance of absorption processes.

widely used for protection in the form of lead bricks, lead glass and lead rubbers and barium, a constituent of shielding materials such as barium plaster and barium concrete.

3.2 EXPONENTIAL ATTENUATION

If a narrow beam of x- or gamma-ray photons is incident upon a certain thickness of absorbing material, perhaps lead or concrete, it has been found that the attenuation of the photon beam is exponential. That is, the same fraction of the total energy of the photon beam is always absorbed by the addition of the same thickness, say *T* mm, of an absorber. Thus if *T*_{1/2} mm attenuates the beam by 50% the attenuation will be as given in table 3.2. This

Table 3.2 Exponential attenuation. The absorbing thickness *T*₁, termed the *half value thickness* (HVT) or *half value layer* (HVL). A *tenth value layer* (TVL) or *thickness* (TVT) would attenuate the beam by 10% rather than 50%. Specification of shielding properties by statements of HVT and TVT is a convenient method (see also table 3.3).

Absorber thickness <i>T</i> (mm)	Photon energy transmitted through absorber (%)
0	100
1 <i>T</i> _{1/2}	50
2 <i>T</i> _{1/2}	25
3 <i>T</i> _{1/2}	12.5

pattern of attenuation is similar to that of *radioactive decay*, illustrated in figure 1.7 when the term *radioactive half-life* was introduced. This exponential pattern of decrease can be expressed using a mathematical formula

$$I_T = I_0 \exp(-\mu T)$$

where exp is the symbol for exponential, *T*, the absorber thickness, *I*₀, the radiation exposure incident on the absorber, and *I*_{*T*}, the radiation exposure after attenuation by a thickness *T* (see tab 3.2 and 3.3). It can also be shown that

$$\mu = 0.693/T_{1/2}.$$

Figure 3.2(a) illustrates the data from table 3.2 and the attenuation follows an exponential curve. However, in figure 3.2(b) a *semi-logarithmic* plot (the vertical axis is a logarithmic scale) shows the data from table 3.2 as a straight line. Semi-logarithmic graph plots are always straight lines for a pattern of exponential decrease or increase. Examples of semi-logarithmic graph plots of radioactive decay for some of the radioactive isotopes used in medicine are shown in figure 3.3. In this figure the horizontal axis is time instead of absorber thickness and the vertical axis is a logarithmic plot of the percentage of remaining activity.

Table 3.3 Tenth value thicknesses for various materials at three x-ray photon energies often encountered in x-ray diagnosis (data are for broad beam conditions) (Keane and Tikhonov 1975, table 5, p 83).

Absorbing material	Density g cm ⁻³	Tenth value thickness (mm)			
		50 kV	100 kV	150 kV	
Lead	11.3	0.18	0.84	0.96	
Concrete	2.35	13	55	70	
Brick	1.8	36	104	145	
Gypsum	0.84	45	172	260	

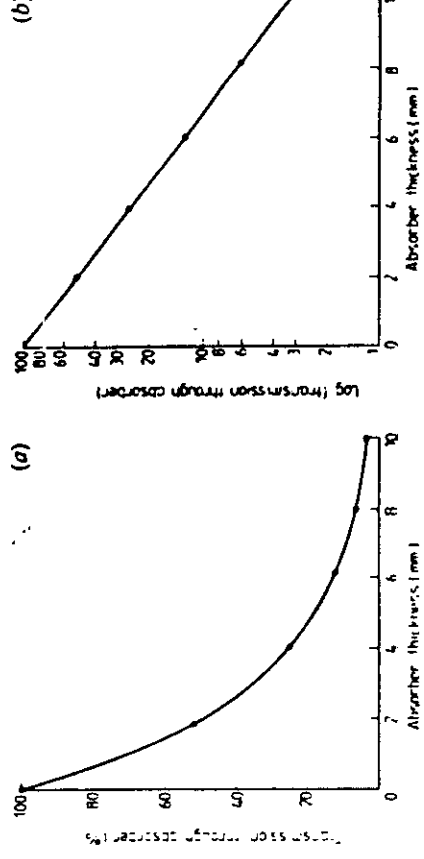


Figure 3.2 Exponential attenuation: data from table 3.2 with *T*_{1/2} = 2 mm, (a) linear plot; (b) semi-logarithmic plot (i.e. the vertical scale is logarithmic, and the horizontal stays linear).

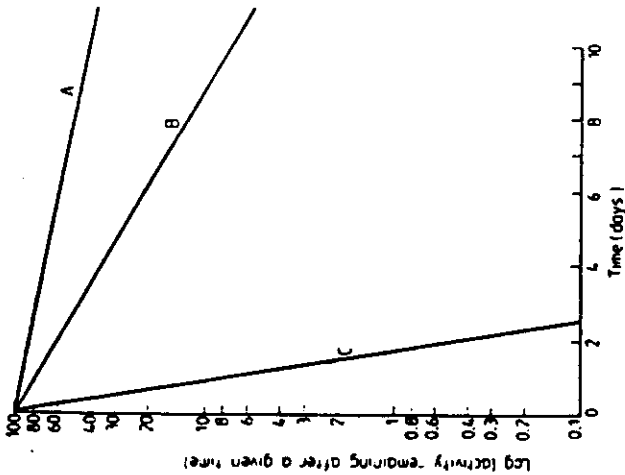


Figure 3.3 Exponential decay of the radioactive isotopes: A, ¹¹¹In half-life = 8 days; B, ¹⁹⁸Au half-life = 2.7 days; C, ^{99m}Tc half-life = 6 hours (see also figure 1.7).

3.3 THE INVERSE SQUARE LAW OF RADIATION

The three important features of good radiation protection can be summarised by the words *absorber*, *distance* and *speed*. The use of an absorbing shield to attenuate a beam of radiation has just been described. In addition, though, use can be made of the distance factor by ensuring that one is not unnecessarily close to the radiation source. For example, when dispensing radioactive materials in a laboratory this should not be undertaken using fingers, but using long-handled forceps, tongs or tweezers—a protective use of the distance factor.

As the distance from a radiation source increases the radiation exposure (see §4.2) decreases, and this relationship obeys the *inverse square law of radiation* which states that

the exposure rate is inversely proportional to the square of the distance from a point source of radiation.

At *large distances* from a source such as an x-ray tube or linear source of radioactive material (radium, caesium-137) the source can be assumed to act as a point source. If the exposure rate at 1 cm from a point source is I_1 and the distance from the source is d , then the exposure rate, I_d equals I_1/d^2 using

Table 3.4 The inverse square law of radiation
 $I_d = I_1/d^2$.

Distance d (cm)	Exposure rate I_d
1	I_1
2	$I_1/2^2 = I_1/4$
4	$I_1/4^2 = I_1/16$
8	$I_1/8^2 = I_1/64$
16	$I_1/16^2 = I_1/256$

the inverse square law (see table 3.4 and figure 3.4). This d^2 factor means the exposure rate decreases rapidly as you move away from the radiation source. Only simple arithmetic is needed to see that it is wrong to assume that quick handling of radioactive sources in the fingers (a very small distance) results in a reduced radiation dose when compared with a longer time using long-

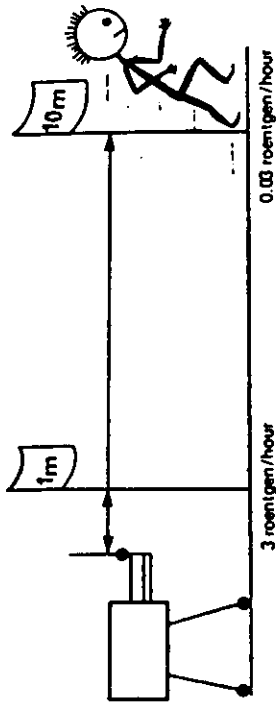


Figure 3.4 The Inverse Square Law of Radiation. Dose rate is proportional to $1/d^2$, thus above $3/10^2$ R/h = 0.03 R/h.

handled instruments to keep a greater distance from the source. Thus, if when handling a radioactive source one used fingers at, say, 1 cm and took one minute then the exposure would be I_1 . If a long-handled instrument was used at, say, 8 cm and one took four minutes then the exposure would be $4 \times (I_1/64) = I_1/16$ (table 3.4). In other words, one would receive a radiation exposure sixteen times smaller than if fingers only had been used, even though it took four times as long. It should be remembered that, when calculating radiation exposures, the inverse square law attenuation *and* the exponential attenuation through absorbing barriers must both be considered.

CHAPTER 4

RADIATION MEASUREMENT

4.1 EARLY RADIATION UNITS

Between the time x-rays and radium were discovered and when the *roentgen* unit was internationally accepted as a unit for both x- and gamma rays, 1937, at least 50 other radiation units were suggested, all based on various radiation effects. For example, units of measurement were defined which depended upon: photographic film blackening, chemical colour change (figure 4.1), fluorescence, temperature variation, x-ray tube current, the change in electrical resistance of a selenium layer, biological effects and ionisation.

In the first few years following the discovery of x-rays, many pioneers used self-irradiation of the arm or hand to test the quality of the x-ray

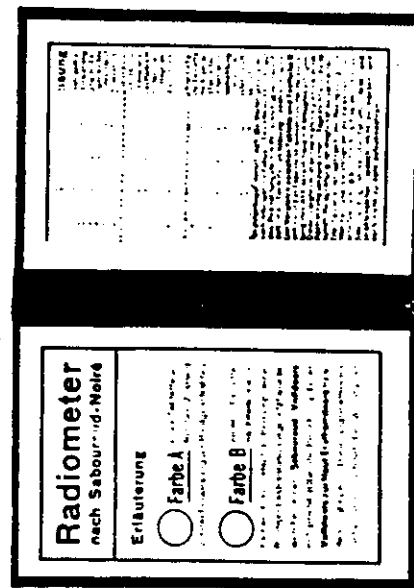
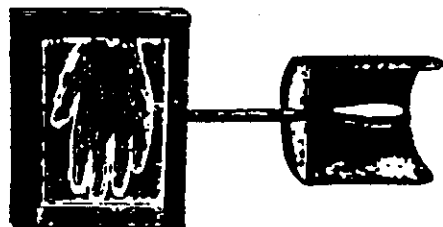


Figure 4.1 The most well known radiation unit depending upon a chemical colour change subsequent to radiation exposure was the *pastille* unit devised in 1904 by Sabouraud and Noire. Small capsules of barium platinyocyanide, purchased in small booklets, were irradiated and the colour change, from Tint A to Tint B, indicated a radiation dose of one pastille unit.

apparatus. The *chiroscope*, using a skeleton hand (figure 4.2) and similar devices such as the *osteoscope* devised in 1904 using a skeleton hand, forearm and elbow joint, did not entirely eliminate the self-exposure to x-rays. For instance, in 1927, when the *erythema dose* was discussed for the determination of x-ray patient exposure, the comment was made that 'because of medico-legal complications it is better for the operator to use his own skin'.

Figure 4.2 The *chiroscope*. The first quality assurance test object for x-rays. At a meeting in May 1903 of the Röntgen Society in London, it was stated that

Almost every worker with x-rays has to use the fluorescent screen very frequently in order to test the condition of his tube by reference to a shadow of his own hand. This process has so often to be gone through that most workers have had to suffer from more or less acute inflammation of the skin of their hands. To obviate this is the function of the *chiroscope*. This instrument consists of an articulated skeleton hand suitably mounted behind a small fluorescent screen which is to serve as a test object. The fleshy parts of the hand are represented by suitably cut-out tin foil, and the whole is mounted on a holder, the construction of which affords protection to the hand of the operator.



Not all measurement methods were very practical, such as the one where a thermometer placed in a depression in the wall of an x-ray tube would somehow provide a good indication of radiation dose (1914), or an idea based on the radiation effect on mice (1926), or a proposal that 'the depilatory property of x-rays, which is most remarkably constant in its effect, should be used as a method of measuring dosage' (1927)—the latter would have resulted in a large number of bald-headed hospital workers if it had been implemented! Units such as the skin or threshold erythema dose were however used for many years with radium and x-rays to provide a working measurement unit. A typical definition in 1933 was

that quantity of radiation which, when delivered at a single sitting, will produce in 80% of all cases tested, a faint reddening or bronzing of the skin, in from two to four weeks after irradiation, and in the remaining 20% will produce no visible effect.

Nevertheless accurate measurement of erythema doses was difficult and comparisons of delivered doses in different institutions were virtually

impossible using biologically based units and those based on the ionisation effect gradually superseded all others. In the late 1970s there was a change from units which had been used for decades to SI units and these are described in §§4.2–4.5 with conversion factors for the previously used units, roentgen, rad, curie and rem.

Some of the more commonly used prefixes for multiples of ten, which are used for absorbed dose, activity (§4.4) and dose equivalent (§4.5), are

μ = micro = 10^{-6}	k = kilo = 10^3
m = milli = 10^{-3}	M = mega = 10^6
c = centi = 10^{-2}	G = giga = 10^9
	T = tera = 10^{12}

4.2 EXPOSURE

The *roentgen* unit mentioned in the previous section was used for more than 40 years as the special unit of the quantity known as *exposure*, where the latest definition of exposure, given by ICRU in 1980 states

The exposure, X , is the quotient of dQ by dm where the value of dQ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated by photons in air of mass dm are completely stopped in air.

Thus $X = dQ/dm$. Exposure therefore relates to ionisation *in air* and not to ionisation in an irradiated medium such as tissue.

The roentgen, as the special unit of exposure until the introduction of SI units, was defined in 1937 as 'the quantity of x- or gamma radiation such that the associated corpuscular emission per 0.001 293 g air produces in air ions carrying 1 esu (electrostatic unit) of quantity of electricity of either sign'. (NB: 0.001 293 g is the mass of air in 1 cm³ volume at 0°C and 760 mm Hg pressure.) In SI units, though, there is no special unit of exposure and measurements are given in coulombs per kilogram (C kg⁻¹). One roentgen is exactly equal to 2.58×10^{-4} C kg⁻¹.

The use of the roentgen unit, denoted by R, was extremely widespread. For example, the radiation output in air from a deep therapy x-ray unit was measured in terms of R min⁻¹. In solid radioactive sources implanted into tumours, the dose calculations involved the use of the specific *gamma ray constant*, Γ , of that radioactive isotope. This relates activity to exposure and the constant, Γ , is numerically equal to the exposure rate in R h⁻¹ at 1 m for an isotope activity of one curie (Ci) source. Alternatively, this constant was earlier known as the *k factor* when expressed in terms of R h⁻¹ at 1 cm from an isotope activity of 1 mCi. Examples of k factors in R h⁻¹ mCi⁻¹ at 1 cm

are:

8.25 for ²²⁶ Ra filtered by 0.5 mm platinum
3.32 for ¹³⁷ Cs
2.34 for ¹⁹⁸ Au
2.23 for ¹³¹ I.

4.3 ABSORBED DOSE

Exposure does not describe the energy imparted to an irradiated material and cannot therefore be used, for example, to specify the radiation energy absorbed by a target volume within a patient treated by external beam radiotherapy. The quantity required is the *absorbed dose*, D , where $D = \Delta E_d / \Delta m$, where ΔE_d is the energy imparted by ionising radiation to the matter in a volume element, and Δm is the mass of matter in that volume element. Prior to SI units, the special unit of absorbed dose was the *rad* where 1 rad = 100 erg g⁻¹. In SI units, the special unit of absorbed dose is the *gray*, Gy, and is equal to 1 J kg⁻¹.

100 rad = 1.0 Gy
1 rad = 0.01 Gy = 1 cGy
1 mrad = 0.01 mGy
10 mrad = 0.1 mGy
100 mrad = 1.0 mGy.

It is also important to note that absorbed dose and exposure may be related using the formula

$$\text{Absorbed dose} = \text{Exposure} \times f$$

where f is a factor dependent upon the quality of the radiation beam and the irradiated material (see table 4.1).

4.4 ACTIVITY

The *curie* was first suggested as the unit of activity in 1910, but was only defined for use with radon, the decay product of radium being used in small seeds for implantation into tumours. The curie unit was defined as 'the quantity of radon in radioactive equilibrium with 1 gram of radium'. Later, it was extended to include all radioactive isotopes as 'A unit of activity which gives 3.700×10^{10} disintegrations per second'. In SI units, the basic unit of activity is the *becquerel*, Bq, which equals one disintegration per second.

Table 4.1 f factor to convert exposure in roentgens to absorbed dose in rads.

Photon energy (Mev)	f factor	
	Water	Bone
0.01	0.90	3.6
0.02	0.87	4.2
0.03	0.87	4.2
0.04	0.88	4.0
0.05	0.90	3.5
0.06	0.91	2.8
0.08	0.94	1.9
0.10	0.95	1.4
0.15	0.96	1.1
0.20	0.96	0.98
0.40	0.97	0.93
0.60	0.97	0.92
0.80	0.97	0.92
1.00	0.97	0.92
1.25	0.97	0.92
1.50	0.97	0.92
3.00	0.96	0.93
5.00	0.96	0.94
10.00	0.95	0.96

Thus $1 \text{ Ci} = 37 \times 10^9 \text{ Bq}$ and $1 \text{ Bq} = 27.03 \times 10^{-12} \text{ Ci}$. Other examples of conversion from curies to becquerels are

$$\begin{aligned} 2 \text{ mCi} &= 74 \text{ MBq} \\ 10 \text{ mCi} &= 370 \text{ MBq} \\ 100 \text{ mCi} &= 3.7 \text{ GBq} \\ 1000 \text{ Ci} &= 37 \text{ TBq}. \end{aligned}$$

4.5 DOSE EQUIVALENT AND RELATIVE BIOLOGICAL EFFECTIVENESS

As part of an attempt to measure the maximum amounts of ionising radiations which people could safely receive, a quantity called the *relative biological effectiveness*, usually referred to as the *rem*, was proposed. Selected values of *rem* were multiplied by the energy of the ionising radiation per unit mass to give the 'rem dose'. The unit of *rem* dose was the *rem*, which denoted roentgen equivalent man. With the introduction of the *rad* as the unit of absorbed dose (§4.3), a quantity called *dose equivalent*, *H*, replaced the old *rem* dose in 1962, where *H* is a weighted absorbed dose given by

$H = D \times Q \times N$, where *D* is the absorbed dose, *Q* is one weighting factor—the quality factor for the ionising radiation—and *N* is the product of all other weighting factors that might modify the biological effects of the absorbed dose *D*. At present, the value of *N* is taken as unity, but future information may cause this to be modified. The *quality factor*, *Q*, is 1.0 for x- and gamma rays, electrons and beta rays, but neutrons have a value of 10.0. Thus the quality factor is extremely important when the effects of different radiations are to be combined, say, for example x-rays and neutrons. In such an instance, the biological response must be taken into account.

The SI unit of dose equivalent is the *sievert*, Sv, where $1 \text{ rem} = 10^{-2} \text{ Sv}$ and $1 \text{ Sv} = 100 \text{ rem}$. Other examples of conversion from rem to sievert are given below:

$$\begin{aligned} 1 \text{ mrem} &= 10 \mu\text{Sv} = 0.01 \text{ mSv} \\ 10 \text{ mrem} &= 0.1 \text{ mSv} \\ 100 \text{ mrem} &= 1 \text{ mSv} \\ 1 \text{ rem} &= 10 \text{ mSv}. \end{aligned}$$

4.6 RADIATION MONITORS

Radiation monitors are radiation detection devices which along with associated electronics can measure ionising radiation exposure or activity for monitoring and surveillance requirements. The types of detector include the ionisation chamber, Geiger counter and the scintillation counter. The first two measure ionising events and the scintillation counter measures fluorescent ones. In addition, radiation effects on photographic film are the basis for the *film badges*. *Thermoluminescent dosimeters* (TLD) are also used in personnel monitoring. However, whereas for the ionisation chamber, Geiger counter and scintillation counter, the associated electronics required for measurement output are physically linked to the radiation detector, film badges and TLD are small devices separated from their measurement recorders, the film densitometer and TLD reader respectively. Illustrations of radiation monitors are given in this chapter but it should be noted that many different types of monitor are commercially available and those presented, although typical, will not be available in all hospitals. However, the type of controls, including push buttons, range switches and meter measurement are likely to be similar.

4.7 IONISATION CHAMBERS

Radiation protection is not designed only for nurses, laboratory technologists, doctors and other health care workers, but also for the patients

themselves. This is illustrated in nuclear medicine diagnostic procedures, in which an amount of a *radiopharmaceutical*, a pharmaceutical 'tagged' with a radioactive isotope, is administered to a patient. Radiation control requires that prior to injection of the radioactive material into the patient, the activity is measured to ensure that it is the correct prescribed activity. This is achieved in the *hot laboratory*, the laboratory where the radioactive 'dose' is dispensed, using an ionisation chamber in the form of a well. Such an instrument is known as an *activity meter*, *dose calibrator* or *radioisotope calibrator* and is one of the most important measuring instruments in a nuclear medicine facility.

Figure 4.3 shows an activity meter with several features common to many

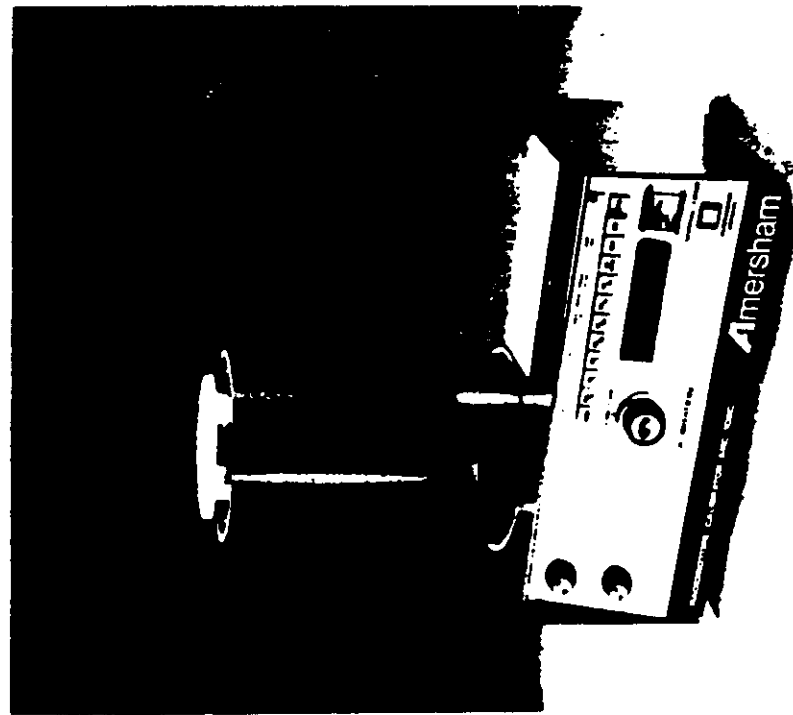


Figure 4.3 A radioactive isotope activity meter. (Courtesy: Amersham International, model number AR110RC.)

of these instruments. The well type ionisation chamber is seen on the left of the figure and the radioactive source in a syringe or sample vial is placed within the well for measurement. With the introduction of SI units, a push button selection of activity units in curies (μCi or mCi) or becquerels (MBq or GBq) is available in most modern instruments. Push button selection for different radioactive isotopes including $^{99\text{m}}\text{Tc}$, ^{131}I and ^{125}I can be seen on the top row of push buttons, a digital readout of activity and a dial for the appropriate calibration factor for the radioactive isotope of interest are provided. In addition, a control for zero errors and background cut-off is available. In these instruments, the radioactive isotope push button selection and calibration factor enable an immediate direct readout of activity and no additional arithmetic calculations are necessary. *Quality control* of all nuclear medicine instrumentation is necessary both at acceptance of new equipment and at specified routine intervals, such as daily, weekly, monthly or yearly, depending upon the quality control test, to ensure that the instruments are in good working order and not producing false results (WHO 1982a, HPA 1983, IAEA 1984). Activity meters are no exception as it is obviously vital to ensure that patients receive correct doses. Thus, activity meters must be regularly tested for precision, accuracy of measurement and for background radioactivity. If there was an unexpectedly high background activity measurement, it could mean that the inner liner of the instrument well is contaminated by some isotope spillage. However, one of the worst problems that can be encountered is the instrument not having linearity of activity response. Thus when $10\text{ }\mu\text{Ci}$ is measured the reading is $10\text{ }\mu\text{Ci}$ but at higher activities, say 10 mCi , the reading might be considerably less than 10 mCi . This fault is shown in figure 4.4 using semi-logarithmic graph paper†. Linearity would imply a straight line graph, yet figure 4.4 shows the values of measured activity over a period of two days lying on a curve. Since the half-life of $^{99\text{m}}\text{Tc}$ is constant at 6 h and certainly does not change, the fault must lie in the instrument and its non-linear activity response—such an instrument should be taken out of service.

A major use of ionisation chamber monitors is as a survey meter for undertaking area monitoring, shielding evaluation and detection of radioactive spillage. An example of a survey meter is in figure 4.5. This particular instrument contains an ionisation chamber protruding about 4 cm from the monitor front and will measure beta and gamma radiation. However, because of the low penetrating power of beta rays the black plastic end cap is removed from the monitor prior to making beta measurements, otherwise the beta rays would be absorbed by the end cap and not reach the ionisation chamber. Portable survey meters are powered by batteries and the range switch includes a built-in battery test, to check the batteries are not

†See also figure 3.3, where the exponential decays of ^{111}In , ^{198}Au and $^{99\text{m}}\text{Tc}$ are correctly demonstrated.

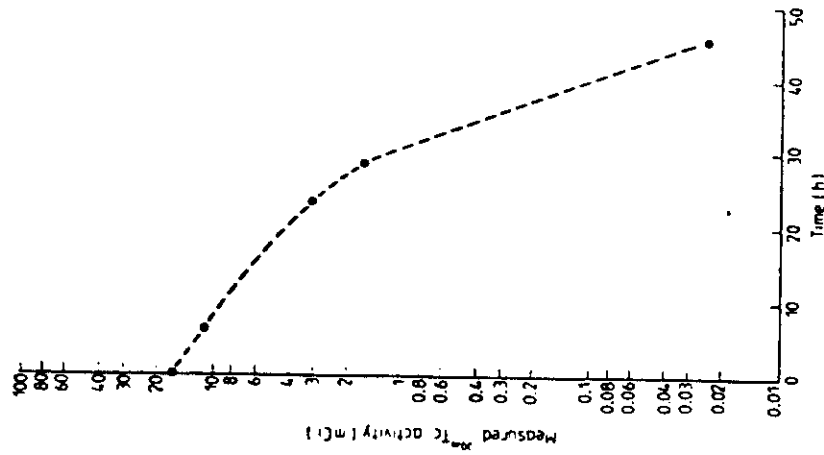


Figure 4.4 Graph of measured ^{99m}Tc activity using an ionisation chamber well activity meter and a vial of activity measured at various times over 45.5 h. Not only do the data points not lie on a straight line but even at low activity during the second 24 h period the meter does not record the correct decay. If the half-life is 6 h then from 24 to 45.5 h is approximately four half-lives and thus one would expect an activity of 2.9 mCi to reduce through 1.45 mCi, 0.72 mCi and 0.36 mCi to 0.18 mCi (180 μCi) whereas the measured activity at 45.5 h was much less, 24 μCi . (Measurements used were recorded during a workshop demonstration on the quality control of nuclear medicine instrumentation organised by the IAEA in South East Asia.)

'dead', plus a zero error test. Using the range switch the survey meter can measure mR h^{-1} in four ranges from 0–4, 0–40, 0–400 or 0–4000 mR h^{-1} depending upon the given situation.

Ionisation chamber survey meters are also available where the associated electronics with range switches, zero and battery tests are connected to the ionisation chamber by a long cable. This has the advantage that the radiation detector, the ionisation chamber, can be placed in close proximity to the

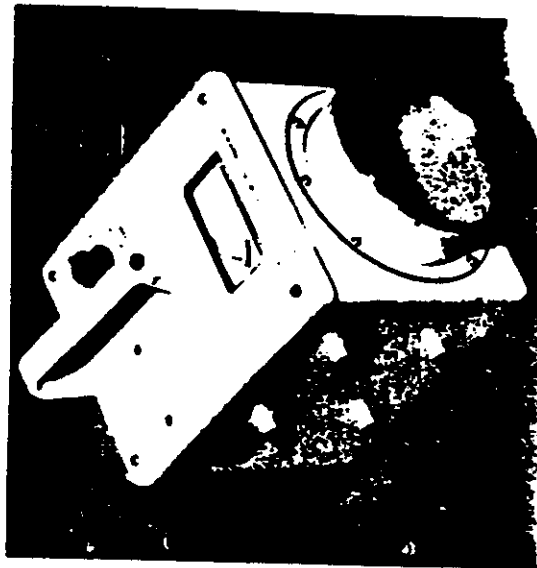


Figure 4.5 A portable ionisation chamber survey meter known as a beta-gamma dose rate meter and measuring approximately $25 \times 15 \times 20 \text{ cm}^3$. (Courtesy: EMI Electronics Ltd model no 95/0030-1/6 1967.)

radiation source, for example an x-ray tube, and measurements can be recorded at a safe distance. This would be impossible in certain situations with a hand-held survey meter. Such instruments can have a selection of ionisation chambers of various sizes and shapes; large volume chambers are particularly useful for low dose measurement since they have a high sensitivity to radiation detection because of their large volume. As an example, three of the chambers supplied with the survey meter, the Pitman Model 37D Portable X-ray Dosimeter (which also measures beta and gamma radiation) are listed below and it is seen that the largest ionisation chamber is the most sensitive to low radiation exposures.

Volume (cm^3)	3.5	35	350
Dose range	3 mR–1000 R	0.3 mR–100 R	0.03 mR–10 R

For high radiation exposures, the smaller volume ionisation chambers would be appropriate. When measuring the radiation output from a radiotherapy x-ray or telecobalt machine an ionisation chamber instrument known as a Farmer is used whose chamber volume is 0.5 cm^3 . However, here we are concerned with radiation protection when low radiation exposure levels are being surveyed and consequently larger volume chambers are required.

One problem with radiation protection surveys is that one is never entirely certain of the scattered radiation energy range one is attempting to measure, say, in a corridor outside a room housing a diagnostic x-ray machine or

within the room behind a lead-lined protective screen. The x-ray energy from the tube may be, for example, 100 keV, but after scattering from a patient, x-ray table, walls, etc, the energy may be much less than 100 keV. It is important, therefore, that the response for any survey monitor is as independent of x- or gamma ray energy as possible. Otherwise, if the response is 1 mR for each scale division at, say, 100 keV but 0.5 mR for each scale division at 60 keV, an accurate measurement of the radiation dose would be difficult if the radiation energy spectrum was unknown. Figure 4.6 shows the energy response of the aforementioned Pitman 37D 350 cm³ chamber and, whereas above 20 keV the response per scale division is within the range 0.9–1.02 and large errors should not occur, at 10 keV the response has reduced to 0.75 per division.

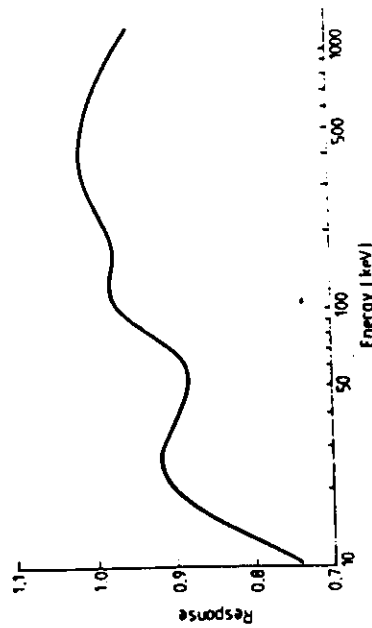


Figure 4.6 Energy response of a 350 cm³ ionisation chamber, x- and gamma radiation [*Instrument Evaluation* No 25, NRPB-IE25, 1982 Pitman Model 37D] (after P H Burgess and W J Iles).

It should also be noted that some monitors will measure either exposure rate, $R\ h^{-1}$, or a total integrated exposure over a given period of time, R .

A third type of ionisation chamber surveillance instrument besides the activity and the survey meter is the *pocket pen* type of dosimeter, designed for personnel monitoring (figure 4.7(a)). These are small ionisation chambers used in conjunction with a suitable charging device, and an electrometer, and have an exposure range usually up to 500 mR and above. When the dosimeter is held towards the light a fibre can be read directly on a scale calibrated in R or mR with a full scale deflection corresponding to the exposure limit. A charging device sets the fibre to zero after which the accumulated exposure received at any time can be observed during work involved with x- or gamma rays. Pocket dosimeters which give a digital readout are now also available. These are usually designed as small rectangular boxes incorporating a variable setting for a maximum accumulated dose level which can be set to trigger a 'beeping' alarm.



Figure 4.7(a) Pocket pen type of dosimeter. These instruments are used not only in hospitals but also the nuclear power industry, fire service, armed forces and in civil defence. (b) Reading the radiation exposure using a pocket pen dosimeter. (Courtesy: R A Stephen and Co Ltd, Mitcham.)

4.8 GEIGER COUNTERS

The operation principle of a Geiger counter is different from that of an ionisation chamber: whereas the latter measures exposure or exposure rate in R or $R\ h^{-1}$, the Geiger counter records ionising events in terms of counts per minute (cpm) and does not differentiate what causes the ionising event, be it a beta particle, a high or low energy gamma ray, etc. Geiger counters are therefore more often used for a qualitative indication, rather than an accurate measurement, of radiation. Figure 4.8 shows a simple portable Geiger counter available in laboratories, wards and operating theatres. The radiation detector is the cylindrical object attached to a long cable. When measuring radiation levels the needle on the dial marked 'radiation level' points either to the left (white area) or to the right (red area). The Geiger counter is connected to a loudspeaker and a series of unmistakable loud clicks are heard when near a radiation source. The monitor is powered by batteries. This, and similar Geiger survey meters, can be used for area monitoring, detection of radioactive spills and contamination, and search for 'lost' radioactive sources such as radium or caesium-137 needles. Other examples of portable Geiger monitors have a rate meter calibrated in counts per second (cps); some can detect beta rays by lifting a hinged shutter at the end of the monitor and exposing a thin mica window of only some $1.5\text{--}2.5\text{ mg cm}^{-2}$ thickness.

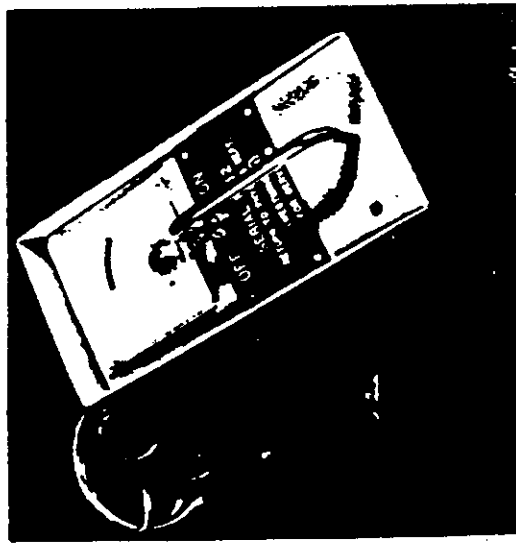


Figure 4.8 Portable Geiger counter survey monitor.

Calibration of these monitors by relating CPM or CPS to activity for a specified radioactive isotope is not particularly easy. Nevertheless, some attempt can be made to provide useful quantitative data for measuring radioactive contamination per unit area if the isotope is known.

4.9 SCINTILLATION COUNTERS

Plastic or crystal *scintillation* counters as survey meters for sensitive measurement of radioactive spills and contamination tend to be more expensive than ionisation or Geiger meters. Consequently they are not so frequently available, except for the regulatory authorities who undertake periodic official inspections of laboratories. Scintillation detectors measure fluorescent events and one method is to incorporate a plastic phosphor with air equivalent response, optically coupled to a photomultiplier tube. Finally, it is noted that in some models of this particular survey meter there is a *logarithmic* dose rate scale (figure 4.9). This dispenses with range switches, and is able to measure from 0.05 to 500 in mR h^{-1} —a very wide range of exposure rates. For scintillation counters there is usually a flat energy response above 45 keV and they have a faster response and higher sensitivity than a Geiger survey meter when used for similar exposure rates.

It is also noted that individual scintillation probes are available for measuring beta and alpha radiation and low energy gamma rays, such as those emitted from iodine-125 (gamma energy = 27 keV). These probes are attached to associated electronics and measurements are recorded in CPM or CPS.

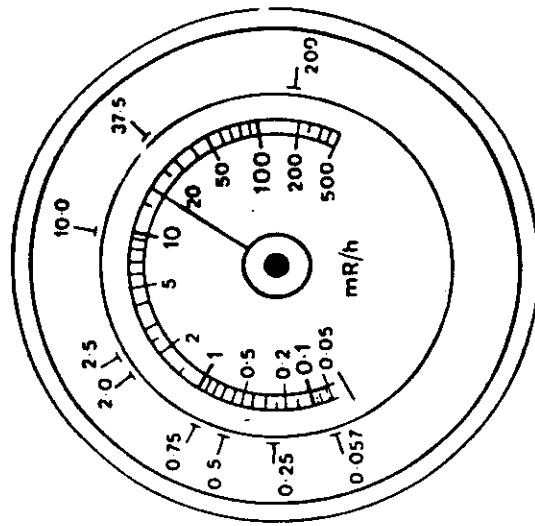


Figure 4.9 Diagram of the logarithmic scale of a survey meter.

4.10 FILM BADGES

The ability of x-rays to blacken silver bromide film was used by Kienböck of Vienna in 1905 as the basis of his *X* unit for measuring x-ray doses. Small pieces of film known as *Kienböck strips*, were exposed on the patient's skin and the tint of the developed film was compared with an arbitrary scale of blackening (figure 4.10). Although Kienböck strips have long fallen into disuse and can now only be found in museums, silver bromide film is still used for measurement purposes as a monitoring device for personnel working in or near an ionising radiation environment. One of the inherent problems of using silver halide emulsion as a dosimeter is the high atomic number of silver ($Z = 47$). Because of the photoelectric effect, this results in proportionately more absorption of low energy x- and gamma ray photons in the emulsion than occurs in tissue with its effective atomic number of approximately 7.4. Film blackening is therefore greater for a given radiation dose in tissue at low energies than for the same dose in tissue at high energies. Compensation for this can be made using filters so that film can actually be used to give sufficiently accurate results for a photon beam with an unknown energy spectrum.

If a high atomic number filter is placed over the film, such as tin-lead, it will preferentially remove low energy photons before they reach the film. This achieves a fairly uniform response of film blackening with energy for photons above 70 keV. The film can be calibrated using a radiation source

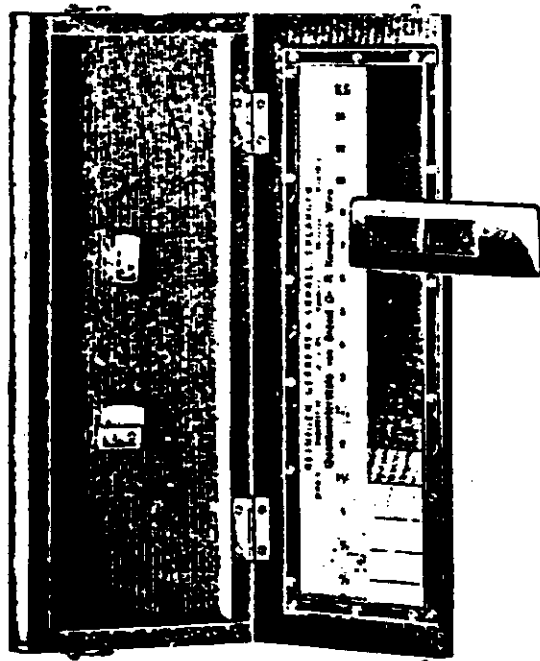


Figure 4.10 Standard blackening scale for Kienböck strips of photographic film as advertised in 1904–5 by Reiniger, Gebbert & Schall.

whose photon energy is well above 70 keV, for example caesium-137 with a gamma energy of 660 keV. The film density for a known dose within the region of uniform energy response can then be found. In practice, several films are usually irradiated to give calibrations over the dose ranges which are expected to occur in practice.

The response under the tin-lead filter falls off at energies below 70 keV since too few low energy photons can penetrate this filter. The response of the film can be extended to low energies by adding a proportion of the effective dose found from the film blackening under unfiltered film (disproportionately high at low energies) to that measured under the tin-lead filter (falls off at low energies). If in addition a filter of intermediate atomic



When measuring patients, who are treated using radionuclides, staff should not forget to wear their personal monitor, such as a film badge

number (for example, aluminium $Z = 13$) is used, a more uniform energy response at the lower energies will be measured. The ratio of the effective doses under these filters will give an indication of the radiation energy received.

By using other filters, different types of radiation (betas and neutrons) can be distinguished from x- and gamma rays and their dose contribution assessed. The attenuation of beta rays depends only on the density of the medium through which it travels and thus plastic filters of low atomic number can be used to assess beta radiation dose. Cadmium (Cd) can be used to assess a neutron dose as the gamma radiation emitted when neutrons are captured by the cadmium atoms will blacken the film beneath the cadmium filter. If the radiation beam is only gamma rays then the blackening will be the same under a tin-lead filter and under a cadmium-lead filter. However, the presence of neutrons will produce excess film blackening under the cadmium-lead filter.

The film badge at present in use in the United Kingdom is shown in figure 4.11. It consists of an open window and five filters: a Dural filter, two plastic filters of 300 and 50 mg cm^{-2} surface densities, a tin-lead filter and a cadmium-lead filter.

A film badge cannot be used for alpha rays and very low energy betas as they cannot penetrate the film paper wrapping. Typically the lowest dose

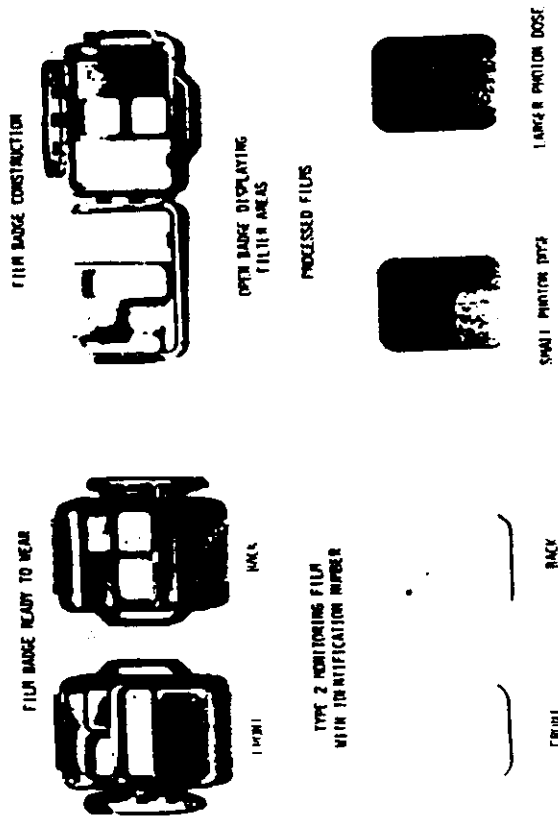


Figure 4.11 The film badge used in the United Kingdom. The term film badge is in widespread use but it would probably be more accurately described as a *monitoring film* used for personnel dosimetry.

equivalent that can be quoted with any degree of accuracy is 0.2 mSv for x- or gamma rays and 0.8 mSv for beta rays.

Another country besides the United Kingdom where film badge monitoring is used is the Federal Republic of Germany. Their film badge design is different from that in figure 4.11 with two films of different sensitivities, rather than only one film with two emulsions. The filters are also different: an open window (no filter) for beta rays and soft x-rays, 0.8 mm Pb beneath which the film will receive almost no radiation dose from betas, and low energy x- and gamma rays and hence the blackening can act as a *fog* level; and three copper filters of thicknesses 0.05, 0.3 and 1.2 mm respectively. The analytical filter procedure was established under the DIN 6816 German standard publication in March 1964, *Film analytic method of film dosimetry for personnel monitoring*.

4.11 THERMOLUMINESCENCE DOSIMETRY

In a scintillation detector the light output from a phosphor after exposure to ionising radiation is measured using a photomultiplier tube and associated electronics to determine dose rate or total dose. Phosphors used for scintillation crystals exhibit fluorescent properties, with the light output generated immediately after the x- or gamma ray photon absorption has taken place. Hence the measuring equipment must be directly attached to the phosphor. Clearly, it would extend the range of applications if the light output from the phosphor could instead be measured at a later point in time, and the equipment would no longer need to be directly linked. This is possible with a phosphor which exhibits the phenomenon of thermo-

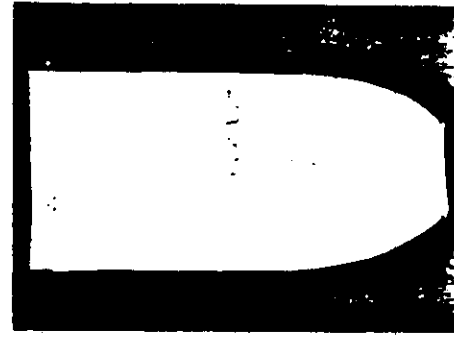


Figure 4.12 Finger stall containing lithium fluoride powder.

luminescence, and is utilised in thermoluminescent dosimeters (TLD). A commonly used TLD phosphor is lithium fluoride to which trace quantities of magnesium or titanium are added. Such a phosphor will give a light output proportional to accumulated absorbed dose after it has been heated to several hundred degrees centigrade. Lithium fluoride is useful in medical applications since it has an effective atomic number similar to that of soft tissue and hence absorbs ionising radiation in a similar manner.

Manufacturing methods vary between companies supplying lithium fluoride dosimeters but the material can be found as a loose powder which can be used in a finger stall to measure finger doses (see figure 4.12) either compressed into a disc (e.g. 12 mm diameter $\times$ 0.4 mm thick) or square chips (e.g. $3 \times 3 \times 0.9$ mm³) or rods. It can also be mixed with a tough substrate such as Teflon to yield a more rugged and flexible detector, such as the disc already mentioned. The actual type used will depend upon a number of factors.

TLD personnel dosimeters in the form of a phosphor-Teflon card enclosed within a plastic badge case are now available commercially as an alternative to the film dosimetry of figure 4.11. Typically, such a badge would contain an open window and three filtered areas. The phosphor-Teflon can be read on either manual or automatic readers and three doses reported: low energy gamma/x- and beta; high energy gamma/x-; neutron.

CHAPTER 5

RADIATION SHIELDING

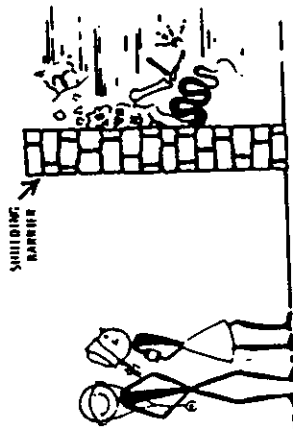
5.1 LEAD EQUIVALENCE

One method of directly comparing the shielding capabilities of different materials is by stating their *lead equivalence* (11), that is the thickness which affords the same attenuation as an actual lead thickness for a given x-ray or gamma ray energy spectrum and a specified beam geometry—narrow or broad. Thus, for example, a 114 mm (4.5") yellow stock brick of density 1.6 g cm^{-3} has a lead equivalence of 1.0 mm for a narrow beam of 100 keV x-rays, 228 mm (9") of the same brickwork has a lead equivalence of 2.4 mm for 100 keV rays, a typical energy encountered in diagnostic radiology.



Remember! that there should be an adequate distance and shielding barrier between staff and radiation source!

However, lead equivalence can be stated for any energy. The protection provided by brickwork can be increased by the addition of barium gypsum plaster (see table 5.1). Examples of lead equivalence for other materials at 100 keV energy are given in table 5.2. It should be remembered that there is *not* a linear relationship between thickness of shielding material and their lead equivalence (see data in table 5.2 for 2 and 4 mm brass) and that designers of radiation shielding have no simple formula to apply to estimate lead equivalence of a material at a given x-ray energy. They must obtain the necessary data from manuals and books of tables published by authorities such as the National Council on Radiation Protection and Measurements (NCRP), Washington, the World Health Organisation (WHO), the British



Standards Institution (BSI), the German Standards Commission and the International Commission on Radiological Protection (ICRP).

Data on lead equivalence are sometimes given as shielding material thicknesses for specified thicknesses of lead such as 0.5, 1.0 or 2.0 mm, as in figure 5.1. At medical diagnostic x-ray energies, normally in the range 50–150 keV and requiring some 1.0–1.5 mm i.e. protection, lead is the preferred shielding material for walls and doors of x-ray rooms when space is at a premium. Concrete walls require more space and are economically attractive, but are not so easy to construct whereas lead-plywood panels with grained or laminated finish can easily be fitted. Protection design will also depend upon whether an x-ray room is being built within a brand new hospital or whether an existing room is being modified.

Table 5.1 Lead equivalence of barium gypsum plaster for various x-ray generating voltages. Data is for rough barytic, an undercoat for brick walls, including 3 mm of barytic finish, from measurements made by NRPB. (British Gypsum 1981 UDC 666.81 June 83.)

Plaster thickness (mm)	Lead equivalence in mm for a given x-ray generating voltage between 50 and 200 kV _p					
	50	75	100	125	150	200
13	0.6	1.4	1.6	1.2	0.9	0.7
19	—	—	2.4	1.7	1.3	1.0
25	—	—	3.1	2.1	1.6	1.2

Table 5.2 Lead equivalences for various shielding materials for 100 keV x-rays. The material's density is given in brackets in g cm^{-3} .

Shielding material	Thickness (mm)	Lead equivalence (mm)
Barium concrete (3.2)	13	2.2
	25	4.1
Steel (7.9)	4	0.71
Brass (8.3)	2	0.48
	4	1.12

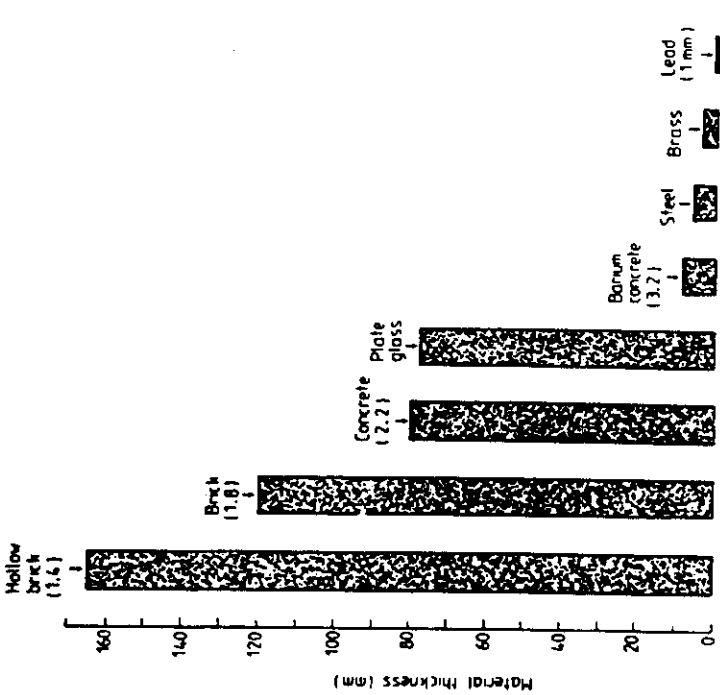


Figure 5.1 Lead equivalence of various materials for 100 keV x-rays, broad beam conditions. The histogram bars give the thickness of the material in mm which affords the same attenuation as 1 mm of lead (Keane and Tikhon 1975, table 4 p83). The material's density in g cm⁻³ is given, where available, in brackets.

For radiation energies used in radiotherapy, cobalt-60 gamma rays and x-rays in the range 4–20 MeV generated using linear accelerators, much greater shielding than the 1.0–1.5 mm lead equivalence for diagnostic x-ray rooms is required. Building a room with lead in this situation becomes an uneconomic proposition and barium concrete bunkers are built for megavoltage radiotherapy installations with specially designed entrances and patient viewing facilities.

5.2 TENTH-VALUE THICKNESS

Although radiation shielding data can be expressed in terms of lead equivalence, it is more often presented using tables or graphs of half-value thicknesses (hvt) and tenth-value thicknesses (tvt), as described in chapter 3, or graphically in terms of barrier *transmission curves*. Figure 5.2 illustrates

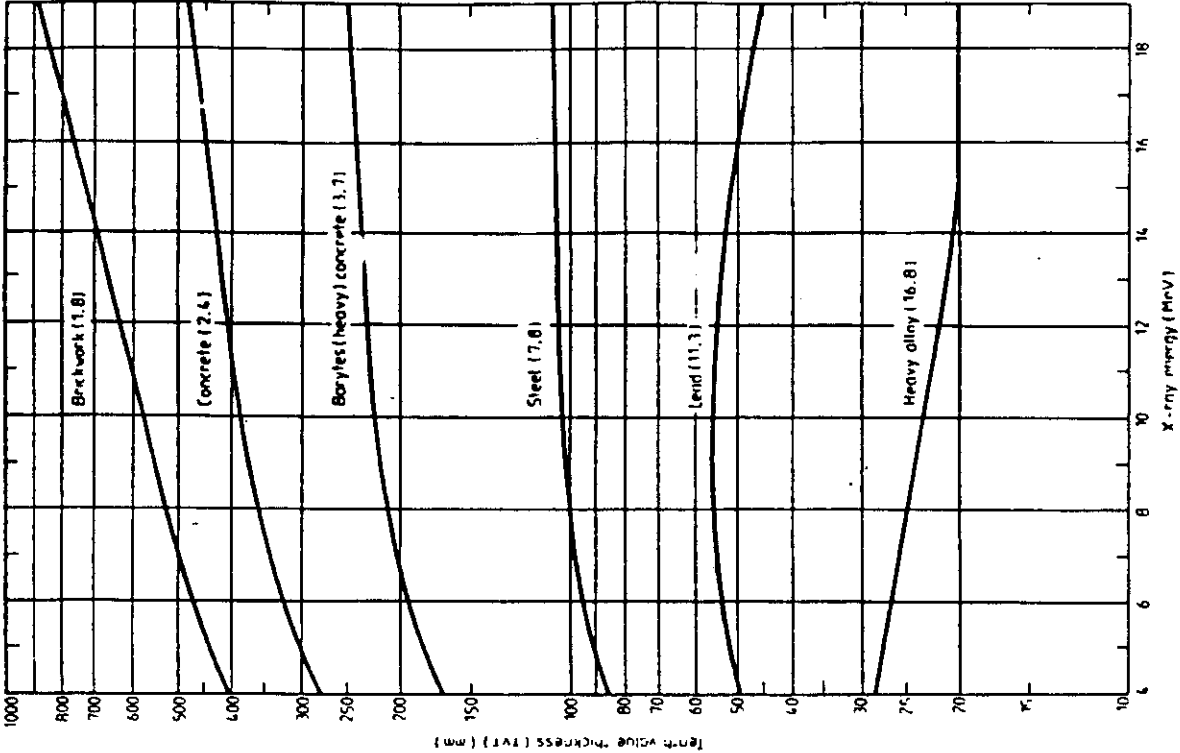


Figure 5.2 Variation of tvt with x-ray energy. Radiation Dynamics Ltd technical information data sheet 33/1. Densities in g cm⁻³ are given in brackets. The vertical axis is a logarithmic scale because of the large differences in the tvt of brickwork and lead.

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the variation of TVT of various materials with x-ray energy from 4–18 MeV, which includes energies encountered in radiotherapy (the lower end of the range) as well as energies used for industrial x-ray applications for non-destructive testing procedures. In table 5.3 the TVT for radioactive isotopes used in therapy are stated for lead, steel and concrete.

Table 5.3 Variation of TVT with radioactive isotope (NCRP 1976).

Radioactive isotope	Gamma ray energy (MeV)	TVT (mm)		
		Concrete density 2.35 g cm ⁻³	Steel	Lead
¹⁹⁸ Au	0.41	135	—	11
¹⁹² Ir	0.13–1.06	147	43	20
¹³⁷ Cs	0.66	157	53	21
⁶⁰ Co	1.17, 1.33	206	69	40
²²⁶ Ra	0.047, 2.4	234	74	55

5.3 TRANSMISSION CURVE

Transmission curves are plotted on semi-logarithmic graph paper with the horizontal axis representing the shielding material thickness and the vertical axis the transmission through the material for a given x-ray energy or gamma ray spectrum. The transmission is usually recorded in powers of 10, reducing from $10^0 = 1$ to perhaps $10^{-6} = 0.000\,001$. This is illustrated in figure 5.3 for the transmission of 50–200 keV x-rays through a lead shielding barrier.

5.4 LEAD

5.4.1 Lead plywood

Lead is widely used in several forms as shielding material in medical and dental practice. Lead plywood panels are used for diagnostic x-ray room walls and doors and also for protective screens and cubicles. A radiographer can stand behind these within an x-ray room while radiation exposure takes place. Figure 5.4 is an example of a fixed screen with a wide front panel and two side leaves.

Protective screens can be movable as well as fixed and commercial suppliers usually have a series of standard models. Alternatively, specially dimensioned screens can be constructed by supplying details of the required

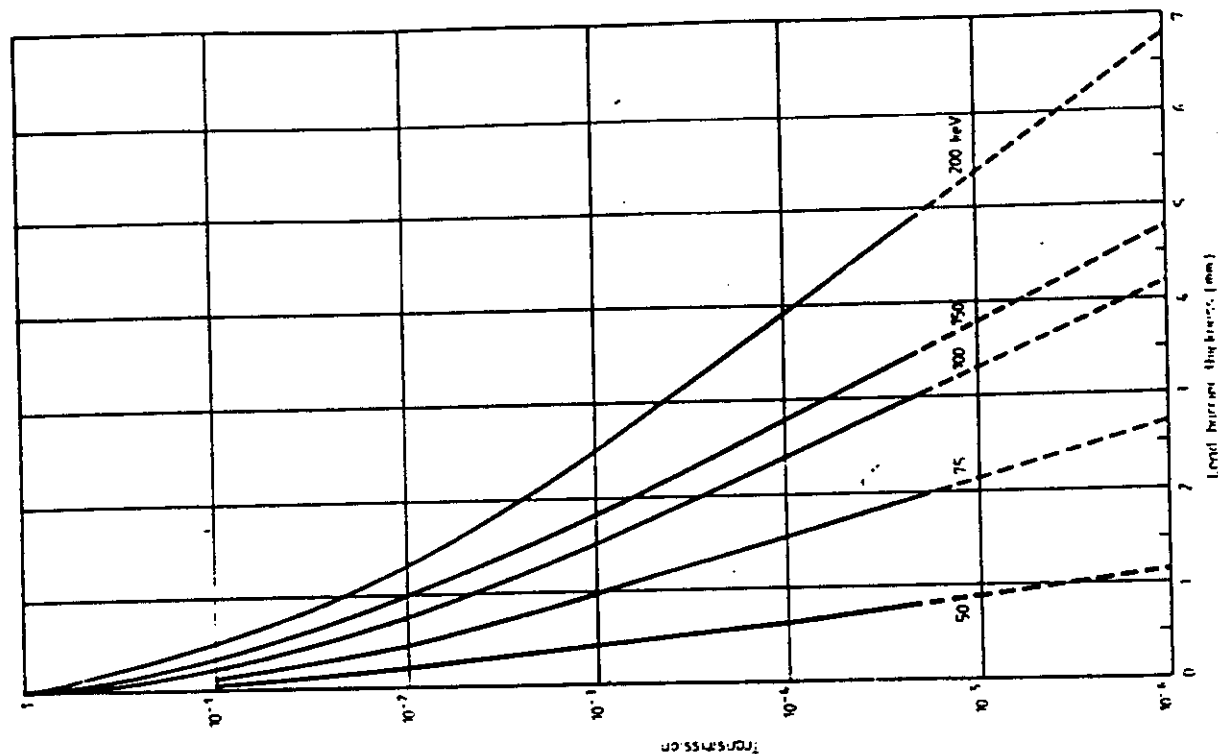


Figure 5.3 Transmission of x-rays through lead (British Standards Institution BS 4094: Part 2: 1971, figure 9 p31).



Figure 5.4 Protection features in a diagnostic x-ray room.

number of millimetres of lead protection required and the screen and window dimensions.

5.4.2 Lead glass

The windows within screen and cubicles in diagnostic radiology are made of lead glass where the thickness is expressed in terms of *lead equivalence* for a particular x-ray energy. It is supplied by several manufacturers who also specify the density and refractive index. The data in table 5.4 presents average lead equivalence values for lead glass currently available. These are given simply as a guide and for more accurate values, the commercial specification sheets should be consulted.

Table 5.4 Lead equivalence of lead glass, density 5.0–5.2 g cm⁻³ and refractive index 1.8.

Lead glass thickness (mm)	Lead equivalence (mm) for x-ray energy	
	100 keV	200 keV
5.0	1.5	—
6.5	2.0	1.5
8.0	2.5	2.0
9.5	3.0	2.5



Figure 5.5 Interlocking lead bricks. (Courtesy: BLM Girdler.)

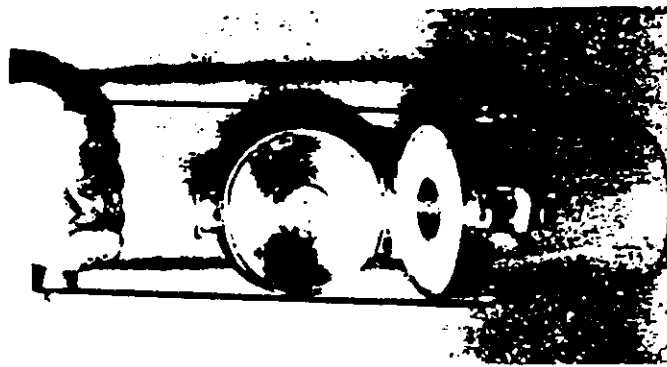


Figure 5.6 Lead carrying pot for radioactive sources. The design illustrated incorporates a detachable handle, a stainless steel inner liner which is replaceable if it becomes contaminated, a locking mechanism for the top of the pot and a hinged stepped lid. The lead thickness of this model is 25 mm.

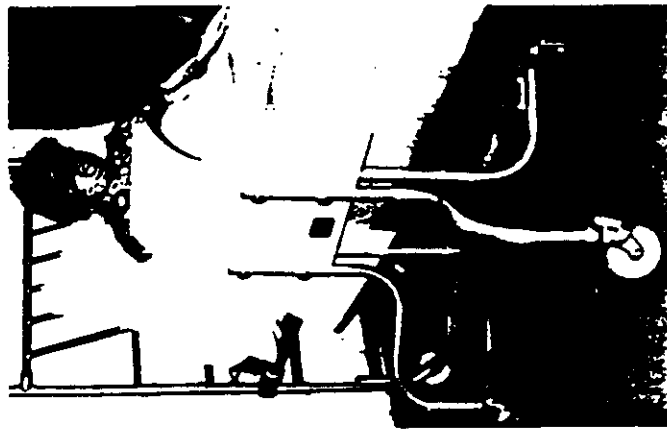


Figure 5.7 Lead bedshield with a thickness of 38 mm and height of 610 mm. Its weight is approximately 181 kg and it is fixed to a tubular framed mounting on four anti-static swivel castors with two of the castors braked. (Courtesy: BLM Girdler.)

5.4.3 Lead rubber

Lead rubber is used in x-ray diagnostic work in the form of lead rubber aprons and gloves. Lead rubber sheets are incorporated into fluoroscopic units for protection of the radiologist.

5.4.4 Lead bricks

Solid lead bricks, and the interlocking brick systems available, are particularly useful since they can be tailored to many specific purposes (figure 5.5) e.g. custom built shields in a dispensing bay for a nuclear medicine hot laboratory; incorporated into a movable trolley designed for handling the solid radioactive sources used in therapy in an operating theatre.

5.4.5 Lead castings

Cast lead items are used for inserts within x-ray tubes, for small lead pots to act as transport containers for delivery to hospitals and for lead carrying pots such as in figure 5.6. Castings can also be made for more substantial items such as lead bedshields. These afford protection to nurses while caring for patients treated for cancer of the cervix or uterus using caesium-137 or iridium-192 sources, or if not yet replaced, radium sources. The bedshield shown has a curved top with two cutaway pieces to facilitate nursing procedures (figure 5.7).

5.5 CONCRETE

Concrete, usually in the form of barium concrete but sometimes with lead or steel shot added, is used in radiotherapy megavoltage apparatus bunkers or industrial x- or gamma radiography installations. Concrete blocks are also used for protection design in high energy research establishments.

CHAPTER 6

CLASSIFICATION OF RADIATION WORKERS

6.1 INTRODUCTION

Radiation protection rules, recommendations and regulations refer to persons being exposed to radiation in defined areas. Hence it is necessary to understand what is meant by classified and designated persons, controlled and non-controlled areas and dose limits which were formerly referred to as maximum permissible doses. Not all countries present their definitions in a similar manner and different definitions apply to industrial and medical situations. Hence there is much room for confusion when reading the mass of official documentation if the basic terms have not already been clearly defined.

6.2 DOSE LIMITS

6.2.1 Historical note

Early x-ray injuries were attributed to many different causes, electrical effects, ultraviolet radiation or platinum particles from the x-ray tubes and were supposedly prevented by a host of other items, such as red silk and thin rubber sheet. There was also a theory, referred to in an 1896 British Medical Journal note, that x-rays were a normal constituent of sunlight, presumably because of the similarity between sunburn and very mild x-ray erythema. Generalised radiation protection measures were eventually adopted, a British X-ray and Radiation Protection Committee being formed in 1921† and an International Radiation Protection Committee in 1928. The US

† Meetings on radiation protection had been held well in advance of 1921 and table 6.1 is taken from the May 1898 volume of the *Archives of the Roentgen Ray*. At the March 1898 meeting of the Roentgen Society it was suggested that because of the importance of Roentgen ray dermatitis, a committee of investigation should be appointed by the Society.

Table 6.1 List of questions recommended by the first British radiological society committee, 1898, the Committee on X-ray Injuries.

(a) Medical	
1	Nature of injurious effects.
2	Description of the case radiographed.
3	Part exposed to rays.
4	Condition of subject:
	(a) well nourished or emaciated;
	(b) temperament nervous or phlegmatic;
	(c) diathesis of patient;
	(d) local condition of part exposed.
5	Did the patient complain of any feeling of warmth, tingling, or other sensation during or after exposure?
6	Duration of effects, temporary or permanent.
7	Remarks.
(b) Electrical	
8	Apparatus employed, influence machine, or induction coil, spark length, voltage and amperage used.
9	Form of tube; length from terminal to terminal.
10	Distance of tube from patient's body.
11	Number of exposures; interval, if any, between exposures; duration of each exposure.
12	Situation of tube with regard to body or limb of patient, i.e. position of anode and cathode.
13	What covering or garment, if any, was used:
	(a) material of which it was composed;
	(b) rough or smooth;
	(c) colour, if dyed?
14	Remarks.

Advisory Committee on X-ray and Radium Protection was the first national protection organisation to consider the principle of maximum tolerance dose of x-rays. This was in 1934 and this dose was derived essentially from a 1921 recommendation that

a sort of grand average of the protective measures could be gleaned from the working conditions of a number of experienced radiologists who had escaped injury and still enjoyed normal health.

However, the general acceptance of protection was too late to prevent radiation injuries to the superficial tissues, blood and internal organs of some of the early workers in the radiation field, and many are remembered by a monument erected by the German Röntgen Society in Hamburg, 1936. This memorial originally contained 169 names from 15 different nations but by 1959 the total had risen to 360. Wilhelm Röntgen is not among them,

probably because his experiments were mainly photographic and his x-ray tubes were housed within a metal box. However, the list does contain Marie Curie and it was also known that Pierre Curie and Henri Becquerel suffered radiation burns on their hands and finger tips from carrying radium tubes.

6.2.2 Dose limits: ICRP, NRPB, NCRP

The dose limits for occupationally exposed workers age 18 years or over are given in table 6.2 from the NRPB (1983) consultative document, prepared in conjunction with the consultative document from the HSC (1982). The data were compiled from the Council of the European Communities' Directive (EEC 1976) and replaces the earlier data (table 6.3) for the UK (DHSS 1972). The latter has been the guiding recommendations for radiation protection in medicine since 1972 but will be replaced by the final issue of the NRPB (1983) draft notes.

In the case where the whole body is not uniformly irradiated, for example when certain organs preferentially take up a particular radiopharmaceutical, the *whole body dose* can be replaced by the *effective dose*, table 6.2. The

Table 6.2 Dose limits for occupationally exposed workers aged 18 years or over. (After NRPB 1983.)

	Annual limit	Other limit
Whole body	50 mSv (5 rem)	
Effective dose (from partial body exposure)	50 mSv (5 rem)	
Abdomen of woman of reproductive capacity		13 mSv (1.3 rem) in a quarter
Foetus of pregnant woman		10 mSv (1 rem) between declaration of pregnancy and delivery
Lens of the eye	300 mSv (30 rem)	
Skin (averaged over any area of 100 cm ² †)	500 mSv (50 rem)	
Hands, forearms, feet and ankles	500 mSv (50 rem)	
Any other organ or tissue (average in organ)	500 mSv (50 rem)	

†100 cm² applies to doses from radioactive contamination; a smaller averaging area should be used for radiation beams.

Table 6.3 Maximum permissible doses for occupationally exposed persons (after Appendix B DHSS 1972).

Part of body	Planned special exposures		
	Annual dose (rem)	Quarterly dose (rem)	Single event (rem) Lifetime (rem)
Gonads, red bone-marrow and whole body	5†	3 (1.3 to the abdomens of women of reproductive capacity)	10 25
Bone, thyroid and skin of whole body	30	15	60 150
Hands, forearms, feet and ankles	75	40	150 375
Any single organ (excluding gonads, red bone-marrow, bone, thyroid and skin of whole body)	15	8	30 75

†If the person was occupationally exposed before 18 years of age, subsequent exposure of the gonads, red bone-marrow and whole body should be controlled so that the dose accumulated up to 30 years of age does not exceed 60 rems.

effective dose equals the uniform dose to the body which would produce the same risk to the individual as the actual non-uniform dose received. The formula for calculating effective dose is

$$\sum W_O H_O$$

where W_O is a weighting factor recommended by ICRP (1977) for each organ or tissue, O , given in table 6.4. H_O is the dose equivalent in tissue O . It follows that for dose requirements to be satisfied:

$$\sum W_O H_O \leq H_{\text{wh}}$$

where H_{wh} is the dose equivalent limit for irradiation of the whole body, namely 50 mSv (5 rem) annually.
From the publication by the National Council on Radiation Protection and Measurements, Washington (NCRP 1976), the maximum permissible dose equivalent recommendations for *controlled areas* are given in table 6.5. These are the same for the whole body, gonads and red bone marrow as

Table 6.4 Weighting factors, W_O , required to calculate effective dose. (After ICRP 1977, NRPB 1983.)

Organ or tissue	W_O
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Each of 5 others	0.06

Table 6.5 Maximum permissible dose equivalents in controlled areas. (After NCRP 1976.)

Part of body	Annual dose (rem)	Quarterly dose (rem)
Whole body, gonads, red bone marrow, lens of eye	5	3
Skin of whole body	15	—
Hands	75	25
Forearms	30	10

those issued by DHSS (1972), London (table 6.3) but differ for the skin, hands and forearms.

6.3 CONTROLLED AREAS

According to NCRP (1976), in the USA a *controlled area* is 'a defined area in which the exposure of persons to radiation is under the supervision of a Radiation Protection Supervisor. (This implies that a controlled area is one that requires control of access, occupancy and working conditions for radiation protection purposes.)' A *non-controlled area* is 'any space not meeting the definition of controlled area'. NCRP also tabulate *occupancy factors*, denoted by T , for *non-occupationally* exposed persons such that NCRP tables of minimum shielding requirements for x-ray installations can

workload of the installation in mA.min and U is a *use factor* for the protective barrier. NCRP recommend $T = 1$ (full occupancy) for work areas such as offices, laboratories, shops, wards and nurses' stations in the immediate vicinity, living quarters, children's play areas and occupied space in nearby buildings; $T = 1/4$ (partial occupancy) for corridors, rest rooms, lifts using operators and unattended car parks; $T = 1/16$ (occasional occupancy) for waiting rooms, toilets, stairways, unattended lifts, cleaners' broom cupboards, outside areas used for pedestrians or vehicular traffic.

In the UK, NRPB (1983) define a *controlled area* as any area where a person might receive a dose or committed dose, other than from natural background or medical exposure, exceeding three-tenths of any of the annual dose limits for adult workers. Where conditions are such that persons might receive more than one-tenth but less than three-tenths of the annual dose limits, the area is designated a *supervised area*. NRPB (1983) further state that the *occupancy factor* of an area must not be considered when deciding upon the designation of controlled or supervised areas. The doses liable to be received are therefore those for a person not wearing protective clothing, spending his whole working time (40 hours per week, 50 weeks per year) in the area.

6.4 CLASSIFIED PERSONS

In the UK, a person is designated as a *classified person*, according to NRPB (1983), if their work or training involves exposure to ionising radiation to such an extent that the resulting annual doses might exceed three-tenths of any of the dose limits. Therefore anyone who will be entering into a controlled area, unless exempt under a scheme of work drawn up by the responsible person for radiation protection advice, is a *classified person*. In the earlier code of practice DHSS (1972), the term *classified person* was not used, and *occupationally exposed persons* were divided into two groups, namely, designated persons who were defined as the above NRPB (1983) classified persons, and *other persons* whose exposure to radiation is such that the resulting annual doses are most unlikely to exceed three-tenths of the annual maximum permissible dose.

The annual dose limits for members of the *general public* were quoted by DHSS (1972) as equal to one-tenth those for occupationally exposed workers (table 6.3) and in 1983 (NRPB 1983) they were again stated to be one-tenth of those for occupationally exposed persons (table 6.2). Thus with a 50 week year and an annual limit of 50 mSv (5 rem) whole body (table 6.2), the *weekly* dose limit for *classified persons* is 1 mSv (100 mrem) and 0.1 mSv for members of the *general public*.

NCRP (1976) subdivides persons into occupationally exposed and non-occupationally exposed (see §6.3) and states

For the purposes of NCRP 49, maximum weekly exposure values of 100 mR for *radiation workers* and 10 mR for *other workers* have been selected for shielding design . . . In most instances shielding design for radiation workers can be based upon an average weekly exposure (e.g. 10 mR average weekly exposure) without an objectionable increase in cost of structural shielding.

PART II

- 7 PROTECTION IN EXTERNAL BEAM RADIOOTHERAPY
- 8 PROTECTION IN INTERSTITIAL SOURCE RADIOOTHERAPY
- 9 PROTECTION IN INTRACAVITARY RADIOOTHERAPY
- 10 PROTECTION IN RADIOACTIVE IODINE-131 RADIOOTHERAPY
- 11 PROTECTION IN NUCLEAR MEDICINE DIAGNOSTICS
- 12 PROTECTION IN DIAGNOSTIC RADIOLOGY

CHAPTER 7

PROTECTION IN EXTERNAL BEAM RADIOTHERAPY

7.1 INTRODUCTION

In external beam radiotherapy, also known as *teletherapy*, the radiation source within the treatment machine is at a distance and hence not in contact with the patient's skin. Figure 7.1 shows this and includes a radiation dose distribution chart described in terms of isodose curves. There are three distinct classifications of external beam therapy, determined for x-rays by the generating voltage

Superficial therapy	10–150 kV
Deep (or orthovoltage) therapy	200–300 kV
Megavoltage (or supervoltage) therapy	above 1 MV

Since the gamma ray energies of cobalt-60 are 1.17, 1.33 MeV, cobalt teletherapy treatment machines are classified as megavoltage therapy units. In addition, external beam radiotherapy includes electron beam therapy

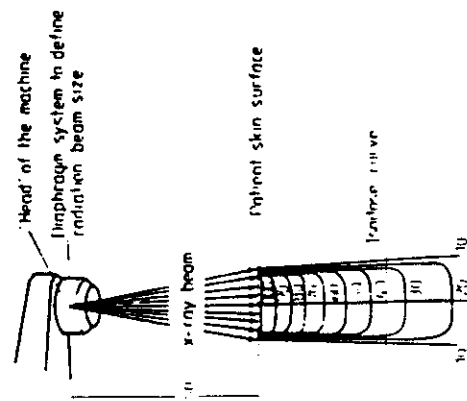


Figure 7.1 Schematic diagram illustrating the irradiation of a patient by an external beam therapy machine such as a linear accelerator. For supervoltage therapy the diaphragm system within the head of the machine defines the radiation beam size, whilst for deep x-ray therapy an applicator is attached to the head of the machine. The applicator sides and bases are constructed of lead and the end-piece of perspex. SSD is the distance from the x-ray focus to the patient's skin surface. For cobalt-60 machines this is termed SSD, the distance from the source to the skin surface. (Mould 1985.)

when electrons are used in conjunction with or as an alternative to x-rays or gamma rays depending upon the tumour to be treated. Electron beams are, in practice, usually generated from the same medical linear accelerators which are used to deliver megavoltage x-rays. Only in a relatively few centres are other forms of specialist equipment, such as betatrons, used for electron beam therapy.

Radiation protection in external beam therapy in its widest sense includes manufacturer's features in the treatment machine, design of the treatment room, provision of safety interlock systems for machine operation so that personnel are not accidentally irradiated and procedures to ensure the patient receives only the correct scheduled radiation dose. This latter can also be termed radiation protection of the patients, albeit they have to receive certain amount of radiation to treat the cancer anyway.

7.2 RADIATION SOURCES

Superficial and deep therapy treatment machines contain conventional x-ray tubes for the x-ray beam production. This type of x-ray tube was invented by William Coolidge of the General Electric Company, USA, in 1913. It was then termed a *hot cathode* tube as the cathode consisted of a heated filament from which electrons were emitted because of the thermionic effect. The electrons are accelerated towards a heavy target, the anode, from which x-rays are produced by the subsequent electron bombardment. Figure 7.2(a) shows an early model in which the cathode and anode can clearly be seen within the glass bulb. The design of modern x-ray tubes, Figure 7.2(b), is much more sophisticated with features such as rotating anodes and oil coolants.

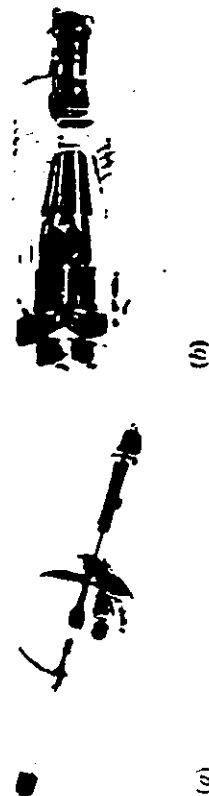


Figure 7.2 (a) Coolidge tube, circa 1913; (b) modern radiotherapy x-ray tube. (Courtesy: Philips Medical systems.)

The design of protection features within an x-ray tube and its housing is the responsibility of the manufacturer but it is still necessary for the purchaser to conduct acceptance tests to ensure the equipment meets the approved specification. For radiation protection this will include measurements of any possible radiation leakage from the radiotherapy machine

'head' (see figure 7.1) and checks that the radiation field size, defined in the patient setting-up procedure, actually corresponds to the real radiation field size with the machine switched 'on'. Recommendations and regulations are available in various countries giving the tolerances acceptable in the design of these units. For example, in the UK there is a Radiotherapy Apparatus Safety Measures Panel (RASMP) which considers not only radiation, but also electrical and mechanical safety. Their recommendations (DHSS 1975, 1977) include guidance on superficial and deep x-ray therapy installations and divides the former into four groups for safety purposes:

- (i) operating around 100–150 kV;
- (ii) operating at relatively low exposure rates around 50–60 kV and below;
- (iii) operating at high exposure rates around 50–60 kV and below;
- (iv) operating over the range 10–100 kV.

For deep x-ray and megavoltage therapy the rso (figure 7.1) is usually constant at, say, 50 cm for deep and 100 cm for megavoltage therapy. Also, with a fixed x-ray energy no interchangeable filters are required for the different energy selections. For superficial therapy, however, there is usually a range of possible rso and also possibly a selection of three or four different energies. Thus during treatment set up, operator errors would be possible without suitable fail-safe mechanisms and procedures. For instance, an incorrect filter associated with a particular energy could lead to a higher radiation exposure rate than intended. To prevent accidents like this DHSS (1977) includes statements for superficial x-ray machines such as

where no shutter is fitted to the machine, the usual practice of applying a suitable correction factor to take into account run-up dose should be followed; timer reliability is of paramount importance; if necessary for group D units where the exposure rates can be high, up to, say, 500 R min^{-1} with very short rso , fitting of dual timers is desirable . . . that visible 'on' signals outside and inside the treatment room are essential.

Interlock mechanisms are always necessary to ensure a machine cannot be switched 'on' with an incorrect filter (or no filter) and if there are any radiation beam modifying devices being used, e.g. lead shields, care should be taken in positioning them and exposure rate calculations must be modified because of the reduced radiation beam size. Other recommendations can be found in a consultative document giving draft guidance notes (NRPB 1983) which when finalised will replace the 1972 *Code of Practice* (DHSS 1972).

Treatments with superficial and deep x-ray therapies are shown in figures 7.3 and 7.4. The field defining applicator mentioned in the figure 7.1 caption is seen in figure 7.4 and one can also see that a shorter rso is used for

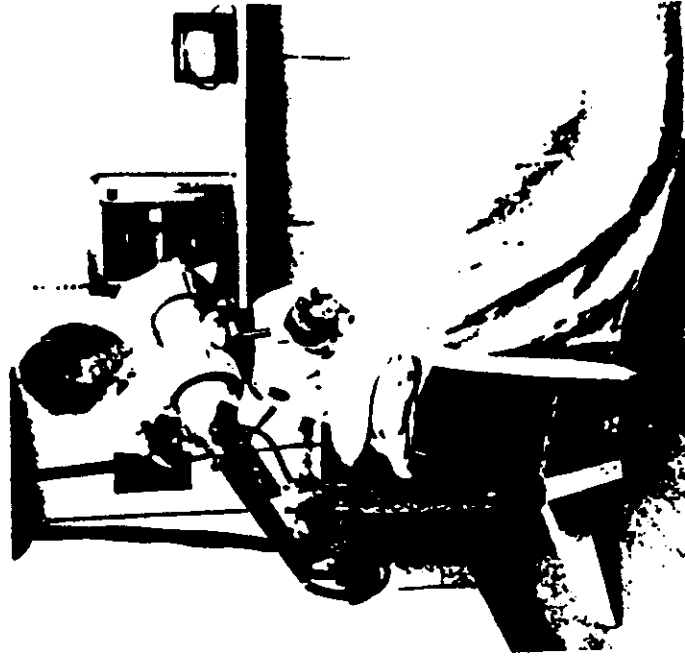


Figure 7.3 Superficial x-ray therapy. The machine is being set up in the treatment position by the radiographer. The radiation beam defining applicator can be clearly seen and will be placed in contact with the patient's skin surface. The lead protective housing around the x-ray tube is also apparent. (Courtesy: EMI Medical.)

superficial therapy than for deep therapy. Superficial therapy is used mainly for skin cancer, such as basal cell carcinomata and rodent ulcers. With the advent of megavoltage machines, deep therapy has been relegated to a relatively minor role, although it is still useful for treatment of breast cancer. Thus the major radiation treatment equipment in a radiotherapy department is now in the megavoltage range: linear accelerators and cobalt-60 machines.

Conventional x-ray tubes shown in figure 7.2 are incapable of producing x-rays in the megavoltage range and so linear accelerators are used. Electrons are accelerated along an evacuated tube, in this case a waveguide, and then magnetically bent through an angle which depends on the accelerator design but is usually 90° or 270° , then finally directed on to a target to produce the x-ray beam. This passes through a flattening filter to obtain satisfactory uniformity and then collimated, as shown in figure 7.1. If the electron beam therapy mode is to be used instead of the x-ray beam therapy mode, the x-ray target and beam flattening filter have to be removed and replaced by an electron scattering foil with a design dependent upon the



Figure 7.4 Deep x-ray therapy. The radiation beam defining applicator is in position to treat malignant nodes in the axilla, secondary to breast cancer. (Courtesy: Philips Medical Systems.)

electron beam energy required. This scattering foil is essential otherwise the electron beam would be too narrow for clinical use. Figure 7.5 shows a linear accelerator being used for megavoltage therapy.

Recommendations for x-ray or electron therapy procedures have been



Figure 7.5 Medical linear accelerator showing the patient on the treatment table. Most treatment techniques involve the application of two or three x-ray beams directed at different angles to ensure that the composite dose distribution gives maximum dose to the tumour and minimal dose to the unaffected tissues. (Courtesy: Philips Medical Systems.)

given in the UK by NRPB (1983) and these are reproduced in table 7.1. In addition there are further recommendations for additional precautions for patient safety when accelerators are used for whole body electron treatments. In the USA, the American Association of Physicists in Medicine published their own *Code of Practice* (AAPM 1975). Table 7.2 lists the section headings of this Code for installation and performance measurements and presents a convenient summary of the requirements for instrumentation and the radiation protection survey. In addition, AAPM (1975) give advice in their Code on: operational performance at initial installation; calibration of the machine; selection of percentage depth-dose data; routine checks and factors affecting dose in the build-up region. This is defined as the region from the skin surface to the maximum dose point. AAPM (1975) also advise ancillary device checks, conventions and necessary data for dose calculation.

Table 7.1 High energy x-ray or electron therapy procedures using accelerators (NRPB 1983).

- (i) Where a timer is provided which can be pre-set by the operator it should be pre-set to a time greater than the estimated duration of treatment but not more than 10% greater.
- (ii) Treatment times of less than 10 seconds are too short to allow for manual switching off in emergency. For normal x-ray and electron beam treatment the dose rate should be limited so that the treatment times used are not less than 20 seconds.
- (iii) It is essential that mental arithmetic under stressed conditions is minimised and that meter readings can be readily converted into terms which are meaningful as regards dose to the patient being treated. Thus dose-meter conversion tables for each mode of operation should be permanently displayed.
- (iv) When accelerators are operated above 8 MeV safety precautions regarding induced radioactivity, e.g. delay in entering the room, may be necessary; the room may need to be designed as a controlled or supervised area on account of this radioactivity. The possibility of induced activity should govern the choice of materials used for collimating the electron beam and for the local shielding of the patient.
- (v) A special problem of high energy electron treatment is that there may be two or more combinations of scatter and/or distance. This gives a multiplicity of calibration factors for attention during operation which does not normally occur in x-ray operation. The number of these dose-meter conversion factors or treatment parameters should be kept to a minimum.

The original tele-isotope therapy machines for the treatment of cancer were developed well before the era of nuclear reactors and artificially produced radioactive isotopes such as cobalt-60. These early machines contained radium and were known as radium bombs (figure 7.6). However,

electrical supply is switched 'off', x-ray therapy machines present no radiation hazard whatsoever. With a cobalt-60 teletherapy machine the cobalt-60 source, however, is continually radioactive. How then can the cobalt-60 machine be made safe in the treatment room while the patient is not actually receiving the gamma ray dose? The cobalt-60 source itself is a small disc or cylinder and is within the head of the cobalt machine. This head is constructed of a protective material such as lead or uranium and while the machine is 'off' the radioactive source is covered by so much protective material that there cannot be any gamma ray leakage through the head of the machine. Figure 7.7 shows a simplified cross-section through the head of the CCR MeV *Aleccon* machine. In the 'off' position shown the cobalt-60 source is well surrounded by lead and uranium. In the 'on' position the drum rotates until the source reaches the collimator and a gamma ray beam is directed towards the patient's tumour as in figure 7.1. In figure 7.8 the large, well protected head of the unit is clearly visible. Lead radiation beam

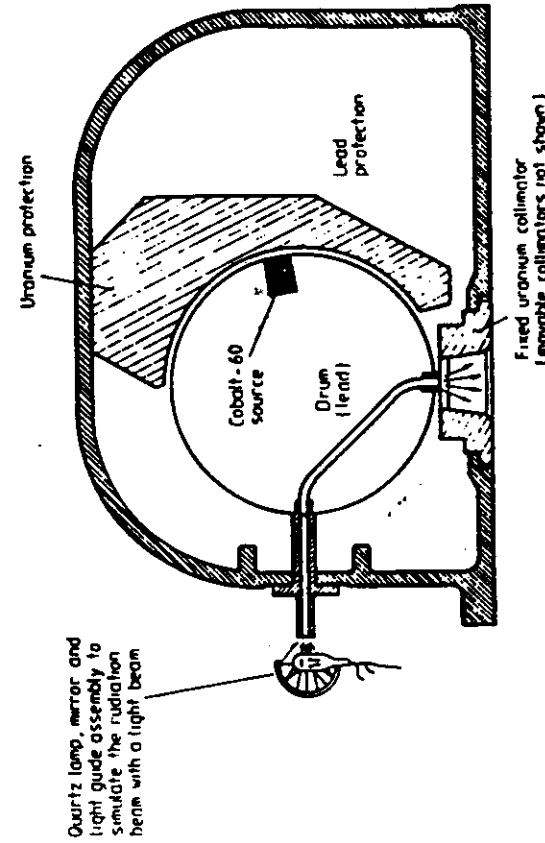


Figure 7.7 Cross-sectional view through the head of a cobalt-60 therapy machine. (Courtesy: CCR MeV.) The radioactive cobalt-60 sources are often made in the form of a small disc-type capsule. These may have, for example, active diameters of 10, 12, 15, 17 or 20 mm and could deliver normal maximum radiation exposures at 1 m between 45 and 65 R min⁻¹ for the 10 mm sources and 170–240 R min⁻¹ for the 20 mm sources.

trimmers can be seen projecting from the head and can be used in addition to the major collimators to shape the radiation beam edge. Possible causes of dose faults have been listed by RASMP and are given in table 7.3 (DHSS 1975). Not all of these are caused by equipment failure.

Table 7.2 Installation and performance measurements for x-ray linear accelerators (AAPM 1975).

Instrumentation
Survey Meters
Calibration Dosimeters
Suitable for a local standard and for initial or reference calibrations
Routine field instrument for ongoing calibrations of equipment subsequent to the initial reference calibration
Care and Maintenance
Radiation protection survey
Surveyor Safety
Head Leakage
Anomalous Leaks
Determination of Absolute Leakage
Occupiable space outside the treatment room

when cobalt-60 became available commercially, its advantages included higher specific activity sources; no hazardous daughter products like radon-222; the maximum energy in the radium gamma ray spectrum was higher than cobalt-60 gamma ray energy, it was thus easier to protect cobalt-60 sources; the half-life of radium, 1620 years, means that these sources remain a hazard for ever, whereas the half-life of cobalt-60 is only 5.26 years. All these factors combined effectively to cause radium to be phased out in favour of cobalt-60 for external beam therapy units. Also, for interstitial and intracavitary therapy radium will soon be totally phased out in preference to artificially produced radionuclides (see §1.6).

For a conventional x-ray unit or linear accelerator, an electrical supply source is necessary before the x-rays can be switched 'on'. When the



Figure 7.6 A radium bomb of the 1920s, known as the 'Sluys-Kepler unit'. Its radium foci were incorporated into the design of the treatment head.

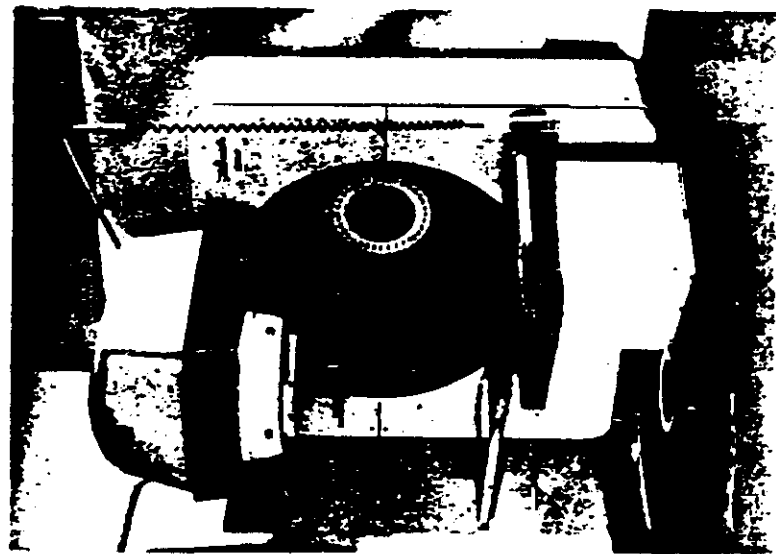


Figure 7.8 Cobalt-60 teletherapy unit and the patient's treatment table. The unit head is in a position such that the gamma ray beam is directed vertically downwards. However, the head can rotate and the angle is recorded on the scale in the centre. At the end of the cable on the right is the radiographer's handswitch control for positioning the head and the treatment table. This handswitch cannot, of course, be used to switch the gamma rays 'on' as personnel other than the patient and the radiographer could be in the treatment room. (Courtesy: CGR MeV.)

some are operator's errors such as an incorrectly set treatment time, but they serve to illustrate some of the faults which must be avoided.

If the treatment terminating device fails and the cobalt-60 source is actually stuck in the 'on' position, there must be a contingency procedure incorporated in the machine design by the manufacturer allowing the source to be returned to the safe 'off' position without undue hazard to personnel. Also, the patient must be immediately requested to leave the treatment room, although the radiographer may be at risk if the patient needs assistance stepping down from the treatment couch. Fortunately, such 'source sticking' is now rare although van Roosenbeek *et al* (1972) from the University of Texas, MD Anderson Hospital, Houston, recorded that it

Table 7.3 Possible causes of dose faults with cobalt-60 therapy units (DHSS 1975).

Failure of treatment terminating device and/or interlocking circuits to shut off the useful beam
Failure to align the source and the beam aperture during treatment
Inadvertent total or partial exposure of the radioactive source to the beam aperture at times other than during the prescribed treatment
Inaccuracy of treatment timers
Incorrectly set treatment times
filter†
treatment distance or field size‡
treatment mode§
Failure in design to anticipate a fault contingency.

†Filters refer to *wedge filters* used to shape the radiation beam and modify the open beam shape of figure 7.1. Several wedge filters with different *wedge angles* are usually available, and suitable interlock systems must be incorporated to ensure that the patient cannot be treated using an incorrect wedge.

‡Treatment distance is specified in terms of *SSD* (figure 7.1), *SSD or SAD* (source axis distance) the distance from the source to the point (the *isocentre*) around which the machine rotates. The usual value for SAD is 100 cm. *Field size* is radiation beam size on the patient's skin surface.

§Treatment mode with a linear accelerator is either x-ray or electron mode but mode also refers to treatment either with a *fixed* or a *moving* beam (rotation therapy), where the machine arcs around the patient during treatment.

occurred about 25 times at this one centre during 1953–1971 and resulted in personnel total body doses of up to several rads.

7.3 TREATMENT ROOM

Since the energy of the ionising radiation for superficial, deep and megavoltage x-ray therapy differs so widely, the design requirements for protected rooms also differ. In practice, in many of the older hospitals and institutes the radiotherapy department has grown in an *ad hoc* manner over a long period of time as more sophisticated and powerful machinery has become available. Expansion to house new units has often been determined by the availability of space, hardly ever unlimited, and by existing building structures. This has led to the existence of departments organised in a far from ideal manner regarding access, patient waiting areas and clinic room sizes, although protection is correct in terms of treatment rooms.

The National Council on Radiation Protection and Measurements (NCRP 1976) state in their report that for x-rays below 20 keV, special structural

shielding is usually not necessary because ordinary building construction offers adequate protection against this low energy radiation. They add that structural shielding is not needed either for 40–50 keV x-rays when a short lead of 2 cm (*contact therapy*) is used, because of the short treatment times. Shielded roomst are, however, necessary in the 50–150 keV x-ray energy range. In practice, though, most superficial therapy rooms have doors and walls protected by some 1–2 mm of lead, usually lead-plywood panels. Construction is relatively easy with the panels simply fixed to the walls, ensuring there are no gaps between the individual panels or at room corners. Doors are hung with a lead protected rebate so that there is no radiation scatter through the door jamb. Observation windows are of 1–2 mm lead equivalent (i.e.) lead glass.

All deep x-ray therapy machines must be housed in individual treatment rooms. Room design is similar to that for superficial therapy except that additional protection is required and walls, doors and observation windows (and if necessary, floors and ceilings) are usually protected by some 3–5 mm of lead. However, not all areas will require the same amount of protection and barriers can be conveniently classified as *primary* and *secondary* barriers. A primary barrier is one which attenuates the direct primary useful radiation beam to the required degree and a secondary one attenuates the stray, scattered and leakage radiation to the required degree. Nevertheless, superficial and deep therapy rooms where only a relatively small amount of protection is required compared with megavoltage installations, usually have walls and doors constructed with a single thickness of lead plywood. This lead protection is only manufactured in standard multiples of 0.5 mm lead and it would not be cost-effective to install barriers measured to the nearest 0.1 mm lead. Superficial and deep therapy rooms also have safety interlocks incorporated to prevent entry to the room when x-rays are 'on', and also warning lights signifying when x-rays are 'on'. Another feature important in the design of these rooms, particularly for deep therapy where treatment times are longer than for superficial therapy, is the air conditioning. This is a feature which, although not radiation protection, is sometimes forgotten in the planning stage when equipment tends to be squeezed into the smallest possible space. In the case of a deep x-ray machine, this could prove most unpleasant for patients and staff.

Lead-plywood wall panels for protective barrier construction in superficial and deep therapy rooms have advantages over concrete barriers in terms of wall thickness, actual building process and space. However, in megavoltage therapy rooms, the high cost of the necessary amount of lead

†This NCRP (1976) publication includes data tables of minimum shielding requirements in lead or in 2.35 g cm⁻³ concrete, for therapy and diagnostic installations, in terms of controlled and non-controlled areas, primary and secondary protective barriers, the factor *WUT* (see §6.3) and the distance of the x-ray source to the protective barrier.

would preclude its use as an alternative to concrete. It should also be noted that, whereas at low energies lead is a more effective shielding material than concrete, at high energies above 1 MeV it loses its advantage over concrete because the Compton effect, which is independent of the atomic number *Z* of the absorber, and not the photoelectric absorption process is now dominant (see chapter 3 and figure 3.1). Figure 7.9 is the cutaway view of a typical concrete bunker, as megavoltage treatment rooms are often called and a cross-section through a similar treatment room intended specifically for a 5 MeV linear accelerator is shown in figure 7.10†. This incorporates several general features found in other concrete bunker designs. For example: remote controlled TV monitors inside the room so that the radiographer outside the room can observe the patient during treatment; maximum wall thickness in the direction of the primary beam; thinner protective barrier on the outside maze entrance corridor wall since the inside wall of the corridor provides most of the required protection; electrically interlocked safety barrier at the entrance to the maze. The radiographer's work table will contain the treatment control unit and a TV monitor linked to those in the treatment room. The calculations used for the treatment room design in figure 7.10 refer to a particular linear accelerator SL75-5 within the Philips range of accelerators available in 1984: SL75-5, SL75-14, SL75-20. For the higher energy machines the protective barriers must be increased. For example, in a typical layout for the SL75-14‡ the primary barrier would have increased from 1.55 m (SL75-5) to 1.8 m concrete, the secondary barrier at the back of the machine from 0.85 to 0.98 m and the inside maze corridor wall from 0.7 to 0.9 m. The overall dimensions of the room in figure 7.9 is 9.5 × 8.2 m² and this would increase to 10.9 × 10.1 m² for the SL75-14 machine. For comparison a small deep therapy x-ray room might be 4 × 4 m².

When estimating the required protective barrier thickness for scattered radiation instead of the primary beam certain assumptions must be made. One is for the use factor, figure 7.10, to be *U* = 1/4, implying that the scattered radiation dose is equal for the floor, ceiling and the two side walls away from the primary barriers. Another factor is *leakage radiation* through the machine head in all directions. For the SL75-14 machine it can be assumed that the maximum intensity of this leakage radiation is 0.2% of the primary intensity when measured at the same distance from the x-ray target inside the head.

With the lower energy megavoltage machines for x-ray photon and electron beams, low level neutrons are produced when the photons or electrons are absorbed in the concrete walls. Hence these can generally be

††I am grateful to J Davies of Philips Medical Systems for supplying the drawing on which figure 7.10 is based.

‡Particle Accelerator Division ME-1 (Crawley) 1982 *Planning Information for the Philips SL75-14 Medical Linear Accelerator* Publ. No 1159 Machines 422 x.

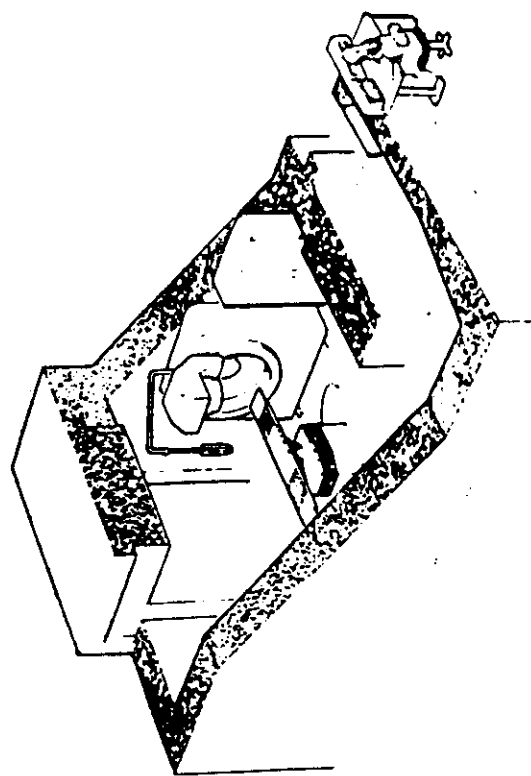


Figure 7.9 A radiotherapy linear accelerator concrete bunker with a maze entrance. Cutaway view shows the treatment machine and patient couch. (Courtesy: CGM Medical Ltd.)

ignored when designing shielding and maze entrances. However, for x-rays from the higher energy megavoltage machines, such as the SL75-20, the neutron attenuating characteristics of the room and its maze entrance must be taken into account. The energy ranges of these machines are given in table 7.4.

X-rays with photon energies above 12 MeV will liberate energetic photo-neutrons from the atomic nuclei of most elements. For the SL75-20 in the 16 MeV x-ray mode the neutron output is between 0.15% and 0.5% of the therapy dose measured at the same distance from the source (Kersey 1979)†. This has to be taken into account when designing the treatment room. For a typical maze such as in figures 7.9 and 7.10, with two bends in opposite directions, attenuation of x-rays is effective but neutron attenuation is poor. This can be overcome either by designing an unusually long maze or incorporating a door of boron-loaded paraffin wax. To summarise, design of megavoltage radiotherapy bunkers is not particularly straightforward and considerations should include the following: attenuation of the primary

†See also the review article by Nath *et al* (1984), the technical report by Palta *et al* (1984), the revised *Code of Practice* by Lillier *et al* (1983) and the German DIN standards on medical electron accelerators and radiation protection rules for installation (November 1977). This last reference is based on concept definitions in accordance with DIN 6814 *Concepts and Designations in Radiological Engineering*.

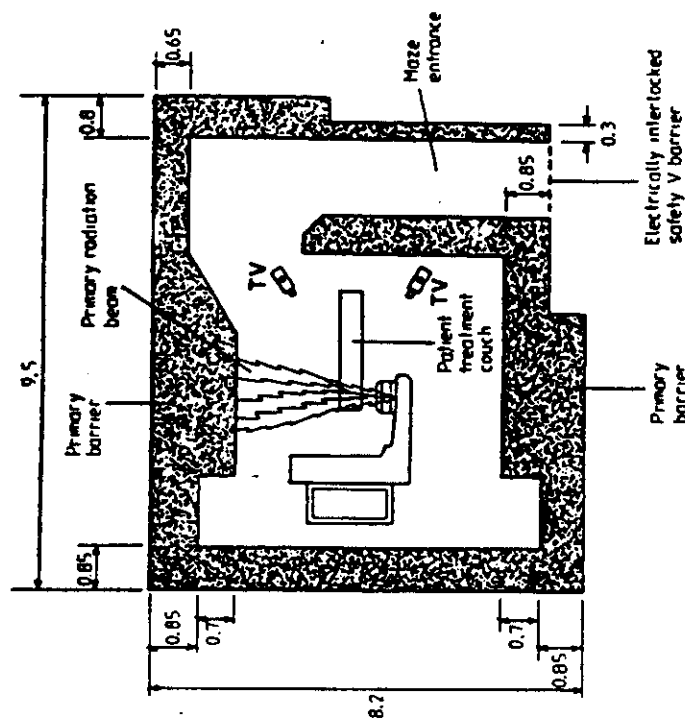


Figure 7.10 Treatment room design for a 5 MeV linear accelerator. All dimensions are stated in m and the radiation shielding is based on the following conditions: (i) maximum permissible dose outside shielding is 0.1 mSv (10 mrem) per 40 hour week; (ii) the weekly workload at the isocentre (1 m from the source for the SL75-5) should equal 10^6 mSv (10^5 rem); (iii) use factor $U = 1/4$, assuming 25% dispersion of primary beam to walls, floor and ceiling; (iv) use occupancy factor $T = 1$. In the plane of this diagram, the primary beam can only be directed vertically and not horizontally, hence there are only two primary barriers, each of 1.55 m concrete, 2.35 g cm⁻².

Table 7.4 Energy ranges of the Philips SL75 machines, as examples of linear accelerators.

Machines	X-ray modes (MeV)	Electron modes (MeV)
SI 75-5	5	none
SI 75-14	8 or 10	4, 6, 8, 10, 12, 14
SI 75-20†	8 and 16	5, 6, 8, 10, 12, 14, 1

†The SL75-20 has been replaced in 1985 by the SL25 with modes 8 and 25 MeV and electron modes from 4 to 22 steps of 2 MeV.

beam, x-ray leakage through the machine head, scattered radiation in areas away from the primary barrier walls, attenuation of neutrons if the x-rays have energies above 12 MeV.

7.4 PROTECTION OF THE PATIENT

The hospital staff and members of the general public who visit a radiotherapy department are protected by the thick walled concrete bunkers or lead-lined walls of the superficial or deep x-ray therapy rooms, by the safety interlock systems preventing accidental radiation exposure and by the radiation warning lights and notices. Staff are monitored using film badges and TLD dosimeters, records are kept in accordance with regulations such as the relevant Code of Practice and working areas are closely controlled. For the patient, though, the situation is different as at the outset they are being prescribed a specific radiation dose schedule. When the treatment is palliative, rather than radical, perhaps because of the extent of the disease or presentation for treatment, the radiotherapy treatment is no less important to the patient. Protection of the patient is therefore not considered in terms of dose limits such as those discussed in chapter 6, but in terms of accurate delivery. This refers to prescribed dose for the primary tumour and areas of secondary spread, and avoidance wherever possible of irradiating healthy tissue, in particular, the radiosensitive organs such as eyes, spinal cord, larynx, rectum and bladder. Accurate treatment planning is therefore essential, with the optimum use of radiation beam shaping devices (e.g. wedge filters and lead shields) to protect unaffected vital organs and allowance in dosimetry plans for tissues with different densities. As an example, lung tissue has a density of 0.3 g cm^{-3} compared with unit density of soft tissue and muscle.

Care must also be taken in treatment planning not to mix up different conventions such as the normalisation or non-normalisation of wedge isodose curves since this could lead to errors in delivered doses. The convention with which one presents the completed treatment plan is also important, since a wrongly labelled right and left could have disastrous results. Nowadays computers play an important part in treatment planning and much of the laborious arithmetical work has been removed. Dosimetry corrections for inhomogeneities and oblique incidence can now be routinely incorporated into planning whenever necessary.

Another feature in planning is the simulation of the treatment such that the tumour (termed the *target volume* in planning) can be accurately localised and defined within the body cross-section. A machine called a *treatment simulator* can reproduce the precise movements of the external beam treatment machine and the patient's treatment couch. An x-ray tube,

image intensifier and camera are incorporated into the simulator and radiographs can be taken to assist in the planning process. Since it is essentially a piece of diagnostic x-ray apparatus, generally used in the x-ray energy range 60–100 keV, the room housing the simulator must be protected as would a room in a diagnostic radiology department. Thus a screen with a lead glass viewing window and lead-plywood panelling is incorporated in the design.

Once the radiotherapy treatment has been planned and simulated, it must be accurately delivered to the patient. This involves an accurate knowledge of the radiation output from the external beam machine, a correct setting up of the patient on the treatment couch, devices ensuring the patient positioning is accurately reproducible and the use of any required wedge filters or other specified beam shaping devices such as lead blocks. Computers are also entering the sphere of treatment verification and references include the British Radiology Special Report No 16 (1979) *London Computers in the Control of Treatment Units*, the *Acta Radiologica Supplement No 353 (1976) Planning, Control and Documentation of External Beam Therapy* and proceedings of International Conferences on the Use of Computers in Radiation Therapy such as the sixth conference, *Computers in Radiation Therapy* (Göttingen 1977 ed. U. Rosenow).

Records and documentation can also be considered an integral part of a patient's protection. If no permanent record of the patient's treatment is available, subsequent follow-up analysis would be difficult if further treatment ever became necessary. Records and documentation of treatment machine acceptance tests, reference measurements related to radiation beam isodose curves, routine radiation output measurements, servicing and maintenance reports are also vital. Although these are directly relevant to patient treatments, they do not involve any recording of individual patient details. For a full record of patient data a *cancer registry* is required and specifications vary among hospitals, regions and nations (Mould 1983, 1984). It should, however, be remembered that it is pointless storing vast quantities of detail on patient treatments for retrospective analysis without first deciding exactly what it is that should be finally analysed: dose, fractionation schedules; effect of age, histology, stage of disease; target, modal or minimum doses. Far too often in retrospective analyses there is a bias in the patient data rendering the subsequent results virtually useless. These can be caused by a combination of cases from different centres with differing treatments or even differences in a single hospital among the individual consultants. Hence only an overall general view is possible and nothing of specific interest can be obtained. Or, maybe so much data has tried to be collected that only a 60% data collection success rate occurs for most patients, the missing 40% being different for each one. The point is, if you wish to investigate whether treatment A is better than treatment B, then a planned prospective clinical trial must be organised with properly defined

aims and clear and understandable protocol and an infrastructure should be set up to ensure proper documentation and follow-up and subsequent statistical analysis. Note that treatment for cancer is often not just by radiotherapy and can be in combination with surgery and/or chemotherapy.

Finally, to destroy a misconception occasionally encountered among those without any knowledge of a radiotherapy department; namely that radiotherapy patients treated by external beam therapy machines are radioactive! When the therapy unit is 'on' and an x-ray beam being emitted then the machine is an x-ray source, *but at no time is the patient a radiation hazard*. This misconception is to be deplored since it is bound to affect the attitude towards the patient and might also unduly upset the patient.

CHAPTER 8

PROTECTION IN INTERSTITIAL SOURCE RADIOTHERAPY

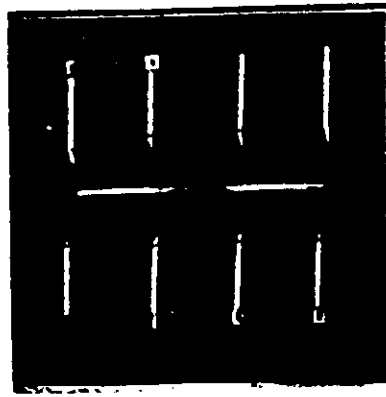
8.1 INTRODUCTION

In external beam cobalt-60 therapy the sealed radioactive source is within a large machine and always remains at a distance from the patient—the source skin distance (SSD). In *brachytherapy* the radioactive source is usually in contact with the patient† and the method of application of the source is either by *interstitial* or *intracavitary* means. Chapter 8 considers only interstitial therapy in which the sources are implanted directly into the tumour-bearing tissue. In intracavitary therapy the sources are inserted into a natural body cavity. There is also a third type of brachytherapy known as mould therapy in which the radioactive sources are placed on a mask which covers the area to be treated. The mask is made of a material such as paraffin wax, hard plastic or, in earlier years, leather. The mask and sources together are termed a surface mould or surface applicator and an example is shown in figure 8.1. These moulds were used to treat many skin cancers, but in recent years the technique has fallen into disuse and is now seldom applied.

Starting with radium and radon-222 sources, different radionuclides in varying forms, wire, seeds, needles, tubes, have all been used for therapeutic purposes (see §8.2). All have their own problems regarding handling, storage and eventually disposal when they are considered to be waste (see §8.4). The most recent feature relating to good radiation protection practice has been the widespread introduction of afterloading techniques (see §8.3) which has markedly reduced the radiation exposure received by staff associated with the interstitial implantation. This also applies to intracavitary therapy (see §9.3).

†The United States NCRP (1978a) define brachytherapy as 'a method of radiation therapy in which an encapsulated source is utilised to deliver gamma or beta radiation at a distance up to a few cm either by surface, intracavitary or interstitial application'.

Figure 8.1 Radium tubes embedded in a paraffin filled metal tray to form a surface applicator (Radium Institute, London, 1920s). This radium applicator is a coplanar arrangement of sources used to irradiate a specified planar area parallel to the plane of the sources. The distance between the plane of the sources and the treatment plane within the cancer is termed the *treating distance*. Various systems were established specifying a series of general rules to determine the spatial position and radioactive loading of the sources so that different sized areas at different treating distances could receive a uniform radiation dose. The most widely used of these systems, the Manchester system, was developed by Paterson and Parker at the Christie Hospital, Manchester. The dosimetric planning for single plane interstitial implants of radium sources by the Manchester system was developed from these surface applicator plans.



8.2 RADIATION SOURCES

The sources most commonly used in brachytherapy for many years were the radium tube and radium needle shown in figure 8.2. The radium cell consists of grains of a radium salt, usually sulphate or bromide, mixed with an inactive filler to obtain a uniform radioactive density. Depending upon the length of the source there may be more than one cell. The needles are used for interstitial therapy and the tubes for intracavitary therapy. Actual linear radium sources are illustrated in figure 8.3 and it can be seen that each source is inscribed with a reference number on the outer platinum sheath surrounding the radium cells. This sheath, usually 0.5 or 1 mm platinum thickness, acts as a filter for the alpha and beta radiations from radium, thus ensuring the tissues only receive a gamma dose. With a half-life of 1620 years

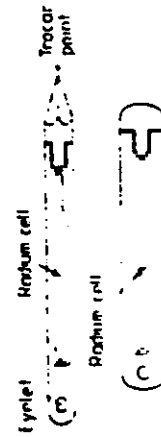


Figure 8.2 Schematic diagram of a radium tube and radium needle. The eyelets in the sources are used when it is necessary to suture the source to the patient's tissue to prevent the possibility of involuntary removal before the end of treatment.

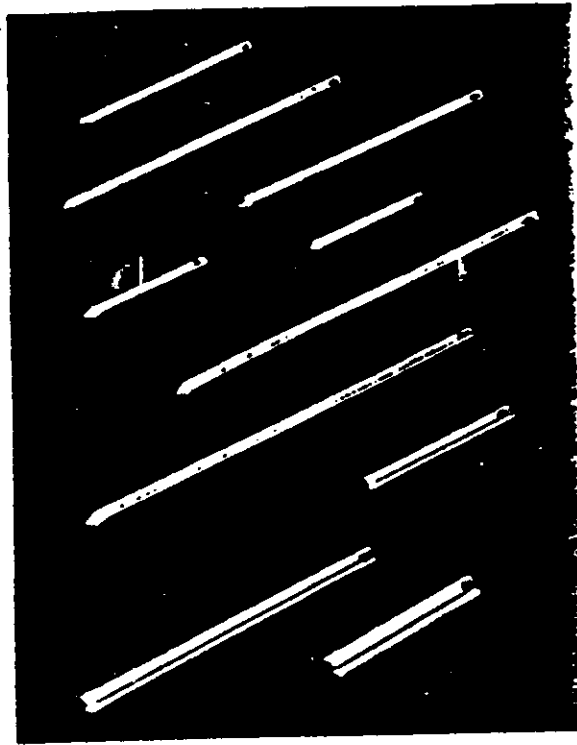


Figure 8.3 A selection of radium needles and tubes produced by the UKAEA Radiochemical Centre during the 1960s. Currently, radium sources are no longer available but similar linear sources are now constructed using radioactive caesium-137.

for radium it is necessary to individually identify each source in case of possible loss.

The interstitial techniques of the Manchester system and other systems developed in the 1930s endeavoured to deliver a uniform dose, defined as within $\pm 10\%$ of the prescribed dose, over a specified treatment area or volume. Earlier methods such as that illustrated for a surface applicator in figure 8.1 did not realise that a uniform dose distribution of radioactivity in the source plane delivered a non-uniform dose distribution in the treatment plane, whereas a non-uniform radioactivity distribution in the source plane could be designed to deliver a uniform dose distribution in the treatment plane. For example, the radioactive distribution rules for Manchester system planar implants, as distinct from volume ones, were:

- (i) The radium should be arranged on a single plane in such a way that for areas of under 25 cm^2 , $\frac{1}{4}$, for areas between 25 cm^2 and 100 cm^2 , $\frac{1}{2}$, and for areas over 100 cm^2 , $\frac{1}{4}$ of the total radium is placed round the periphery of the area. The remainder is spread evenly over the area itself.
- (ii) A common arrangement will be found to be a row of parallel needles with active ends crossed by means of needles at right angles to the first part of the implant.

- (iii) Needles arranged as a series of parallel lines which should not be more than 1 cm from each other or from the crossing ends.
- (iv) In two-plane implants the radium on each plane should be arranged as in (i), (ii) and (iii) above and the planes should be parallel to each other.

Dosage tables accompany the Manchester system and the total amount of radium (now caesium-137) to be distributed according to rule (i) above can be found by calculation.

Figure 8.4 shows an isodose distribution around a linear caesium-137 source (see figure 7.1 for isodose curves in external beam therapy) and one can see that there is a peculiar end-effect. This is due to the radium gamma rays having to travel further through platinum at the dead ends of the source where there is a greater thickness of platinum filter (the eyelet surround and trocar point as in figure 8.2) than on the source's linear axis. Crossing needles are necessary in an implant to compensate for these end effects. A radiograph of a radium needle implant to the neck is shown in figure 8.5.

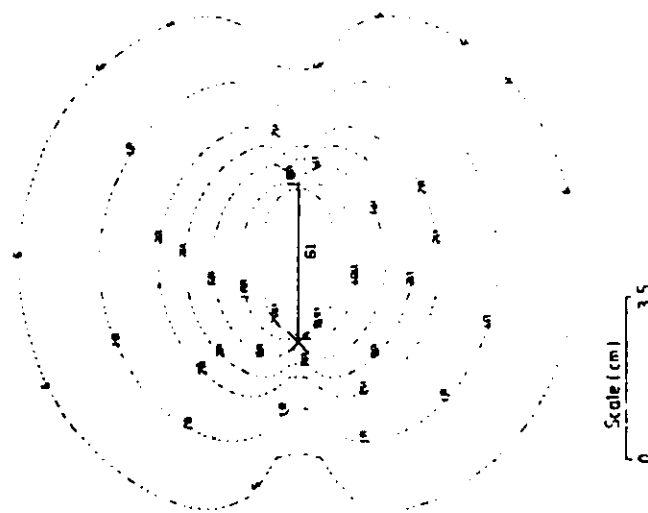


Figure 8.4 Isodose curves around a linear caesium-137 source of 2.11 CiBq (57 mCi) activity (equivalent to 25 mg radium), with an active length of 2.5 cm, an overall length of 3.5 cm (solid black line labelled S1) and a diameter of 0.25 cm. The isodose curves are specified as a dose-rate in cGy h^{-1} (rad h^{-1}) and range from 5 to 200 cGy h^{-1} . The source is assumed to be embedded in unit density tissue.

This is an implant of four parallel needles with both ends of the implant crossed by smaller needles. Sometimes, however, it is not possible to cross both ends, as in the case of an implant for cancer of the tongue in which the lower implant end within the floor of the mouth cannot be crossed. For events such as this, or platinum filtrations other than 0.5 mm, correction factors are applied to the Manchester system dose tables.



Figure 8.5 Radiograph of a radium needle interstitial implantation to a tumour in the neck.

There was a limit to the specific activity of radium which could be achieved within a source, that is, a lower limit of radioactive density below which a radium source could not be constructed. In practice, this meant that the smallest available radium sources were usually around 2 cm in length. For situations in which smaller radioactive sources were required the use of the gaseous radium daughter product, radon-222, was used in the form of small seeds typically 0.5 cm long, in which the radon gas was sealed into platinum or gold containers. Strings of threaded radon seeds were also used at some centres as an alternative to linear radium sources. Since radon has a half-life of only 3.8 days, the seeds were sometimes left permanently implanted into the tissues as the radioactivity would soon decay to a negligible amount.

One of the major radiation hazards with radium sources is the gaseous daughter product radon which builds up under pressure in the sealed source. As time passes, therefore, there is a danger of radon gas leakage, particularly if the sources have been mishandled in any way and become mechanically damaged. Any hospital stock of radium sources must therefore be routinely tested for radon leakage. This will inevitably lead to additional radiation exposure to the technical staff undertaking the leakage tests. Since the maximum gamma ray energy of radium is 2.4 MeV the shielding problems when working with radium sources are considerable when compared with other sealed radioactive sources such as caesium-137 which has no gaseous

daughter products and a gamma ray energy of only 0.66 MeV. Although radon has a short half-life and the seeds could remain *in situ* after treatment, there was still the hazard of handling gaseous sources prior to implantation. Moreover, there was, of course, the much greater industrial hazard associated with the radon seed production plants. All these problems of handling radium and radon have resulted in their replacement by artificially produced radionuclides such as those listed in table 8.1.

Table 8.1 Radioactive isotopes, their half-lives and gamma ray energies.

Isotope	Half-life	Gamma ray energy (MeV)	Source type
Radium-226	1620 years	0.2-2.4	Needles, tubes
Radon-222	3.8 days	0.2-2.4	Seeds
Caesium-137	30 years	0.66	Needles, tubes, beads, pellets†
Cobalt-60	5.26 years	1.17, 1.33	Needles, tubes, beads, pellets†
Iridium-192	74 days	0.3-0.6	Wire
Tantalum-182	115 days	0.05-1.24	Wire
Gold-198	2.7 days	0.41	Seeds

†Beads and pellets are employed in source trains for afterloading machines used to treat cancer of the cervix by an intracavitary method, see chapter 9.

The advantages of caesium-137 and cobalt-60 over radium for needles and tubes include the absence of hazardous gaseous decay products and a lower maximum gamma ray energy. Caesium-137 is normally preferred to cobalt-60 since it has a longer half-life and hence lower replacement costs. Also, it is easier to protect against 0.66 MeV gamma rays than against the higher energy radiation from cobalt-60.

The replacements for radon seeds are gold-198 grains, also with a half-life of a few days, which can thus be permanently implanted in tissues. The gold seeds, or gold grains as they are sometimes termed, are smaller than radon seeds, 0.25 mm length and 0.08 mm diameter, and are implanted using a specially designed gun (figure 8.6) with a magazine containing 14 gold grains. These small sources are useful in the treatment of malignant nodes and also bladder tumours, particularly those near the urethra which would be difficult to implant using a larger source (figure 8.7).

One of the earliest radium replacements in medicine was tantalum-182 in the form of hairpin wires, specifically designed for use in the treatment of bladder cancer. However, tantalum-182 has been superseded by iridium-192 with its shorter half-life and lower gamma ray energy spectrum. Iridium wire can be delivered in a coil and cut to appropriate lengths or purchased in the form of hairpins or single pin sources. These wires, unlike linear radium sources, are malleable and can be produced in a nuclear reactor to a range



Figure 8.6 Gold grain implantation gun.

of specified linear radioactive densities. They have enabled treatment techniques to be developed which were impossible with radium tubes and needles. However, regular monitoring of the theatre and preparation room areas is needed to ensure no hazard exists from small unused pieces of wire which are classified as radioactive waste.

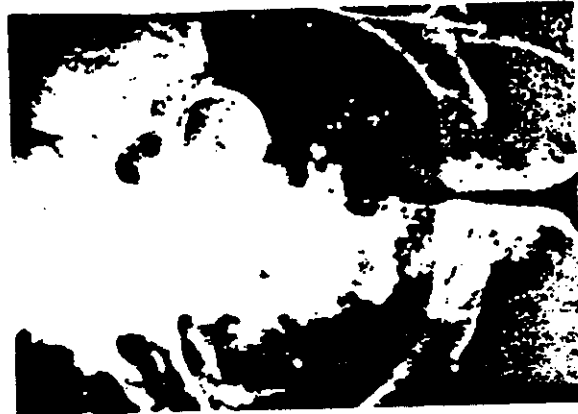


Figure 8.7 Radiographs of gold grain implants to (a) the bladder and (b) the neck.

8.3 MANUAL AND AFTERLOADING TECHNIQUES

In the manual method of inserting radioactive sources for interstitial therapy, the radiotherapist or surgeon has to use some kind of holding mechanism and push the source into the correct position in the tumour tissue. For radium or caesium needles the sharp end of the needle enables the tissue to be punctured to allow insertion of the source, and the implantation gun with a sharpened point is used for gold grains. Radiographs are then taken to determine the relative positions of the implanted sources so that the radiation dose to the tumour can be calculated. The radioactive sources are therefore an unshielded hazard from when they are removed in the operating theatre from the lead storage container, while the radiograph is taken using a diagnostic x-ray machine up until the patient is on the hospital ward. Here, too, there is a radiation hazard, albeit a controlled one, but the periods when staff are in closest proximity to the sources are in the theatre and during the radiography setting-up procedure.

An *afterloading* technique reduces these radiation hazards since the initial implantation is of hollow non-radioactive guide needles. Only when they are confirmed to be in the correct position can the radioactive sources be inserted. Thus when radiography is taking place after insertion of the guide needles there is no radiation hazard from gamma rays. The radioactive isotope normally used for interstitial afterloading is iridium-192 in the form of wire (figure 8.8). The procedure is such that the guide needles (figure 8.9) are first inserted, then packed for positioning and only after this are the wire sources inserted into the slotted guides. After the iridium wires are in position, the guide needles are withdrawn. Once the treatment has been delivered over a period of a few days, the iridium wires are finally removed. Figure 8.10 shows wires inserted for a treatment of cancer of the anterior two-thirds of the tongue.

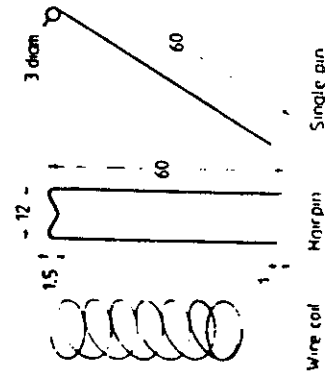
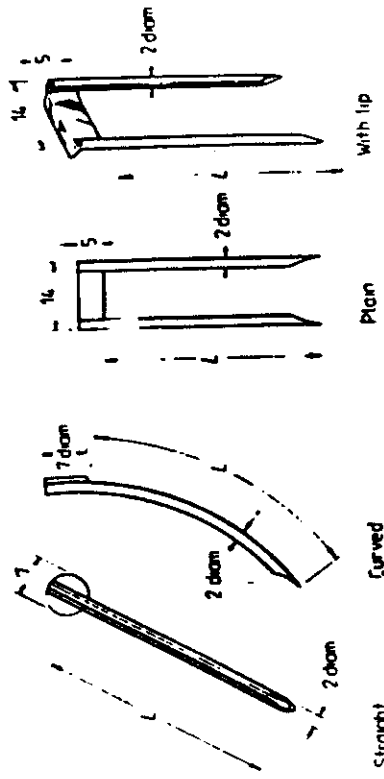


Figure 8.8 Iridium-192 sources for use in interstitial therapy. Measurements are given in mm. (Courtesy: Amersham International plc.)



$L = 40 \text{ or } 60$

Figure 8.9 Stainless steel guide needles for use in iridium afterloading interstitial therapy. Measurements are given in mm. (Courtesy: Amersham International plc.)

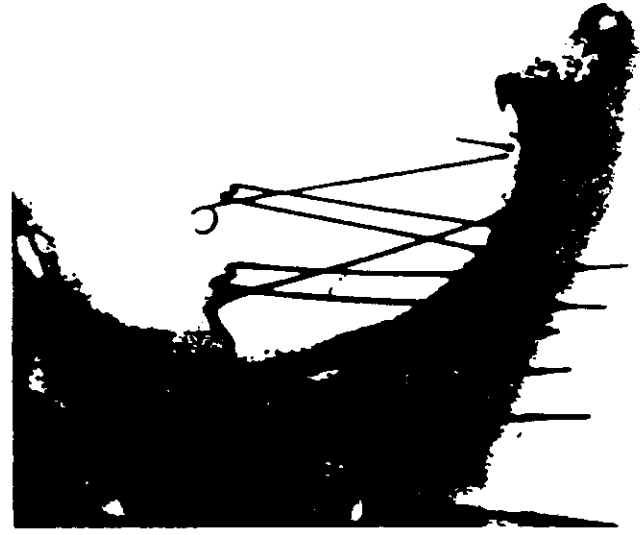


Figure 8.10 Use of four iridium wire hairpins and two single pins for treating a locally advanced cancer of the anterior two-thirds tongue. A radiograph magnification marker is shown. (Courtesy: Dr C H Paine, The Churchill Hospital, Oxford and Amersham International plc.)

Another technique of interstitial implants using iridium-192 wire was devised for cancer of the breast, by Pierquin for Paris and Paine in Oxford. In this technique the guides are not stainless steel but nylon tube and the iridium wire is encapsulated within a nylon tube also, the inner tube in figure 8.11. It is for this technique that the wire coils in figure 8.8 are required, and a specially designed iridium wire loading device is also needed to encapsulate the wires prior to implantation. The nylon balls and lead discs in figure 8.11 are necessary to fix the source in position during treatment. Several iridium wires are required for this technique, but for simplicity only one wire has been illustrated in figure 8.11.

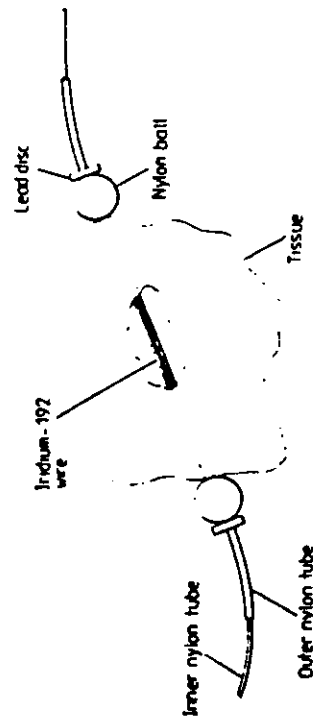


Figure 8.11 Iridium wire interstitial therapy technique for treatment of cancer of the breast. The Pierquin-Paine technique. (Courtesy: Amersham International plc.)

8.4 SEALED SOURCE ROOM

In brachytherapy there are two types of room to be considered. Firstly the sealed sources room housing the storage facilities for the caesium-137, iridium-192 and other radioactive brachytherapy sources; secondly the room or ward in which the patient will stay whilst the radioactive sources are within the tumour. A separate room should be provided in which there are storage facilities for the sources, lead protected bench space for handling sources plus equipment such as forceps, clamping devices and threading devices. When only radium and radon sources were available this room was usually known as 'The Radium Room' but nowadays would be more appropriately termed 'The Radioactive Sealed Source Room'. When sources are unsealed, such as iodine-131, source handling is conducted in a different room, known as a dispensing or 'hot' laboratory (see chapter 10).

The UK National Radiological Protection Board (NRPB 1983) provide three guidance notes for the room where brachytherapy sources are prepared and afterwards cleaned before storage (table 8.2). The USA National

Table 8.2 Sealed source room guidance notes (NRPB 1983).

- (i) It is essential to provide a separate room for the make-up and cleaning of sources and applicators and this room should be occupied only during such work. The room will usually need to be designated as a controlled or supervised area on account of external radiation from the sources which are used, although every effort should be made to reduce the dose rate in the room by the use of local shielding. There may be slight contamination from sources which are not sealed sources but it is unlikely that the room will need to be designated on account of contamination (unless a source is damaged). The room should be designed so that it can be easily cleaned and decontaminated; benches and most shielding should be fixed; work benches, floors and walls should have smooth impervious surfaces.
- (ii) It is essential that the door of the room is marked with a warning sign indicating ionising radiation and if the room is a controlled area this sign may form part of the necessary warning notice.
- (iii) Storage for closed sources must be arranged. This may be in a storage safe in the preparation room or in a separate source store.

Council on Radiation Protection and Measurement (NCRP 1978a) have also made recommendations concerning storage facilities (table 8.3).

There are many different designs of lead protected storage safes commercially available, and one is shown in figure 8.12. Any safe is basically a lead-walled container, with security lock and a single storage cavity or series of cavities within individual lead drawers. For storage of radium replacement sources such as caesium-137 tubes and needles no ventilation is needed (table 8.3) since there is no radon risk, but adequate amounts of lead

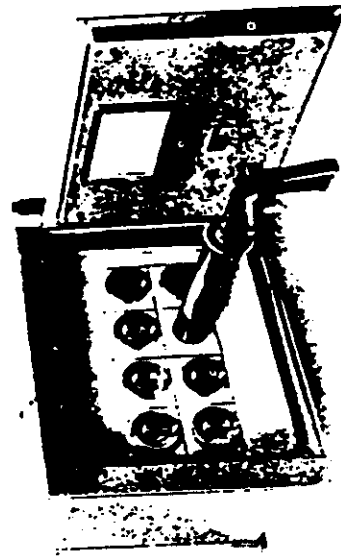


Figure 8.12 Lead protected safe for the storage of brachytherapy sources. One of the eight source drawers is shown with the lead protection in front of the cavity in which the sources are placed. (Courtesy: Buchler.)

Table 8.3 Recommendations on storage facilities for brachytherapy sources (NCRP 1978a).

Storage Room

- (i) The protective locked storage safe should be installed in a room provided with means to prevent unauthorised access to the sources in storage.
- (ii) The storage room facility shall be under the administrative control of a responsible user.
- (iii) A storage area for radium should be ventilated, preferably by direct exhaust to the outdoors, because of the possibility of radon leaks.
- (iv) Storage rooms, particularly for brachytherapy sources, should include a sink for cleaning. The sink should be provided with a filter or trap suitable for preventing loss of sources. The trap should be easy to dismantle, and should be easily accessible for routine monitoring.
- (v) A radiation survey meter should be available for this storage room. It should be capable of measuring radiation in the range 2 mR h^{-1} to 1 R h^{-1} . A beta-gamma radiation monitor sensitive enough to detect $10^{-4} \mu\text{Ci}$ should be available.

Storage Safe

- (i) Important factors to be considered for personnel protection are:
Distribution of the sources
Shielding of subdivided amounts
Time required by personnel to remove sources from, and return sources to the enclosure
Amount of radiation that is scattered around the protective barriers
- (ii) Separate compartments in the safe should be provided for different source activities. Each compartment should be marked so as to permit immediate and easy identification of its contents.
- (iii) The protection provided by the individual compartments and the safe as a whole should be such that a person standing in front of the safe in performance of his duties receives in that time only a small fraction of the maximum permissible dose.

protection are still necessary. To assist in planning brachytherapy source shielding, NCRP (1978a) list half-value and tenth-value thicknesses in lead (table 8.4) and concrete for relevant radioactive isotopes (see also table 5.3). It is clearly seen that the current radioactive isotopes of choice in brachytherapy, caesium-137, iridium-182 and gold-198 require less protection in terms of lead shielding than the higher gamma energy emitting isotopes, radium and cobalt-60.

Handling equipment is essential in a sealed source room since sources should never be touched by hand and there should always be as much distance as practical between the sources and the operator. This is in addition to lead shielding on the bench, such as L-shaped lead shields in figure 8.13. These protect the operator's chest with the vertical shield and the gonads and lower abdominal organs with the horizontal shield.

Table 8.4 Half-value and tenth-value thicknesses in lead for selected radioactive isotopes (NCRP 1978a)†.

Radioactive isotope	HVT (cm)	TVT (cm)
Radium-226‡	1.4	4.6
Cobalt-60	1.2	4.0
Caesium-137	0.65	2.1
Tantalum-182	1.2	4.0
Iridium-192	0.3	2.0
Gold-198	0.33	1.1

†NCRP state that the HVT and TVT are approximate values obtained with large attenuation.

‡Radium gamma rays filtered by 0.5 mm platinum.

An L-shaped lead shield can also be incorporated into a trolley for use as a mobile handling bench in an operating theatre during interstitial or intracavitary therapy. Here the sources have to be safely stored immediately prior to insertion/implantation by the radiotherapist/surgeon. The L-shaped shields can be topped with a lead glass viewing window to reduce the radiation exposure to the face (figure 8.13). NCRP (1978a) state that the usual barrier in an L-shield for use with brachytherapy sources in the storage room has a minimum lead equivalence of 5 cm. It also states that the maximum allowable working times will normally be determined by the exposure rate to the hands rather than exposure rates to the parts of the body shielded by the L block.

For the actual handling procedure where a series of individual needles or

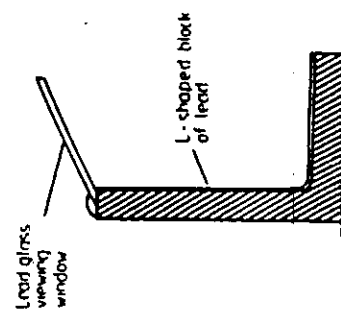


Figure 8.13 Lateral view of an L-shaped lead shield and the lead glass shield.

tubes are required for a specific patient treatment, the procedures to be followed are outlined in figure 8.14. A *lead block holder* is necessary since it would be hazardous to try and thread a source without any surrounding lead protection and the needle requires fixing in a constant position to enable the threading procedure to be accomplished quickly. An example of a lead block holder is shown in figure 8.15. This particular design has a handle fitted so

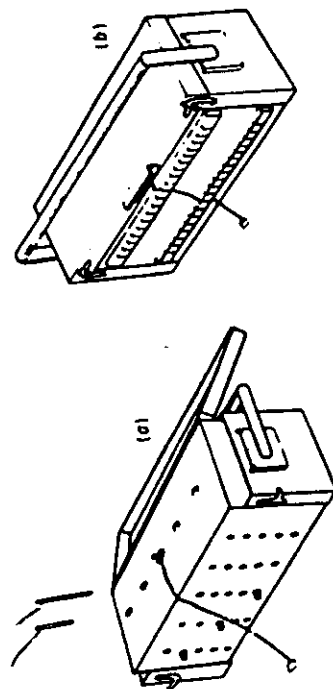


Figure 8.15 A lead block holder for radium (or caesium-137) needles. (a) shows two needles of different lengths about to be placed into cylindrical openings on the top of the block. On the front block face, channels are drilled perpendicular to the vertical direction of the cylindrical slots and studs placed in the appropriate channels (three are shown with the shortest needle and thus the highest studs on the far left) such that the inactive eyelet of the needle protrudes just above the top of the lead block. (b) shows the lead block with its lid closed and a facing plate in position on the front of the block to hold the studs in place and to fix the strings attached to the needles (only one shown).

that it can also act as a *transport container* and an extra procedure (4 in figure 8.14) is eliminated with a consequent reduction in radiation exposure. A good design of forceps is essential, and NCRP (1978a) recommend that they should have the following general characteristics:

- (i) Be as long as practical.
- (ii) Grip the source firmly with a minimum of force exerted by the fingers.
- (iii) Forceps used to lift easily damaged sources should have a spring-tip adjusted to prevent excessive pressure.
- (iv) Self-retaining forceps are desirable for some delicate manipulations.
- (v) Be light in weight.
- (vi) The jaw should be notched, grooved or otherwise formed to fit the sources to the handle.

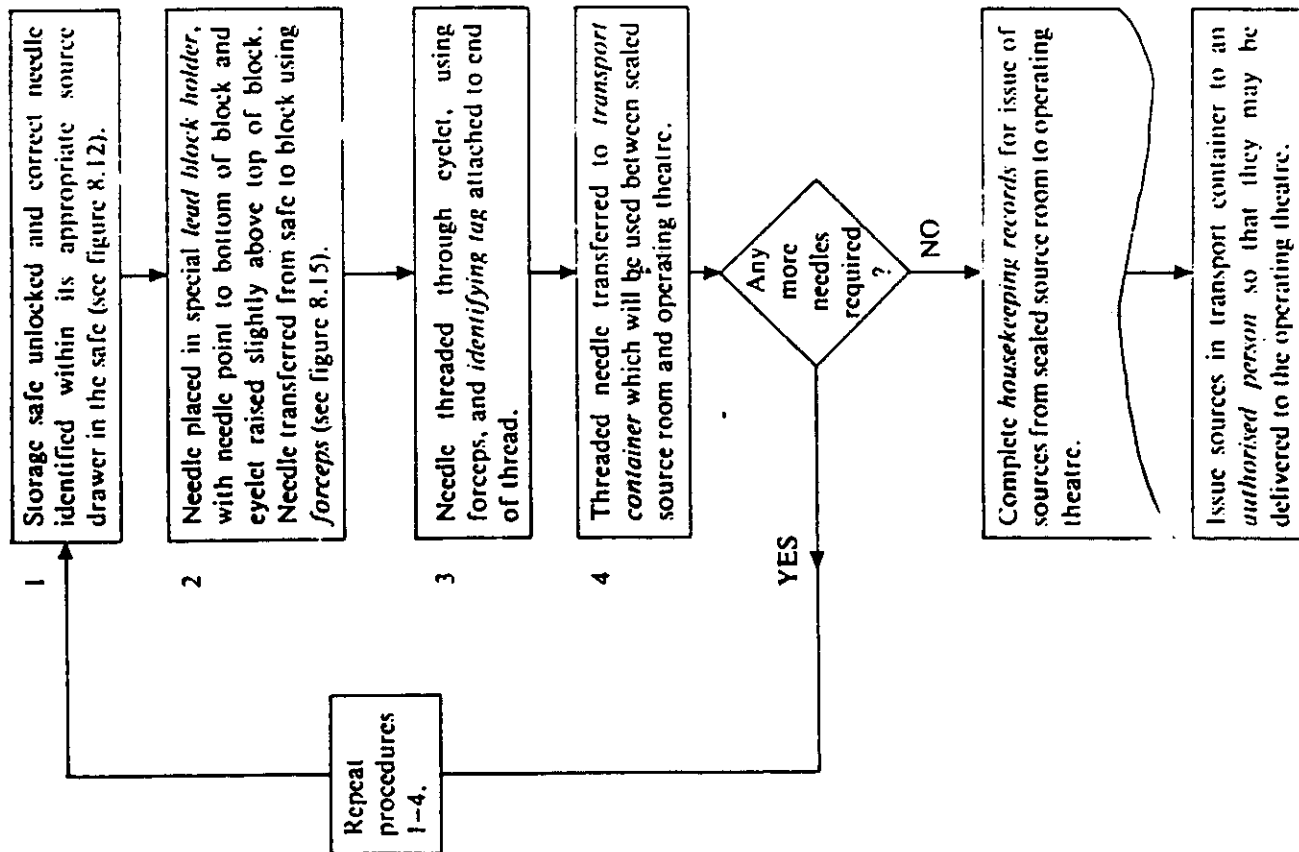


Figure 8.14 Procedure for handling radium or caesium-137 needles for issue to the operating theatre for interstitial implantation.

8.6 NURSING CARE

A patient receiving treatment by external beam therapy is not radioactive and does not present a radiation hazard to the nursing staff. However, a patient receiving brachytherapy treatment is a radiation hazard, but only for as long as the treatment duration. General considerations for nursing care have been stated by NCRP (1978a) (table 8.5), and NRPB (1983). They recommend that, where practicable, treatment should be carried out in wards having only one or two beds, care being taken to ensure that adjoining rooms are adequately protected. However, if the patient beds are in a general ward, they should be positioned:

- (i) In accordance with arrangements for area designation and the terms of any scheme of work.
- (ii) Taking into consideration the consequential radiation doses, both individual and collective, to other patients, particularly those not under treatment.
- (iii) So that the distance between bed centres is at least 2.5 m.

Table 8.5 Nursing care recommendations (NCRP 1978a).

- (i) The length of time for nurses to spend in attendance upon patients should be limited by the exposure they may receive.
- (ii) To minimise exposure to hospital personnel, one approach might be that such patients should not be concentrated in one area, but be dispersed. In some institutions, it may be preferable to place these patients in special rooms or wards, under care of specially trained personnel who shall be classified as radiation workers.
- (iii) A special duty nurse, not classified as a radiation worker, should not be assigned to care for more than one radioactive patient per month without the approval of the radiation protection supervisor.
- (iv) The problem to be considered is the amount of time the attendant is to be allowed to spend in various activities connected with patient care, which depends on the radiation exposure rates at various positions.
- (v) Patients who are disoriented and are not fully aware of the nature of their treatment should be restrained in order to prevent loss or misposition of a source.

Local rules should always be issued to nursing staff and the rule section headed 'Precautions' used in the Royal Marsden Hospital in 1968 is given in table 8.6 as a typical example. Other information also available in the rules included the advice that the collection of urine, faeces and sputum is not required and the dose rate at two feet (61 cm) from a 100 mCi source was

220 mrad h ⁻¹	for radium
350 mrad h ⁻¹	for cobalt-60
90 mrad h ⁻¹	for caesium-137.

Table 8.6 Nursing care instructions on the precautions to be taken with patients receiving therapeutic doses (10–300 mCi) of radium, cobalt-60 or caesium-137. (After Royal Marsden Hospital, London, 1968.)

- (i) The patient is to be restricted to bed and must not be allowed to roam therefrom during the period while the insert, implant or applicator is in position.
- (ii) The time occupied by nursing procedures must be reduced to a minimum while the radioactive sources are in position, and no unnecessary time must be spent in close proximity to the patient.
- (iii) All bed linen, dressings and other waste material from such patients must be monitored before it is allowed to leave the ward.
- (iv) In the event of any radioactive source becoming loose or detached, the medical staff must be advised at once. The nurse must not attempt to replace such sources.
- (v) Instruments and containers which have been used to manipulate or house radium, cobalt or caesium sources do not become radioactive. Special instruments are used merely to simplify handling and to keep the sources at a distance away from the fingers and the rest of the body.
- (vi) Visitors should not remain in the vicinity of the patient for a time longer than that indicated by the bed warning notice. Children and pregnant women should not be allowed to visit the patient while the warning notice is operative.
- (vii) After the radioactive sources have been withdrawn or otherwise removed at the end of the treatment time, the patient ceases to be radioactive, there is no residual activity. The bed warning notice must be removed and nursing may then proceed without restriction, and visitors be permitted in accordance with hospital rules.

In addition, the Royal Marsden also used bed warning notices as a guide to nursing staff, indicating the permissible times which could be spent in close proximity to the patient whilst the warning notice was displayed. The times were such that a nurse remaining at a distance of two feet from the patient for the time indicated each day, would after five consecutive days have received her maximum permissible dose (usually set by the hospital radiation protection adviser as a percentage of the dose limit in the Code of Practice, thus preserving an additional margin of safety) for the working week. For radium, cobalt-60 and caesium-137 these nursing times remained constant whilst the sources were in position because the treatment duration was negligible compared with the radioactive isotope half-life (table 8.7).

Similar instructions for nursing time allocations were available for other radioactive isotopes used therapeutically, iodine-131 and gold-198. However, with the much shorter half-lives of these two isotopes, 2.7 and 8 days respectively, the nursing times increased as the days went by following the implant/insertion of the source. For gold-198 grains permanently implanted the instructions for nursing times were as in table 8.8.

Table 8.7 Recommended permissible nursing times for radium (after Royal Marsden Hospital 1968).

Activity administered (mg)	Nursing times for radium (min)
5-10	60
10-20	30
20-40	15
40-60	10
60-100	5

Table 8.8 Recommended permissible nursing times for different administered activities of gold-198. These times are also used for treatment with gold-198 colloid for ascites. RN denotes remove notice (after Royal Marsden Hospital 1968).

Day	Nursing times for administered activity (min)				
	20-40 mCi	40-60 mCi	60-80 mCi	80-120 mCi	150 mCi
1	60	30	30	15	10
2	RN	45	30	30	15
3	—	60	45	30	15
4	—	RN	60	45	30
5	—	—	RN	45	30
6	—	—	—	60	45
7	—	—	—	RN	60

will be determined in part by the current governmental recommendation on the maximum activities of radionuclides for patients permitted to leave hospital. In the UK, for example, the limits are specified in terms of travel by public and private transport (table 8.9). However, care must still be exercised when applying these rules, if for instance the patient when returning home will be in close contact with young children or a pregnant mother. It would then be acceptable to keep the patient in hospital for a further period until the gold-198 sources had further decayed. Hospital radiation protection advisers can suggest appropriate levels depending upon the individual situation. However, most cases are fairly straightforward.

Table 8.9 UK transport activity limits (after DHSS 1972).

Radionuclide	UK transport activity limits (mCi)	
	Public transport limit	Private transport limit
Iodine-131	15	30
Gold-198	30	60

A series of general instructions should also be available on the wards within the set of local rules and should state the responsibilities of the Ward Sister as Ward Radiation Safety Officer. These will include: ensuring that all ward staff are wearing a personal film badge (or TLD dosimeter) when appropriate; responsibility for any storage safe on the ward premises; having a knowledge of the responsibilities of the house surgeons and registrars regarding removal and cleaning of radioactive sources after treatment ends; and knowing the radiation protection instructions for domestic staff who clean the ward. In a similar manner, general instructions should also be available in theatres for the Theatre Sister who is Theatre Radiation Safety Officer. Theatre local rules, however, will contain additional specialist information about implantation and insertion techniques, for example those associated with the interstitial use of small gold-198 grains. These can present particular problems to those not aware of the pitfalls. For example, in a gold grain implant to a bladder tumour (figure 8.7):

- (i) A sucker is used during the operation to remove blood so that the radiotherapist/surgeon can see more clearly. It should be remembered that it is also possible to extract implanted gold grains during this procedure. A diagnostic radiograph should be taken to confirm that the sources are in position before closing the bladder (see figure 8.7(a)).
- (ii) The gold grain implantation gun is not particularly robust and the stilette could bend and jam with radioactive grains stuck in the barrel of the gun.
- (iii) If the grains fall onto the floor, usually constructed of grey, white and black marble chips, it is extremely difficult to see the small 2.5 mm grains, which are not gold but silver in colour. A radiation detector, for example a Geiger monitor (figure 4.8), is essential.

It is not unknown for radioactive gold grains to end up in the U-bends of sinks, in trouser turn-ups of surgeons, on the bottom of theatre overshoes and even in the barrel of a supposedly cleaned implantation gun being returned to the hospital from which it had been borrowed. These examples indicate that great care must be taken with implantation procedures and that local rules are essential for guidance.

8.7 PROTECTION OF THE PATIENT

Protection of the patient in interstitial therapy is essentially a matter of ensuring that the planned therapy is actually delivered. For example, at the implantation stage of a treatment such as in figure 8.5, this would include ensuring that the sources are adequately separated. Otherwise, an unwanted hot-spot could occur resulting in over-irradiation and possible necrosis. In

Gold-198 grains which are unused can, with their short half-life of 2.7 days, be allowed to decay to a negligible activity in a lead protected safe in the sealed source room or can be sealed in a lead container and placed in a radioactive waste store room if such a room is available. The radioactive waste store room is subject to just as strict controls as the sealed source room, with entry permitted only to authorised personnel (figure 8.16). It has the advantage that waste material does not have to be stored within the sealed sources room or for nuclear medicine waste, within the nuclear medicine dispensing laboratory.

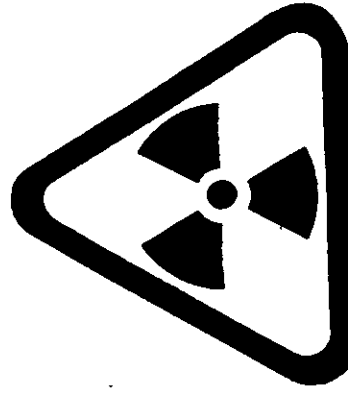


Figure 8.16 Example of a radiation warning notice. The symbols and lettering are in black on a yellow background.

Iridium-192 wire presents a somewhat different problem. The half-life, although very much shorter than for radium or caesium-137, is still too long (74 days) for the waste activity to quickly decay to a negligible amount. Disposal therefore has to be made in the UK using the National Disposal Service based at Harwell. Thus it is a positive advantage to have available a radioactive waste store room for the temporary storage of iridium-192. Another radiation protection factor to be aware of with iridium wire is that, unlike needle and tube sources, the wire often has to be cut to size, as for example in the technique of figure 8.11, and this can produce small pieces of radioactive wire during preparation for the implantation. These have to be located and stored for disposal. One of the advantages of using iridium-192 for interstitial therapy is that it is malleable and can be cut to requirements and, in addition, the commercial suppliers claim that the sources can be reused, but in practice the wires are usually bent so much out of shape in the first patient's treatment that they can seldom be used for a second patient. This can lead to a build up of iridium wire, and waste stores should be regularly monitored to ensure that radiation exposure levels are within acceptable limits.

such a situation the procedure would be either to remove one or two of the sources if this would produce an acceptable treatment dose distribution, or alternatively start again. At the source removal stage it is essential that no mistakes occur with regard to the treatment time and that the sources are not removed too early or too late. Also, care must be taken to ensure that no sources other than short half-life gold-198 grains are left implanted in the patient. If, for example, a series of ten iridium wires are implanted in a technique such as in figure 8.11, then obviously ten must be removed. If there is any doubt, a check radiograph must be taken to confirm the absence of any remaining source. However, this will not be necessary if a Geiger counter has been used to check the patient.

It is self-evident that the correct activity sources should be used. For caesium or radium needles there should be some sort of coding to distinguish, for example, between 1 mg, 2 mg and 3 mg sources. This can be achieved by using some sort of colour tag coding on the strings attached to the source eyelets. However, for small sources such as gold grains or iridium hairpins, a tag label system is impossible. Nevertheless the activity can be checked by using an ionisation chamber system (figure 4.3) and measuring the activity of a magazine of gold grains or an individual iridium hairpin wire.

As well as colour tagging, there should also be a written label describing the type of source, the activity and quoting the name of the patient for whom it is intended. This will help avoid accidents of one patient receiving another's sources. In interstitial therapy this is most unlikely, but the policy of clearly labelling radioactive sources is excellent practice, not only for interstitial therapy but also for intracavitary therapy and nuclear medicine. In the latter, when syringe sources of the short half-life (6 h) radioactive isotope technetium-99m are used, the room for error is greater because of the much higher patient workload in any one day.

8.8 RADIOACTIVE WASTE DISPOSAL IN BRACHYTHERAPY

Legal requirements for radioactive waste disposal vary among different countries and in the USA also vary among the individual states. Most of the radioactive waste disposal problems relate to liquid nuclides, such as those used for cancer treatment of the thyroid and for nuclear medicine. These are discussed further in chapter 11.

Caesium-137 needles and tubes are considered to have approximately a 10 year mechanical life, as distinct from the 30 year radioactive half-life. They, and cobalt-60 and radium sources, are returned to the supplier, usually the national atomic energy authority (in the UK, this is at Harwell) for disposal and replacement sources are then ordered (not radium). Disposal procedures for such sources are therefore not a regular event.

CHAPTER 9

PROTECTION IN INTRACAVITARY RADIOTHERAPY

9.1 INTRODUCTION

Intracavitary treatment is the brachytherapy technique in which radioactive sources are introduced into a natural body cavity. This has in the past included intracavitary treatment of cancers of the antrum, nasopharynx, rectum, bladder and oesophagus. Nowadays when these cancers are treated using radiotherapy, the technique is usually external beam therapy. In the 1980s the only cancers which are routinely treated by intracavitary techniques are cancers of the cervix, uterus and vagina. The overall radiotherapy often includes both intracavitary and external beam irradiation.[†] The latter is required either to reduce the size of bulky primary lesions before intracavitary sources can be inserted or to irradiate the areas of secondary spread of cancer in the lymphatic nodes adjacent to the pelvic wall. The intracavitary radiation treatment is too localised in terms of radiation dose to provide an adequate treatment for these nodes.

For the treatment of cancer of the cervix the radiation sources can be placed in close contact with the cancer. Thus with cervical smear tests for early diagnosis and intracavitary therapy for treatment, cancer of the cervix is one malignancy which has a good prognosis if treated at an early stage, much better than, say, cancers of the lung, stomach or oesophagus.

9.2 RADIATION SOURCES

The treatment of cancer of the cervix or cancer of the body of the uterus by brachytherapy involves the positioning of radioactive sources, usually caesium-137 or cobalt-60 (previously radium) in the uterine cavity and the vagina. For cancer of the body of the uterus, less often treated by

[†]The whole treatment may include surgery too.

brachytherapy[†] than cervical cancer, most techniques involve many small sources closely packed together within the uterus, and additional sources packed in the vagina against the cervix. For cancer of the cervix, the uterine source is a linear source and this is generally used in conjunction with two vaginal sources, although techniques exist in which treatment is delivered using one or three vaginal sources. Needle sources are not used since they will not be directly implanted into the tumour, as in interstitial therapy. Tubes, pellets and capsules are the necessary sources depending upon the particular technique. There are many different brachytherapy techniques with varying designs for vaginal and uterine source holders, known as *colpostats* or *applicators*. There are also different treatment time schedules which are classified as low or high dose rate techniques. However, all were developed from essentially three systems used for many years prior to the afterloading era (see §§9.3 and 9.4).

All three techniques used radium and the first two were described in 1929:

Paris system (figure 9.1)

Continuous treatment for 120 h

Uterine tube of 33.3 mg radium

Two vaginal applicators, 13.3 mg radium each

Vaginal applicators were cylindrical corks joined by a metal spring.

Stockholm system

Three treatment fractions each of 22 h, separated by 1–2 week intervals

Uterine tube of 50 mg radium

Two vaginal boxes containing a total of 60–80 mg radium

Vaginal applicators were silver boxes with grooves for individual linear radium sources.

The scheduled total radiation dose to the cervical cancer was similar in both systems, but the Stockholm method used a higher dose rate. The third technique, and the one which was to prove the most popular worldwide, was the Manchester method (figure 9.2). This was based on the Paris technique and first described in the 1930s:

Manchester system

Two treatment fractions of duration approximately 72 h delivered over a period of 10 days.

Three uterine sources were available and the choice depended upon the length of the uterine cavity. Source activities were 15 + 10 + 10 mg radium, 15 + 10 mg radium and 20 mg radium, for uterine lengths of 6 cm, 4 cm and 2 cm respectively.

Vaginal applicators were hard rubber ellipsoids with a cavity for the radioactive source, and three different sizes were available depending

[†]External beam radiotherapy and surgery are more common treatment techniques.



Figure 9.1 Cylindrical cork vaginal applicators of the Paris system. A third single cork is shown between the two applied to the metal spring. The radium sources were kept in place within the corks by the cork plug. (This photograph is not intended to imply that the radium loaded applicators should be handled in this fashion, *close to the fingers*. The metal spring made this a poor design in practice for radiation protection for the physician-handler.)

upon the width of the vagina. A washer or spacer was available to separate two ovoids—as the vaginal applicators were called. The source activities for the large, medium and small ovoids were 22.5 mg, 20 mg and 17.5 mg of radium respectively.

Many hospitals followed the Manchester system, modifying their techniques to a greater or lesser extent as was felt necessary. One such

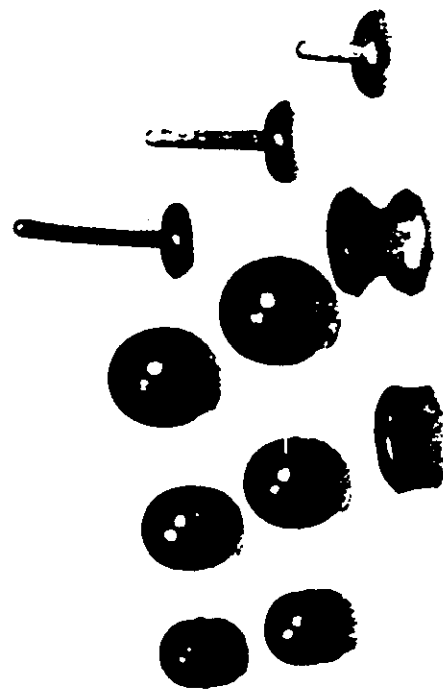


Figure 9.2 Manchester system applicators: three pairs of ovoids (small, medium, large), uterine tubes (long, medium, short) and a washer (bottom left) and spacer (bottom centre).

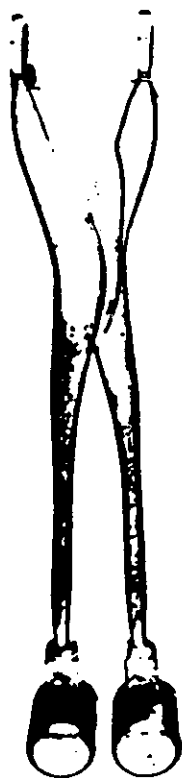


Figure 9.3 An early Fletcher system vaginal applicator set. This is a conventional non-afterloading version. For the later afterloading version, see figure 9.8.

modification was developed by G H Fletcher at the MD Anderson Hospital, Houston, USA (figure 9.3). Here the Manchester rubber ovoids were replaced by a metal applicator into which the radioactive sources could be introduced in the modified ovoids. The ovoids were kept in place by a locking screw (not shown, but would be beneath the crossover point of the applicator handles). Figure 9.4 shows an anterior-posterior radiograph of a



Figure 9.4 Anterior-posterior radiograph of conventional Fletcher-type of intracavitary therapy using the vaginal applicators illustrated in figure 9.3.

Fletcher brachytherapy technique using the applicator in figure 9.3. The uterine source is also clearly shown. The tube sources were encased in plastic and a metal plug sealed the bottom of the tube. A string was attached to the plug with an identification tag and gauze packing held the uterine tube in position.

Techniques such as the Manchester, Fletcher and Stockholm ones are conventional techniques in the sense that the vaginal and uterine sources have to be pre-loaded in the sealed source room and then transported to the operating theatre for insertion into the patient. Radiation exposure is therefore received by staff during pre-loading in the sealed source room and by the theatre staff, including the radiotherapist or surgeon, as the radioactivity loaded sources are introduced into the patient. With a technique which to a large extent depends on gauze packing for correct positioning, radiation exposure to the hands and fingers of the radiotherapist or surgeon cannot be avoided. There are none of the radiation protection advantages of the afterloading principle as described for interstitial therapy in §8.3. Because of this, conventional techniques in intracavitary brachytherapy are now being abandoned in favour of afterloading whenever possible. Although some of the afterloading sources are still in the tube form (e.g. caesium-137 tubes), many afterloading techniques use *source trains* consisting of a series of small cylindrical sources (figure 9.5) and spacers. As an example, a medium length uterine tube available for the Amersham caesium-137 manual afterloading system is shown in figure 9.6. Several source trains can be purchased corresponding to short, medium and long uterine 'tubes' and small, medium and large vaginal 'ovoids'. These are then 'used in conjunction with plastic uterine and vaginal afterloading applicators (figure 9.6(b)). An alternative approach to ready made-up source trains is a microprocessor controlled after-loading unit in

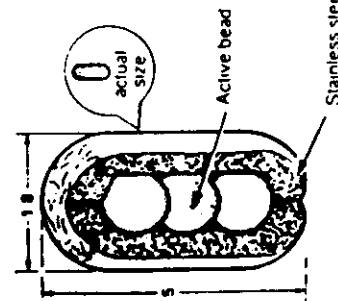


Figure 9.5 Miniature caesium-137 cylindrical source for use in the make-up of source trains for afterloading techniques. As depicted, the actual diameter is 1.8 mm and the length is 5 mm. (Courtesy: Amersham International plc.)

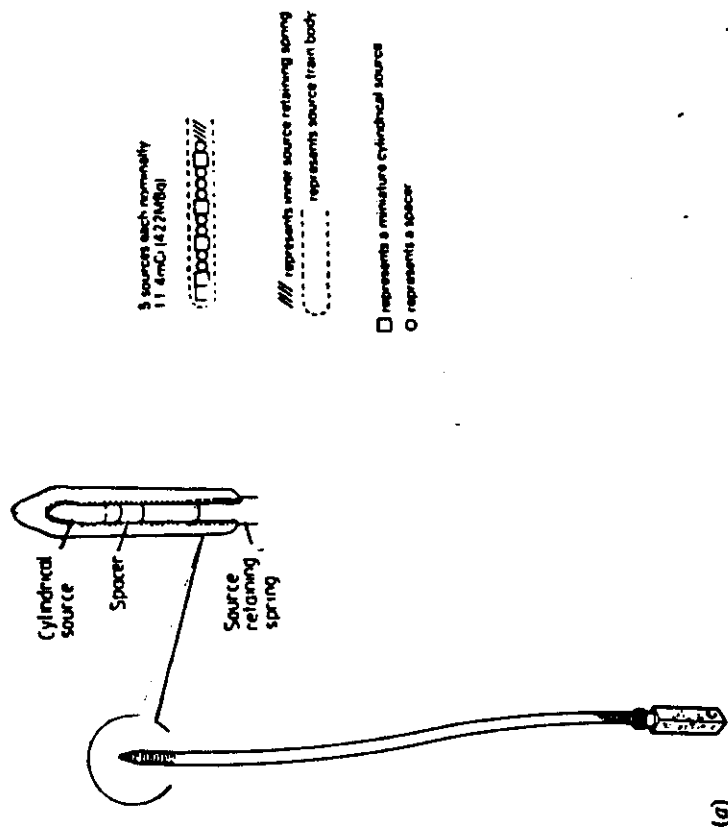
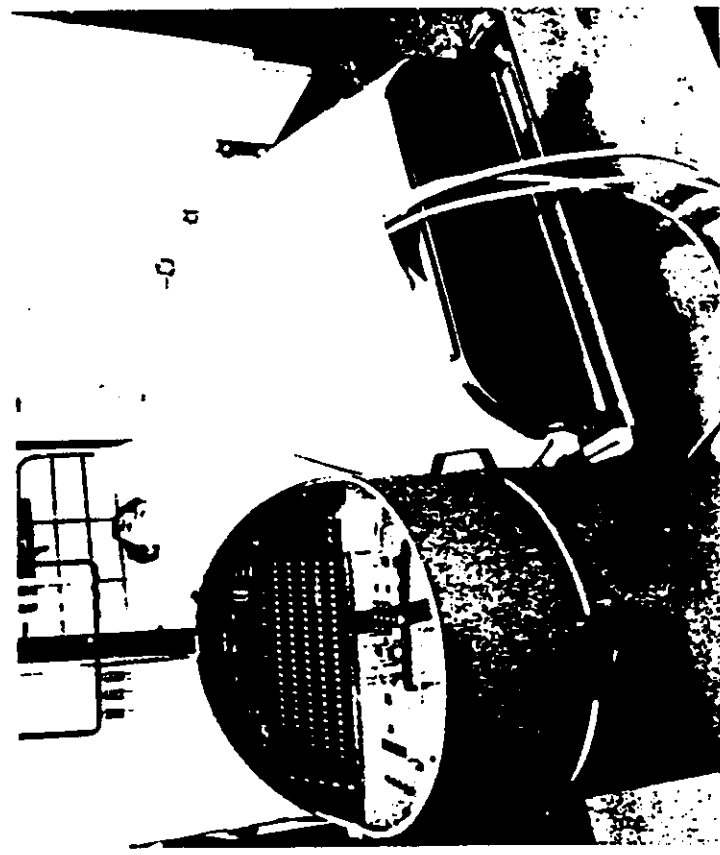


Figure 9.6 (a) Example of a caesium-137 source train for afterloading, using small cylindrical sources and spacers, and having an active length of 35 mm. (b) Amersham system plastic applicators with source trains in position in uterine tube and both vaginal ovoids. (Courtesy: Amersham International plc.)

which the choice of source train configuration is made immediately prior to treatment and the pattern of active sources and inactive spacers is then produced (figure 9.7).

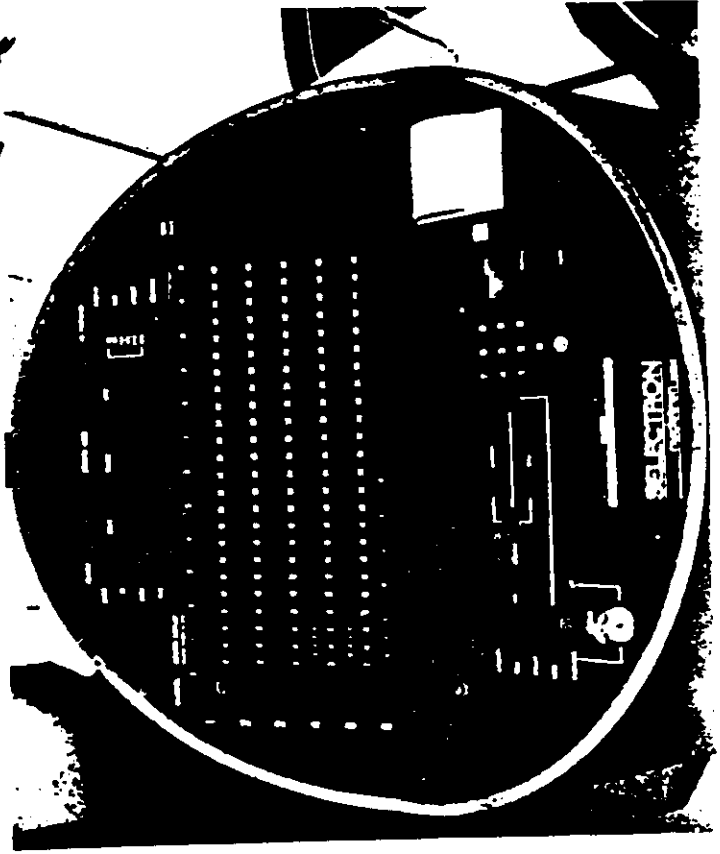
Radioactive isotopes currently used for intracavitary brachytherapy are caesium-137, cobalt-60 and iridium-192. Caesium-137 is used for low dose



(a)

Figure 9.7 Microprocessor controlled afterloading machine, the Selection 1108, which uses caesium-137 sources. (a) The Selection 1108 showing three source channels positioned within the patient for treatment delivery. The caesium-137 pellet sources are in a safe within the body of the machine. (b) An expanded view of the face of the Selection 1108 showing details for the six channels and the number of active and dummy (i.e. spacer) pellets and the total number and (bottom right) the hardcopy output from the printer, which gives a permanent record of treatment to be placed in the patient's hospital case notes. (1108 = low dose rate.) (Courtesy: Nucletron Trading Ltd.)

rate treatments such as Amersham manual afterloading and remote afterloading by the French Curietron and the Dutch 1108 Selection (see Mould 1985b). For the high dose rate German Buchler remote afterloading a mixture of caesium-137 (for two stationary ovoid sources) and iridium-192 (for an oscillating uterine source) is used. For high dose rate treatments such as with the Dutch 1108 Selection, the British Cathetron or Japanese Ralstron, cobalt-60 is used. The three radioactive isotopes mentioned have different advantages and disadvantages and hospitals vary according to their choice of optimum equipment, often itself largely determined by financial considerations, although also dependent on the decision to purchase either low dose rate or high dose rate machines.



(b)

Cobalt-60: half-life = 5.2 years, gamma energies = 1.17 and 1.33 MeV. High gamma ray energy and therefore protection is expensive. Unsuitable for conventional or manual afterloading techniques but suitable for remote afterloading. Shorter half-life than caesium-137 means that replacement of sources is more frequent than with caesium.

Caesium-137: half-life = 30 years, gamma energy = 0.664 MeV. Less protection required than with cobalt-60 (or radium). Life span of sources is approximately 10 years. Radioactive isotope of choice for most manual afterloading techniques.

Iridium-192: half-life = 74 days, gamma energies 0.1–1.06 MeV. High specific activity (i.e. radioactive density) attainable. Less protection required than with cobalt-60 (or radium). Short half-life of only 74 days means a requirement for regular replacement of sources and regular alterations in dosimetry calculations to take account of the relatively rapid decay of iridium.

For afterloading machines which contain a mixture of iridium and caesium sources the dosimetry is more complicated and computer programs should be available for the necessary calculations.

Low dose rate intracavitary therapy essentially duplicates the earlier conventional technique dose rate schedules. However, in high dose rate intracavitary therapy using a machine such as the Cathetron, the treatment time is some 20–25 min overall and the radioactive sources are only *in situ* within vagina and uterus for some 2–5 min. High dose rate machines are housed in specially protected rooms and provide a number of advantages over the lower dose rate methods:

- (i) avoidance of all radiation exposure to medical and nursing staff;
- (ii) patients prefer the treatment since it only takes a few minutes;
- (iii) treatment can be given on an out-patient basis because of its short duration;
- (iv) sources are fixed in rigid tubes for such a short period of time that greater accuracy of treatment is obtained; for a long period treatment sources may move, leading to higher doses to bladder or rectum and a greater probability of treatment complications.

However, high dose rate techniques also have disadvantages such as the large initial financial outlay necessary for machine and treatment room and the requirement for radioactive source replacements. Special radiation measuring instruments for monitoring doses are required as accurate radiation dosimetry is absolutely essential because of the much smaller room for error in high dose rate treatment times.

9.3 MANUAL AFTERLOADING TECHNIQUES

Conventional techniques modified from either Manchester or Stockholm methods (e.g. Fletcher in figure 9.3) were often later converted to manual afterloading systems. Figure 9.8 shows, as an example, equipment from a later Fletcher–Suit technique. Figure 9.8(a) illustrates the vaginal applicators which are hollow tubes of rectangular cross-section with a locating flange (the semi-circle of metal on the lower applicator half) and an adjustable fixing screw near the handles of the applicators. The vaginal source containers are solid steel rods of rectangular cross-section with a bucket cavity at one end to hold the tube source. The source containers are within the afterloading hollow tubes in figure 9.8(a) and they are shown separately in figure 9.8(b). Intracavitary techniques must be able to accommodate different uterine lengths and vaginal vault widths, and in the Manchester technique this is achieved using small, medium and large ovoids (see figure 9.2). Four different sizes of hard plastic caps are available for

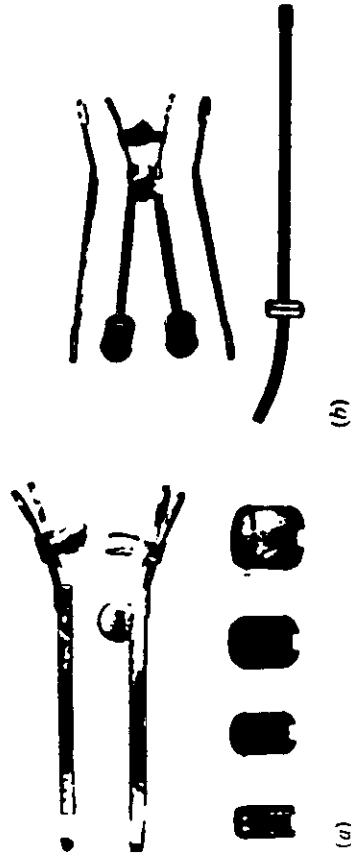


Figure 9.8 Fletcher–Suit method of manual afterloading: (a) vaginal applicators and plastic caps for different vault widths; (b) vaginal and uterine applicators.

Fletcher–Suit afterloading (figure 9.8(a)) which fit over the ends of the vaginal applicators as in figure 9.8(b). The uterine source afterloading applicator is shown at the bottom of figure 9.8(b). Figure 9.9 shows an anterior–posterior radiograph of this technique. It should be noted that this is only one example of many currently available rigid applicator designs.

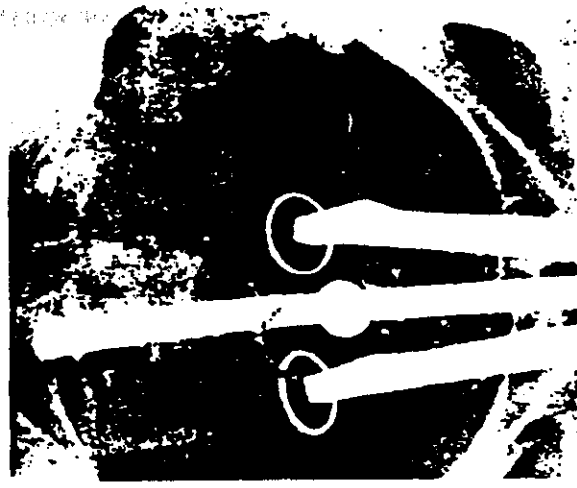


Figure 9.9 Anterior–posterior radiograph of manual afterloading Fletcher–Suit type of intracavitary therapy using vaginal and uterine applicators as in figure 9.8. The plastic caps on the vaginal applicators are not radio-opaque and hence are not seen on the radiograph. The two rings are inset into the tops of the caps (see figure 9.8) and act as radiograph magnification markers.

Disposable plastic applicators have been designed for manual afterloading techniques, as well as the stainless steel ones. In particular, Amersham International have devised their system (figure 9.6(h)) based on the Manchester method; this was originally designed for use in developing countries and currently (1983-6) is being assessed in an IAEA/WHO intracavitary brachytherapy project in Egypt (Mould and Hobday 1983, Mould 1985c).

9.4 REMOTE AFTERLOADING TECHNIQUES

In a manual afterloading technique, less radiation exposure is received by staff involved in the operation than in conventional non-afterloading techniques. However, some exposure is unavoidable while the source trains are introduced into the applicators. In remote afterloading techniques even this exposure is avoided since the programmed (microprocessor controlled or electro-mechanically operated) machine ensures that the source trains are loaded into the applicators whilst staff are standing behind protective barriers, usually the walls of a specially designed treatment room.

The machine must have a lead protected safe incorporated into the design, such as the Selectron in figure 9.7. Thus the room will need to house the protected safe, the source trains and applicators, the patient's treatment couch with attachment to hold applicators, the control panel, the rectal and bladder dosimeters plus adequate protective barriers between the sources and the operating staff.

9.5 TREATMENT ROOM

For manual afterloading machines the comments concerning treatment rooms and general wards are similar to those expressed in §8.5 when interstitial therapy was being considered, except that lead bedshields (see figure 5.7) should also be used. These are necessary since the administered radioactive sources have greater activities in intracavitary therapy than in interstitial therapy. It should also be remembered that a lead shielded carrying container must be available by the patient's bedside to contain the sources when they are removed. This should be larger than the one in figure 5.6, with wheels attached, and a longer handle for pulling the pot along the corridor or ward floor.

For remote afterloading machines a specially protected room is necessary and figure 9.10 shows a room housing a Curietron LDR machine. The source channels are in position within the patient and the operator and nurse standing *outside* the room use the wall control panel to activate the machine and the source trains in position. Two other single bed Curietron wards are

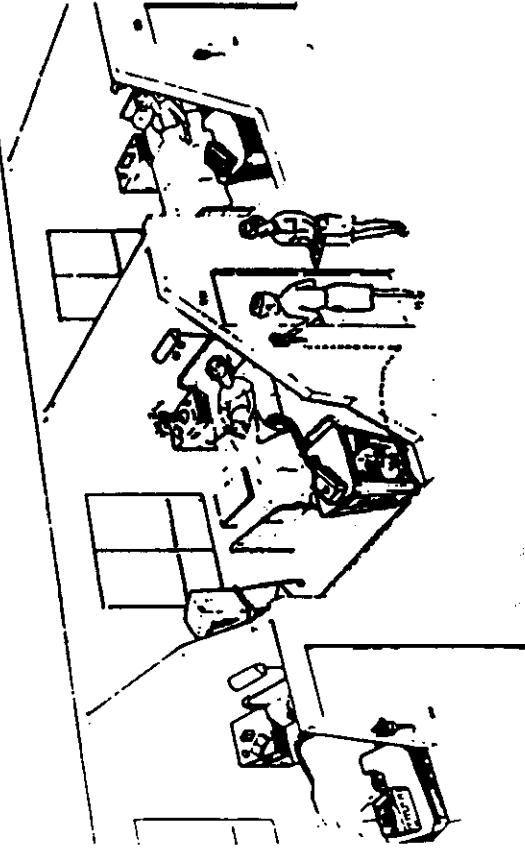


Figure 9.10 Treatment room for a low dose rate Curietron remote afterloading machine. One nurse is operating the control switch to return the sources temporarily to the safe within the Curietron before the second nurse takes in the patient's meal. Later, when all staff are outside the room, the sources will be returned to the vaginal and uterine applicators to enable the treatment to be completed. (Courtesy: CGR.)

shown adjacent. It is also possible to design a two-bedded ward for links to one remote afterloading machine such as a Selectron LDR unit with six channels. Three are connected to each patient and one outside wall control panel operates either unit. A protected barrier is built between the two beds. Figure 9.11 shows a cut-away view of an HDR Buchler unit in the treatment

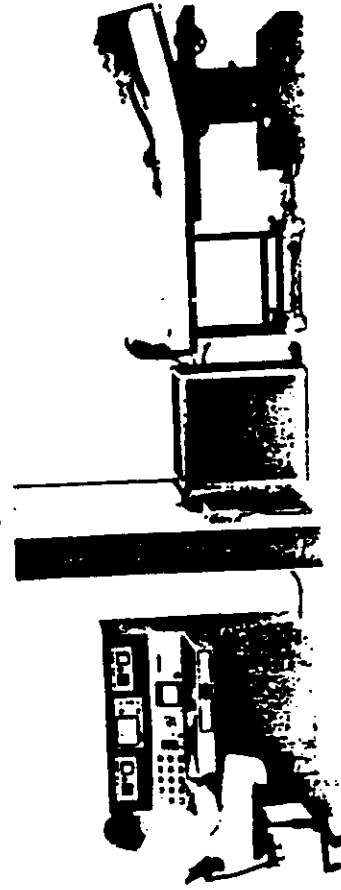


Figure 9.11 A Buchler high dose rate remote afterloading machine. (Courtesy: Buchler.)

position. One can see a protected safe at the patient's feet and the wall barrier which separates the control console and operator from the unit. A plan view of a typical remote afterloading treatment suite of rooms for a Cathetron is shown in figure 9.12. It will be noticed that there is a maze entrance, similar to those for megavoltage external beam therapy in figure 7.9. Typical maze entrance room areas recommended for the Cathetron by the manufacturer are $8 \times 4.3 \text{ m}^2$ ($26 \times 14 \text{ ft}^2$) and $7.3 \times 5.8 \text{ m}^2$ ($24 \times 19 \text{ ft}^2$) which compare with $9.5 \times 8.2 \text{ m}^2$ in figure 7.9. Consequently there are much greater financial implications when installing a high dose rate remote controlled afterloading machine such as the Cathetron, than when planning to use manual afterloading techniques.

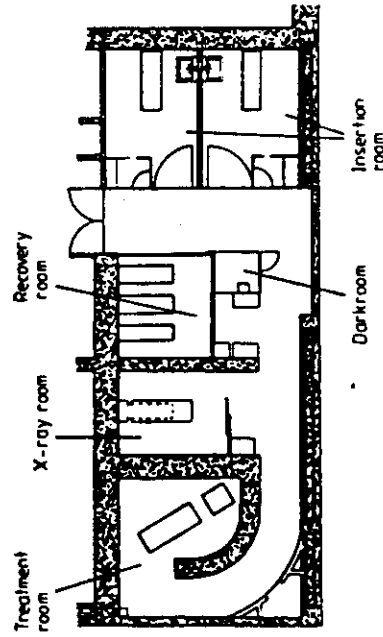


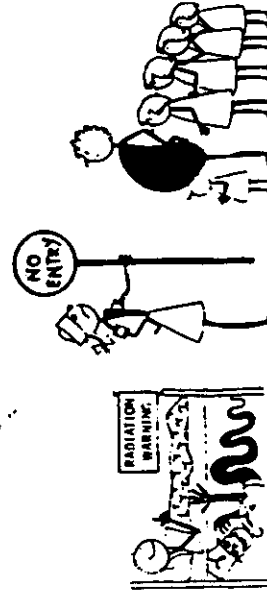
Figure 9.12 Cathetron area in the radiotherapy department of the Hospital de Oncología, Instituto Mexicano del Seguro Social. The treatment room has two television cameras and an intercom system so that the medical staff can observe and be in contact with the patients throughout the treatment. Localising films are taken in the x-ray room to determine the exact position of the applicators, and the darkroom contains an automatic film developer. Applicators and a rectal retractor are positioned in the insertion room. (After a diagram in the *British Journal of Radiology Spec. Rep.* No 17, on an international workshop held in London, 1978, *High Dose Rate Afterloading in the Treatment of Cancer of the Uterus*.)

9.6 NURSING CARE

For conventional intracavitary therapy or for manual afterloading techniques a protective lead barrier such as the bedshield shown in figure 5.7 is required during nursing procedures. Similar advice to that given for interstitial therapy in §8.6 is also relevant to intracavitary methods such as:

- (i) Display of radiation hazard notices.

- (ii) Limitation on the time any one nurse should spend with an individual patient.
- (iii) Provision of a lead storage container near the bed in the event of unexpected removal of radioactive sources.
- (iv) Monitoring dosimeters, film badge or TLD, should be worn by staff.
- (v) Radiation survey meter, such as a Geiger counter (figure 4.8) should be readily available.
- (vi) Provision of local rules including information on permitted visiting times for the general public, on cleaning the radiation sources following removal (only relevant for conventional techniques), on permitted times when domestic staff can clean the ward, on book-keeping procedures for radioactive sources.
- (vii) Instructions not to allow pregnant women or young children to visit a patient with radioactive sources *in situ*.
- (viii) Instructions never to handle the radioactive sources with fingers but always to use long handled forceps/tongs, if handling becomes necessary.
- (ix) Emergency telephone numbers of a Radiation Protection Advisor should it be suspected that a source has become damaged, or is lost.
- (x) Information on the siting of the nearest emergency lead storage safe in the hospital, for use out of normal working hours.
- (xi) Instructions to ensure that the patient does not go for a walk-about around the hospital, thus presenting a radiation hazard to other patients, staff and the general public. (This would be impossible with afterloading equipment *in situ* and highly unlikely with conventional treatment, but in interstitial therapy, with perhaps only a few implanted needles in the tongue or cheek, such an event is not too improbable if the decision is left to the patient. This must be avoided.)



Pregnant ladies and children should not be allowed to visit patients treated using radioactive sources.

Nursing procedures are no longer a problem for remote afterloading as staff should ensure the sources are back within the machine's lead safe before entering the room. This can be visualised for a low dose rate machine

in figure 9.10 where the controls outside the treatment room are being operated prior to taking a meal in to the patient. A short break in treatment, taken into account by the afterloading machine's timers for the overall scheduled treatment duration, is sometimes required with these low dose rate machines. However, the treatment duration is so short with high dose rate remote afterloading that the treatment need not be interrupted.

9.7 PROTECTION OF THE PATIENT

As with interstitial therapy, protection of the patient is essentially a matter of ensuring that the planned therapy is actually delivered. There is maximum automated control with remote afterloading, and therefore, assuming that the necessary expertise is available while planning the treatment, there is little that can go wrong in the treatment delivery phase. With manual afterloading the procedure of checking the position of the applicators prior to loading the source trains helps to ensure that the prescribed treatment is given. Yet it is always possible, although not probable, that sources can move within the uterus and vagina during treatment and significantly affect the dose distribution to the tumour and the dose received by the rectum, sigmoid and bladder (see figure 9.13)—the origin of possible treatment complications if too high a radiation dose is received. However, it is in conventional, non-afterloading methods that there is most room for error in the positioning of sources, although if this is realised immediately following the insertion, the sources can be removed and repacked correctly. In many

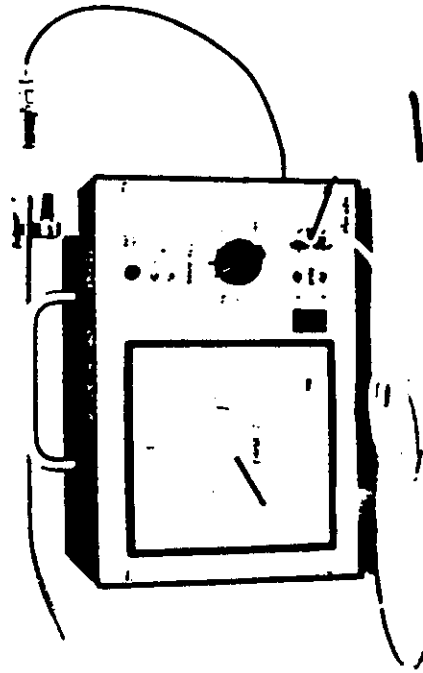


Figure 9.13 An example of a dual channel dose rate monitor (Therados DPM-2) for rectal and bladder dose measurements during intracavitary therapy. The probe is a semiconductor detector but other models exist in which the detector is an ionisation chamber. (Courtesy: Vinten)

hospitals rectal and sometimes bladder dose rate measurements are made during the intracavitary therapy. This enables the treatment duration to be curtailed if the rectal dose rises to a value which, in the judgement of the clinician, might lead to unwanted complications. Opinion as to rectal and bladder tolerance doses varies among hospitals and depends to a certain extent on whether the treatment is a low or high dose rate treatment.

Confirmation that the prescribed treatment has been delivered is obtained with some remote afterloading machines, such as the Selectron and the Buchler where a paper print-out of treatment details is produced by the machine on the treatment's completion. These hardcopy outputs will contain information such as date of treatment, patient identification, source activity in the applicators. Duration of treatment for each individual applicator will be noted since this can be different for the vaginal and uterine sources.

Radioactive iodine is also used in much smaller activities for diagnostic tests, not only as the isotope iodine-131 but also as iodine-123. Table 10.1 lists the half-lives, radiation energies and some of the uses of these isotopes and the remainder of this chapter deals only with the therapeutic administration of iodine-131 for thyroid cancer.

Table 10.1 Data for the radioactive isotopes of iodine.

Isotope	Half-life	Main gamma ray energy (MeV)	Examples of medical use†
Iodine-131	8.04 days	0.364	Treatment of thyroid cancer Treatment of hyperthyroidism Diagnosis of thyroid cancer Labelled protein (as iodinated human serum albumin (IHSA)) used to measure blood volume Kidney function studies (renogram) using sodium iodohippurate (hinipuran) Iodine uptake measurements
Iodine-125	60 days	0.027(x)	IHSA, see above Diagnosis of deep vein thrombosis using iodinated human fibrinogen
Iodine-123	13 hours	0.027(x), 0.160	Iodine uptake measurements

†For additional information on diagnostic uses see Chapter 11.

10.2 RADIATION SOURCES

Radioactive iodine-131 is usually administered for thyroid cancer therapy in its liquid form, generally as an oral administration, or, if this is likely to prove difficult, by intravenous injection. Radiopharmaceutical suppliers such as Amersham International also market therapy gelatin capsules. However, many people find difficulty in swallowing pills, although providing adequate precautions are taken oral administration of the dose is acceptable.

The iodine-131 will be delivered by the commercial supplier to the hospital, within a form of packaging to comply with national code of practice requirements, such as a lead pot sealed with adhesive tape placed within a sealed tin and then within a cardboard carton suitably labelled in accordance with transport regulations for radioactive sources (figure 10.1). The activities of iodine-131 sources will be quoted for a weekly reference

CHAPTER 10

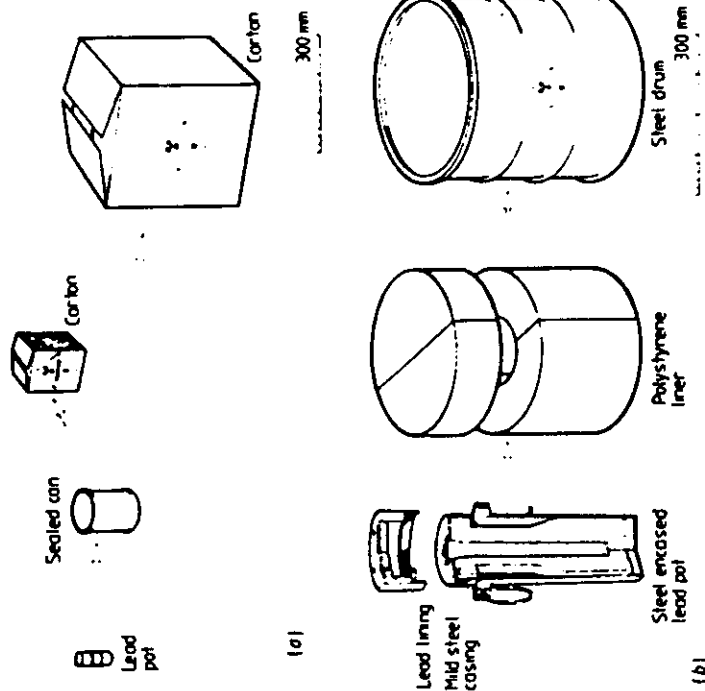
PROTECTION IN RADIOACTIVE IODINE-131 RADIOTHERAPY

10.1 INTRODUCTION

Radiation protection (therapy) rules, regulations, guidance notes and recommendations are usually subdivided into *sealed sources* (e.g. those used in interstitial and intracavitary therapy) and *unsealed sources*. The latter include iodine-131, gold-198 in colloidal form used mostly for the treatment of malignant effusions in the pleural or peritoneal cavities, and phosphorus-32 which has been used in the treatment of polycythaemia vera and certain types of leukaemia.

Radioactive iodine-131 in liquid form is used as an internal gamma ray emitter for the treatment of thyroid disease and is the only unsealed radioactive source used to any great extent for therapeutic purposes. The role of the thyroid gland is to synthesise, store and secrete the thyroid hormones thyroxine (T_4) and tri-iodothyronine (T_3), and this is controlled by the pituitary thyroid-stimulating hormone thyrotrophin. Iodine is an essential part of the thyroid hormones and since the gland contains about 90% of total body iodine any orally or intravenously administered radioactive iodine will in large part be deposited in the thyroid. Hence a sufficiently high concentration of radioactive iodine can deliver a prescribed radiation dose to the thyroid gland without over-irradiation of other tissues. However, malignant thyroid tissue will take up less iodine than normal thyroid tissue and therefore treatment of cancer of the thyroid often involves the use of both surgery and iodine therapy, with the latter playing a useful role in the treatment of residual local disease and metastatic disease. A therapeutic administration of iodine-131 might be 3.7–5.55 GBq (100–150 mCi) but much smaller activities, of the order of 74–370 MBq (2–10 mCi), are used for the treatment of the non-malignant condition of hyperthyroidism†.

†The condition of an overactive thyroid gland is called *hyperthyroidism* and of an underactive thyroid gland, *hypothyroidism*. An alternative term for hyperthyroidism is *thyrotoxicosis*.



(c)

Figure 10.1 Examples of packaging of radioactive isotopes: (a) for iodine-131 sources and isotopes used for diagnostic nuclear medicine procedures; (b) for sealed radioactive sources used in brachytherapy, such as the caesium-137 source trains described in chapter 9. Much greater protection is required for the latter during transport because of the higher activities and higher gamma ray energies. For the lead pot shown, the height may be between 59 mm and 84 mm and lead shielding in the range 3 mm to 38 mm dependent upon the contents. (C courtesy Amerham International.) (c) Radioactive warning label used in Italian hospitals.

date by the supplier and pack sizes such as 9.25 GBq (250 mCi), 7.4 GBq (200 mCi), 5.55 GBq (150 mCi) and 3.7 GBq (100 mCi) are available. The date at which a patient is scheduled to receive 5.55 GBq may not always be the reference date and therefore a larger activity than required has to be ordered, e.g. 7.4 GBq, and the requisite patient dose dispensed in the dispensing laboratory (see §11.3 where dispensing techniques for various isotopes, not only iodine-131, are described).

Radioactive half-lives were discussed in §1.11. This is a physical half-life which is not affected by biological functions. However, for iodine-131 there is also a *biological* half-life to be considered in addition to the physical half-life of eight days. This is because, unlike the sealed radioactive sources previously discussed, iodine is administered as an unsealed source and a proportion is accumulated into the thyroid whilst the remainder is excreted in the urine and also, to a much lesser extent, in sweat. In the normal person, over half the iodine is excreted in the urine the first 24 hours after administration and by 48 hours three quarters has been excreted (figure 10.2). Hence a calculation of remaining iodine-131 activity in a patient using only the eight day physical half-life would grossly over-estimate the residual activity. What is required is an *effective* half-life which takes into account both the physical (or radioactive) half-life and the biological half-life. For

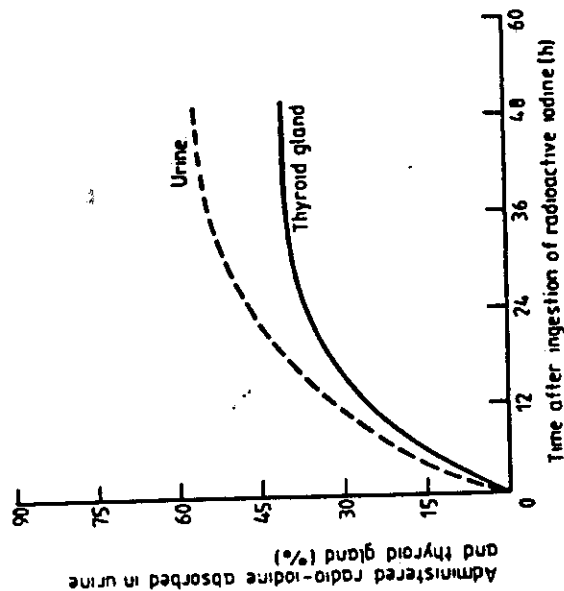


Figure 10.2 Representative normal values for the sequential changes in thyroid iodine uptake and cumulative excretion of radioactive iodine in urine, after an oral administration of iodine-131. (Data from Radiochemical Centre Medical Monograph 5 1967, *Diagnosis of Thyroid Disorders using Radioactive Iodine*.)

Iodine-131 this will depend upon several factors including whether the patient has received a previous therapy iodine dose, and upon the type of patient: normal, cancer patient, infant or adult, thyrotoxic or hypothyroid.

10.3 TREATMENT ROOM

Specially shielded treatment rooms are required in brachytherapy, however with iodine therapy there is the additional hazard of contamination from radioactive urine, particularly in the first two days following administration. Because of this hazard, the ideal arrangement within a hospital is to build a special suite of rooms for iodine therapy patients which can also be used for brachytherapy interstitial treatments. Figure 10.3 shows the bed arrangement in a nuclear medicine (therapy and diagnosis) ward in the Rudolf-Virchow Hospital, Berlin. In contrast to the usual symmetrical arrangement of hospital wards, this nuclear medicine ward is arranged from high to low activities, with the highest activities on the left of the ward and rooms for non-radioactive patients on the right. The patients rooms were constructed in three groups on this ward:

- (i) at least one highly shielded single bed room for activities up to 450 mCi of cobalt-60;
- (ii) two or three single bed rooms shielded for up to 150 mCi of cobalt-60 (the shielding being completely sufficient also for 250 mCi of gold-198);
- (iii) several double bed rooms shielded for up to 5 mCi of iodine-131 or gold-198 per bed.

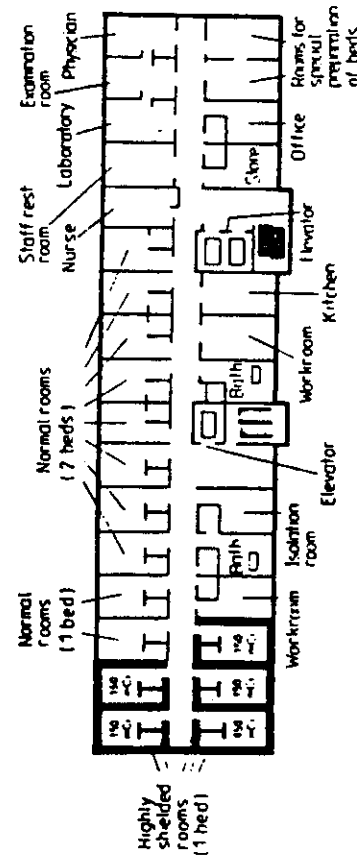


Figure 10.3 Example of a bed arrangement in a nuclear medicine ward. (From a WHO Manual, Frost and Jannet 1975).

It is, however, not always possible to construct purpose built nuclear medicine wards and the only practical course may be to convert one or two existing single bed rooms. Figure 10.4 illustrates various features which may

have to be incorporated in such a conversion of rooms in an old hospital building. For example:

- (i) It is most important to have a separate toilet for the patient which is not used by other patients or staff.
- (ii) Windows should not overlook occupied areas. Windows should have extractor fans fitted, more for convenience of the patient, to circulate the air, rather than for radiation protection requirements.
- (iii) Some rooms which are converted for iodine therapy will not have sufficient built-in protection. Protection can be added in the form of lead shields at the back of the bed, on the floor below the bed, or on the floor of the room above, directly above the treatment bed.
- (iv) A mobile lead bedshield (see figure 5.7) can be used between the bed and the door to reduce the radiation exposure in the corridor.

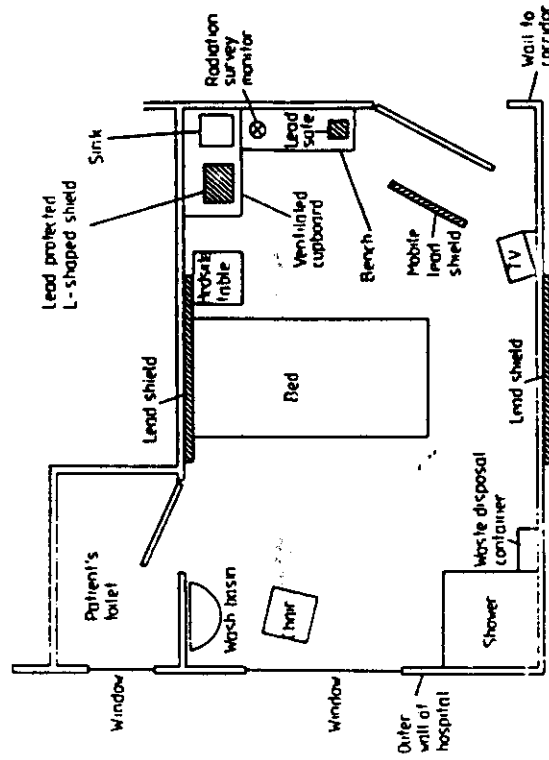
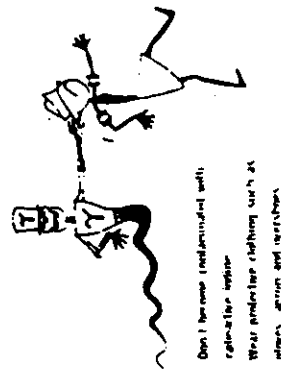


Figure 10.4 Iodine-131 therapy equipment room built by modifying an existing room previously used for non-radioactive patients at Westminster Hospital.

A problem sometimes encountered when an existing room is modified to become an iodine therapy room is that it may be some distance from the radioactive isotope dispensing laboratory (see §11.3). This can therefore involve a journey via several flights of stairs or a lift used by the general public. An alternative is to incorporate into the therapy room (figure 10.4) a ventilated cupboard in which there is an L-shaped dispensing shield and a

sink designated for radioactive waste disposal only, unlike the wash basin near the window, which is also for the use of the patient. Dispensing can then be undertaken in the actual therapy room with the source being safely transported in its lead pot (figure 10.1) and the remaining activity returned to the dispensing room storage facilities in the same lead pot. After checking with an activity meter (such as in figure 4.3) that the activity delivered is that stated by the commercial supplier, the dispensing and administration of the iodine to the patient can be as follows.

- (i) Dilute the volume of the iodine to about 50 ml so that, should the patient cough after drinking the iodine, the droplets will not be too concentrated.
- (ii) The iodine may be dispensed into a narrow-necked screw-capped bottle, surrounded by more than 1 cm lead shielding, taken to the treatment room in a long handled container.
- (iii) The patient is asked to sit at a table covered with polythene sheeting and the floor beneath the patient should also be covered by polythene sheeting.
- (iv) A plastic bag should be available for any items contaminated during the iodine administration. Paper tissues should be provided in case the patient needs to cough.
- (v) If the patient has dentures, these are removed and the iodine is then taken through a straw.
- (vi) Fresh water is then added to the bottle and the patient is also requested to drink this to ensure that all the iodine has been administered. This to some extent decontaminates the bottle and straw.
- (vii) The patient is requested to swill the mouth out with fresh water and to swallow before replacing dentures.



Polythene sheeting should remain beneath the bed during the treatment to avoid any possibility of contaminating the floor with spilt urine. The lead safe in figure 10.4 is required in case the iodine dose has to be stored in the room before administration, and also for storage of brachytherapy sources when the room is used for interstitial solid source therapy.

10.4 NURSING CARE IN IODINE THERAPY AND IN NUCLEAR MEDICINE DIAGNOSTICS

10.4.1 Iodine therapy

The two main hazards when nursing radioactive iodine-131 therapy patients are exposure from external radiation from the patient, and exposure from radioactive contamination. Of these, the external radiation hazard can be kept to a minimum by limiting nursing times for any individual nurse and by well designed protective features within the treatment room. The contamination problem therefore presents the major hazard. Extracts from recommendations from the United Kingdom NRPB and the United States NCRP are given in tables 10.2 and 10.3 and the data in these two tables cover most of the nursing problems which are encountered with iodine therapy patients.

Decontamination procedures are dealt with in chapter 11 since they are also relevant to nuclear medicine (diagnostic) studies. They are more likely to occur in a dispensing laboratory (see §11.3) where unsealed sources are continually being handled than in an iodine therapy room which is used on average for perhaps one cancer of the thyroid patient per month, since this is a relatively rare cancer in the UK. The incidence in England and Wales in 1978 was 183 males and 521 females compared with 27 174 registered cases of cancer of the lung in males and 21 196 registered cases of female breast cancer.

10.4.2 Nuclear Medicine Diagnostics

The large majority of patients undergoing nuclear medicine diagnostic tests do so as out-patients. When in-patients are involved, this is usually because they are also receiving other treatment, such as radiotherapy for breast cancer and the diagnostic study concerns possible bony metastases. Alternatively, the patients may be too ill to be out-patients. Nevertheless, the activities administered are very small and below the limits allowed (DHSS 1972) for patients to be discharged from hospital. In the United Kingdom for iodine, this is 30 mCi for travel by private transport and 15 mCi for public transport. Therefore these patients can essentially be regarded as non-radioactive patients unless otherwise stated by the hospital's Radiation Protection Adviser. Guidance given by NRPB (1983) is listed in table 10.4.

10.5 PROTECTION OF THE PATIENT IN IODINE THERAPY AND NUCLEAR MEDICINE DIAGNOSTICS

Protection of the patient both for therapy iodine administrations and nuclear medicine diagnostic tests are based on ensuring that the correct

◀ Table 10.2 Unsealed source therapy guidance notes (NRPB 1983).

Table 10.3 Unsealed source therapy recommendations (NCRP 1978b).

- (i) The length of time that nurses may spend caring for patients should be limited by the exposure they may receive.
- (ii) As soon as the radionuclide has been administered and the exposure rate determined, the responsible person (Radiation Protection Supervisor or Radiotherapist) shall attach the radioactivity labels and issue any special nursing instructions and limitations on visitors.
- (iii) Pregnant nurses should not be responsible for the routine care of patients with appreciable radioactive burdens.
- (iv) A special duty nurse should not be assigned to care for more than one radioactive patient per month unless an exception is approved by the Radiation Protection Supervisor.
- (v) The patient who has received a therapy administration of iodine-131 may contaminate his food dishes with salivary excretion. Hence he should have his own tableware, kept separate for a few days or use disposable articles.
- (vi) Whenever it is necessary to collect urine for assay, special containers should be provided and since the patient is usually ambulatory, he should be instructed to collect his own urine. If the nurse must perform this duty, then rubber gloves should be worn. The gloves should then be washed thoroughly while still on the hands. Then the gloves should be removed and the hands washed thoroughly.
- (vii) If the patient treated with radio-iodine vomits or is incontinent within the first 48 hours of administration, or if he perspires excessively, there may be contamination of the bed linen or even the floor. In any such emergency the Radiation Supervisor shall be summoned immediately to supervise the decontamination.

Table 10.4 Guidance notes relating to the use of unsealed sources for diagnostic studies, and in particular, those referring to the use of technetium-99m (NRPB 1983).

Precautions will normally be required for therapy; patients whereas for patients who have undergone diagnostic tests they will be necessary only after administration of comparatively large activities.

Source	Activity limit
Technetium-99m	200 MBq (5.4 mCi)
Iodine-125, 131	2 MBq (0.054 mCi)
Gallium-67	50 MBq (1.4 mCi)
Indium-111	20 MBq (0.54 mCi)

Any special precautions which have been instituted following administration of technetium-99m may be terminated after 24 hours. For other radionuclides the instruction sheets should state for how long the precautions should be maintained.

- (i) Where unsealed radioactive substances are administered to patients either in therapy or diagnosis, laboratories and areas may need to be provided for the following types of work:

Radiopharmacy and local storage

Excreta and specimen storage, and radioactive waste disposal, with measuring equipment and sluice

Radionuclide administration to patients

Clinical measurements

Sample measurements

Decontamination.

Patient waiting and changing areas and toilets may also be required. Where radioactive substances are used for *in vitro* diagnostic tests, a laboratory for labelling and sample preparation, rather than a radiopharmacy, will be needed unless all radionuclides are dispensed in kit form; some of the other areas will not be required.

- (ii) Patients undergoing treatment with therapeutic activities of unsealed radioactive substances should not be placed in general wards in which there are patients whose treatment does not involve such therapy.
- (iii) Patients undergoing treatment should either be provided with a toilet and bathroom in the same suite for their exclusive use or should share such facilities only with other patients undergoing similar treatment.
- (iv) A place should be provided for keeping protective clothing for staff.
- (v) It is essential that a section of the local rules on procedures in wards is prepared in consultation with the radiation protection adviser, the radiation safety committee and the chief nursing officer. These rules should be issued to all nursing staff and ward cleaners.
- (vi) If a high activity has been administered, it is essential to impress upon the staff that nursing procedures which are not urgent should be postponed as long as practicable to take full advantage of reduction of activity by decay and excretion. During the initial period there should only be minimum handling of contaminated bed linen, clothing, towels, crockery etc.
- (vii) Administration of radioactive substances should not be carried out in general wards.

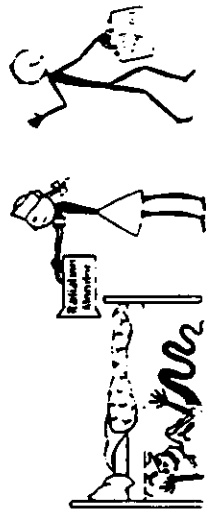
(viii) It is essential that beds in which there are patients undergoing treatment with unsealed radioactive substances have a notice which includes a radiation warning sign. The notice should give the nature and activity of the radioactive substance, the time and date of administration and any relevant nursing instructions.

(ix) It may be necessary to reallocate duties for staff who are known to be pregnant.

(x) It is essential that protective gowns and gloves are worn when handling the patient, the excreta, any contaminated clothing, bed linen or other articles.

(xi) The ward should be cleaned sufficiently often to ensure that contamination is kept as low as reasonably practical.

(xii) It is essential to determine the maximum dose rate at a distance of 1 m from each patient undergoing treatment. If this dose rate exceeds $50 \mu\text{Sv h}^{-1}$ (5 mrem h⁻¹), the local rules should specify the daily time allowable for nursing procedures and for visitors and, in the case of the latter, the closest distance of approach. When a time restriction is imposed it should be explained to any other patient in the ward that he is protected by the bed separation.



When the patient leaves after radiotherapy before therapy, make sure that the treatment room, including the bed linen, is monitored for radioactive contamination.

activity is administered to the patient, that the quality of the radiopharmaceutical is assured† and that no contaminating spills occur onto the patient's clothing during the oral or intravenous administration. Nuclear medicine diagnostic doses of technetium-99m and other isotopes are given by intravenous injection. It is therefore most important that patient isotope doses are correctly labelled—to ensure that the patients each receive the correct dose. For example, if an injection of technetium-99m sulphur colloid was prepared for a liver imaging study, and a technetium-99m pertechnetate solution for a brain imaging study, but the liver patient received the brain dose, the resulting gamma camera image of the patient's abdominal region would reveal the stomach and not the liver.

It is also important when scheduling a diagnostic test using a radioactive isotope, that the clinician is aware of any recent test of a similar nature with an isotope with a half-life long enough to interfere with the proposed study. Thus, residual iodine-131 might cause a problem, or residual selenium-75. The latter has a physical half-life of 121 days and is used for diagnostic imaging of the pancreas.

The aim should also be to limit the radiation exposure to the patient as far as this is possible. In one instance in the United States it was not discovered that the patient was suffering from a variant of Baron Munchausen's syndrome until they had received six or seven lung imaging studies using a radionuclide, all at different hospitals (Buddemeyer *et al* 1983). At this point in time the last hospital became suspicious and finally found that all the apparent symptoms leading up to the lung scan and other associated tests, were faked—all in the course of some days of hospital bed rest.

†Quality control of the radiopharmaceutical is most important, but this will be undertaken by the commercial supplier or the hospital radiopharmacist. For example, NRPB (1983) guidance notes state 'quality control on radiopharmaceuticals should include checks for radioactive impurities when these are liable to be present. This applies to short-lived radionuclides with a longer-lived impurity. The eluate from a radionuclide generator should therefore be checked for *breakthrough* of the parent nuclide before the first administration and, where the generator is still in use (e.g. for indium-113m) monthly thereafter.

CHAPTER 11

PROTECTION IN NUCLEAR MEDICINE DIAGNOSTICS

11.1 INTRODUCTION

The organisational structure for the use of unsealed radioactive isotopes varies among hospitals. In some, the department of radiotherapy and oncology is responsible for iodine therapy, whereas in others there is an independent department of nuclear medicine which covers both therapy and diagnosis, or the nuclear medicine diagnostic studies are within the department of radiology. In addition, medical research laboratories are sited within teaching hospitals and both short-lived and long-lived radioactive isotopes may be used in these laboratories for *in vitro* studies. This is distinct from diagnostic *in vivo* studies in which only shorter lived radioactive material such as technetium-99m is injected into a patient. However, for the purposes of discussing radiation protection in hospitals, therapy and diagnosis have been arbitrarily divided into chapters 10 and 11 but the topics of nursing care, protection of the patient and waste disposal in therapy and diagnosis have been covered in single sections (§§10.4, 10.5 and 11.6 respectively).

The major uses of radioactive isotopes in diagnosis can be divided into *in vitro* and *in vivo* techniques:

In vitro techniques:

Radioimmunoassay (RIA) for measurement of peptide hormones, steroid hormones, thyroid hormones, drugs, etc.

In vivo techniques:

Non-imaging studies such as thyroid uptake and blood volume measurements

and

Imaging studies for brain, liver, lung, bone, kidney, heart, thyroid and other organs.

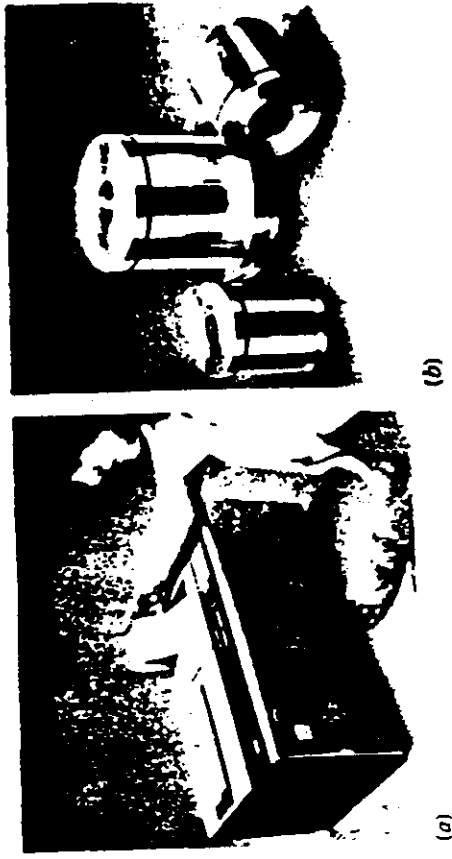
In radioimmunoassay, which is often undertaken in a hospital's department of biochemistry or pathology, the principle of measurement involves an

immune reaction between the substance of interest and specific antibodies to this substance. The substance of interest is present in two forms, one radioactively labelled (or *tagged*) and the other in its natural form and of unknown quantity—which is to be determined. These two amounts compete for the limited binding capacity of a fixed quantity of antibody and, depending on the relative quantities of labelled and unlabelled material, there will be a variable amount of radioactivity in the bound state. The bound and free fractions are separated and one or other used in the subsequent assay process. The radioactive isotope almost always used is iodine-125 which has principal energies 0.035 MeV and 0.027 MeV and a half-life of 60 days. Cobalt-57 or cobalt-58 are sometimes used for Schilling tests to study vitamin B₁₂ absorption. Cobalt-57 has a gamma ray energy of 0.122 MeV and a half-life of 270 days and cobalt-58 a gamma ray energy of 0.81 MeV and half-life of 71 days. The activities of the *RIA* samples to be measured are very small, of the order of hundredths of MBq (tenths of μ Ci) and *RIA* counters are available which can handle bulk assays. Some of these have a maximum throughput of 6000 samples in 24 hours with a one minute counting time per sample. Others are designed for handling fewer samples, and instead of a single sodium iodide crystal as the radiation detector over which each sample is automatically moved, the instrument contains a crystal for each sample. These are now available for measurement of 8, 12, 16 and 20 samples (see figure 11.1).

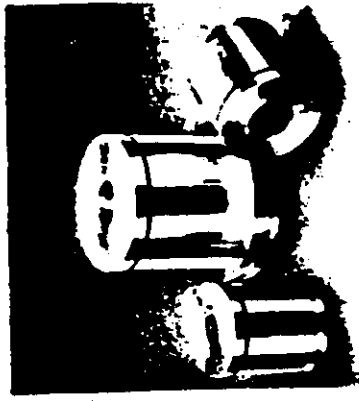
Two examples of *in vivo* non-imaging studies are thyroid uptake measurements and renography. For the thyroid study a single-probe unit such as in figure 11.2 is used to measure thyroid uptake. The patient is given a tracer dose of iodine-131 (or iodine-123) and after a specified period of time, which for iodine-131 has in practice varied from 10 minutes to 48 hours, the amount of radio-iodine in the thyroid is measured. Comparison is made with an aliquot of the administered dose which is measured under conditions which approximate as closely as possible to the *in vivo* conditions. Corrections for various factors such as background radiation are made, and the thyroid uptake is finally expressed as a percentage of the administered dose.

In renography, kidney function is studied with a multi-probe rather than the single-probe system used for thyroid uptakes. Time activity curves from both kidneys and for the blood background are obtained after administration of the radiopharmaceutical iodine-131 hippuran and are analysed to determine whether the kidneys are functioning normally or abnormally.

By far the greatest workload in diagnostic nuclear medicine is *in vivo* imaging procedures of organs following administration of a radiopharmaceutical which localises in the organ of interest. For the majority of these studies the radioactive tag is technetium-99m, with a gamma energy of 0.140 MeV and a six hour physical half-life, although other radioactive isotopes such as gallium-67 and thallium-201 are also used for specific



(a)

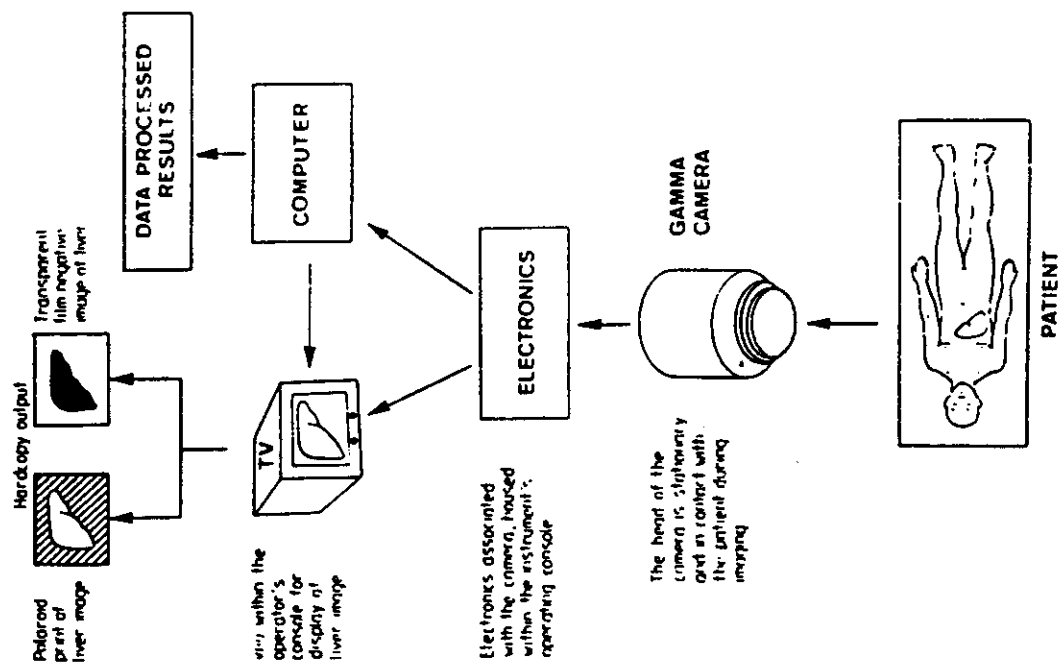


(b)

Figure 11.1 (a) A multi-well counter for radioimmunoassay measurements. Simultaneous counting can be obtained for 12 samples containing iodine-125 or cobalt-57. Lead protection is required within the instrument to avoid cross-talk between counting channels. (b) Single well-type crystals, surrounded by lead shields. (Courtesy: Nuclear Enterprises.)



Figure 11.2 Thyroid uptake measurement using a scintillation probe detector. (Courtesy: Nuclear Enterprises.)



(a)

Figure 11.3 (a) Schematic diagram of a gamma camera-computer system for nuclear medicine studies. These studies may be either static investigations such as liver imaging, or dynamic investigations in which measurements are made over a period of time, as in cardiac studies. A computer is essential for all but the most simple dynamic studies or for static imaging. The hardcopy outputs, which can be filed in the patient's hospital record, are usually termed *scans* or *scintigrams*. (b) Gamma cameras are manufactured as either stationary units or as mobile equipment. That shown is a large field of view stationary camera. (Courtesy: Technicare Imaging Ltd.) (c) Bone scan (9 views) of a 14 year old male, using a Technicare Sigma 438 gamma camera. Scanning time seven minutes per view. (Courtesy: Technicare Imaging Ltd.)



(b)



(c)

imaging procedures. The instrument used to detect the gamma radiation pattern from the organ of interest and to display the result on a television monitor (visual display unit, vdu), on film or on polaroid print, with or without computer data processing, is a *gamma camera*. One type is shown in figure 11.3(b) with a schematic diagram of a camera-computer system shown in figure 11.3(a).

The objective in organ imaging is to detect whether an organ (or its function) is normal or abnormal, by making a diagnosis based on the scan (or on a real time series of scans) which is a pictorial representation of the distribution of radioactivity. An abnormal pattern may show either an increase or decrease in uptake from the normally acceptable levels. Using the liver scan (figure 11.3(a)) as an example, technetium-99m sulphur colloid is the typical radiopharmaceutical and a high concentration of activity is expected in the normal liver. Tumours, cysts and haematomas within the liver will take up a decreased amount of colloid compared with normal liver tissue. They will therefore be seen on the scan as areas of decreased radioactivity within the normal pattern. An actual series of bone scans is shown in figure 11.3(c). An earlier type of instrument than the gamma camera is the *rectilinear scanner*, but this can only be used for static studies and is now only manufactured in one country.

When *dynamic studies* are undertaken with a gamma camera, a computer is necessary for comprehensive data processing, and nuclear cardiology, in which dynamic studies of the heart are investigated using thallium-121 is a very useful and growing field of medicine. Details of radioactive isotopes used, including typical values for administered activities, are given in §11.2. Computer tomography (γ) scanning in diagnostic radiology is mentioned in chapter 12, and this advance has provided excellent x-ray generated tomographic views for patient diagnostics. More recently, rotating gamma cameras have been designed for single photon emission tomography (SPECT) following administration of a radiopharmaceutical. This is currently one of the most exciting prospects in nuclear medicine. However, in terms of radiation protection, interest lies in procedures prior to administration of the radiopharmaceutical: in the dispensing laboratory (or hot laboratory) where the radiopharmaceuticals are prepared and issued for patient use; in protection features in the measurement laboratory or gamma camera room, in emergency procedures for decontamination, and in radioactive waste disposal.

11.2 RADIATION SOURCES

Radiation sources in nuclear medicine are mainly administered in liquid form by intravenous injection although radio-iodine for thyroid studies is usually taken orally. Exceptions include radio-iodine gelatin capsules and

radioactive gases used in lung ventilation studies, xenon-133 (half-life 5.3 days, gamma energy 0.081 MeV) and krypton-81m (half-life 13 seconds, gamma energy 0.191 MeV). Examples of radiopharmaceuticals used for imaging studies plus some typical administered doses are

Brain	Technetium-99m pertechnetate	555 MBq (15 mCi)
Liver	Technetium-99m sulphur colloid (for routine liver imaging)	37–111 MBq (1–3 mCi)
	Technetium-99m HIDA (for biliary obstruction and gall bladder function)	74 MBq (2 mCi)
	Gallium-67 citrate (for localisation of liver abscesses and diagnosis of hepatomas as distinct from liver cancer)	74 MBq (2 mCi)
Skeleton	Technetium-99m pyrophosphate or diphosphonate	555 MBq (15 mCi)
Thyroid	Iodine-131-sodium iodide	0.6–0.9 MBq (15–25 mCi)
Lungs	Technetium-99m human serum albumin microspheres (for perfusion lung imaging)	74 MBq (2 mCi)
	Xenon-133 gas (for ventilation imaging)	370 MBq (10 mCi)
Heart	Thallium-201-Thallos-201 chloride (myocardial imaging whilst exercising)	37–74 MBq (1–2 mCi)

^{67}Ga is an isotope with a 78 h half-life and gamma energies 0.091, 0.185 and 0.3 MeV and ^{201}Tl is an isotope with a 73 h half-life and gamma energies of 68–80 keV (Hg K x-rays).

Typical activities used for non-imaging techniques are lower than for imaging techniques. For example, 1.11 MBq (30 μCi) chromium-51 for red cell volume studies and 3.7 MBq (100 μCi) chromium-51 (half-life of 27.7 days and gamma energy of 0.32 MeV) for red cell survival studies and 3.7 MBq (100 μCi) iodine-125 labelled fibrinogen for deep vein thrombosis. This latter is investigated using a portable scintillation probe as distinct from the fixed probe shown in figure 11.2 for thyroid uptake counting.

Some of the radiopharmaceuticals are delivered direct from the commercial supplier, such as ^{131}I -sodium iodide; whereas others such as $^{99\text{m}}\text{Tc}$ -pyrophosphate are made up from kit form by the hospital radiopharmacist. For short-lived radioactive isotopes such as $^{99\text{m}}\text{Tc}$, it is not feasible unless the distances involved are short and the transport facilities excellent, to obtain deliveries from a centralised radiopharmacy outside the hospital undertaking the nuclear medicine imaging studies. Fortunately, this is not a real problem since individual $^{99\text{m}}\text{Tc}$ generators can be purchased from commercial suppliers, and the generator (or *cow* as it is sometimes termed) can be *milked* (eluted) each day in the dispensing laboratory to obtain the required amount of $^{99\text{m}}\text{Tc}$ for that day's patients. The $^{99\text{m}}\text{Tc}$ eluate

in the form of sodium pertechnetate can be subdivided into the scheduled brain doses or used with bone scan kits, liver scan kits, etc.

Guidance on radiation procedures necessary when dealing with patients to whom radiopharmaceuticals labelled with not more than 1 GBq (27 mCi) have been administered has recently been published by the Hospital Physicists' Association (1984). These are intended to assist the Radiation Protection Advisers (RPA) and Radiation Safety Officers (RSO) within the UK when they produce local rules. However, they will also be helpful to those responsible for radiation protection in other countries. They confirm that the basis on which most nuclear medicine departments run, namely that only nursing mothers and patients receiving extreme intensive care represent possible ^{99m}Tc radiation hazards, is correct and reasonable. Thus for nursing mothers the HPA (1984) made three recommendations:

- (i) Close contact with an infant should be avoided whenever possible for a period of 24 h.
- (ii) Due to the variable amounts of radioactivity appearing in breast milk, a delay of 24 h prior to recommencement of feeding is recommended.
- (iii) If clinical requirements conflict with these recommendations, the advice of the department undertaking the test should be obtained before requesting the investigation.

The HPA (1984) made five recommendations for nurses:

- (i) With normal nursing procedures, no restrictions are recommended with respect to the external radiation hazard from patients who have received not more than the stated level of radioactivity. In the special case of intensive nursing, involving prolonged periods at distances of 0.5 m or less from the patient, it would be possible under certain circumstances for a nurse to receive doses in excess of the Dose-Equivalent Limit.

In practice, such circumstances are most unlikely to occur, but RPAs should verify that this is the case in their particular situation.

- (ii) If there is spillage of excreta from the patient or the patient vomits, this should be dealt with promptly using normal hygienic procedures which include the wearing of disposable gloves and plastic aprons.
- (iii) Contaminated linen should be dealt with as though it were soiled linen. Disposable gloves should be worn.
- (iv) Patients should use normal, hygienically maintained lavatory facilities. When this is not possible, normal hygienic procedures including the wearing of disposable gloves should be adopted during the collection or disposal of excreta.
- (v) Further advice may be obtained from the department undertaking the test.

11.3 DISPENSING LABORATORY

The dispensing laboratory, often referred to as the *hot* laboratory, is the focal point for the receipt, storage, handling and issuing of unsealed radioactive material used for diagnostic purposes within the hospital (sealed sources used in therapy are dealt with in the sealed source room discussed in §8.4). There are many important aspects which have to be considered when planning the design of a dispensing laboratory, not all of them directly related to radiation protection. For example, good pharmaceutical practice requires proper quality control of materials and the following recommendations on premises were made by the World Health Organisation in their 1982 publication *Quality Assurance in Nuclear Medicine*:

Premises (WHO 1982a)

Most handling of radiopharmaceuticals requires the use of aseptic techniques. For a sterile product, environmental factors such as air quality must be controlled. Special requirements for radiation protection and for hygiene may be required. Such considerations require the installation of special ventilation systems, including fume hoods and laminar-air-flow cabinets, and these must be regularly controlled with regard to air-flow velocity and directions and the effectiveness of the filter. All premises should be regularly monitored for contamination in accordance with national and international regulations, and instruments such as autoclaves and dry-heat sterilisers must be checked with spore samples for sterilising effectiveness.

They also make recommendations on necessary equipment which includes an activity meter such as shown in figure 4.3.

Equipment (WHO 1982a)

To perform quality control in a hospital environment, various instruments are required; according to the class of radiopharmaceutical used. For 'ready-for-use' radiopharmaceuticals, an activity meter is required. For radionuclide generators and kits, the following items are required:

- (i) activity meter,
- (ii) equipment for radiochromatography, including measuring

†The World Health Organisation have also published recommendations for quality assurance in diagnostic radiology (WHO 1982b) (see tables 12.12–12.16). These WHO publications are the results of WHO international workshops. The one for radiotherapy is to be held in December 1984 and will be followed by a quality assurance publication in 1985–6. At the time of writing, the most recent quality assurance reference for radiotherapy only relates to brachytherapy (Goldson and Nibhamphudy (1984). Since the authors are from Washington, it draws heavily on NCRP (1978, 1974) recommendations and the code of Federal Regulations of the US Nuclear Regulatory Commission, Title 10, Chapter 1, Part 19, 20 (March 1981), Part 35 (August 1980).

instruments, such as a well counter, gamma camera, or chromatograph scanner,

(iii) microscope for control of particles,

(iv) equipment for sterility testing.

For 'home-made' radiopharmaceuticals a fully equipped analytical chemistry laboratory is required. For autologous labelled biological material additional equipment may be required for staining cells and for the separation of proteins; a special microscope may also be needed.

'Ready-for-use', 'home-made', autologous labelled material and generators and kits are referred to above, and these four classes of radiopharmaceuticals are described by WHO (1982a) as follows:

'Ready-for-use'

This class of radiopharmaceuticals refers to products which are delivered to the nuclear medicine facility by the producer and are ready for immediate administration to the patient. They may be radionuclides in simple ionic form, such as ^{201}Tl , or a labelled compound, such as (^{131}I) hippurate.

Radionuclide generators and kits

Radionuclide generators (e.g. ^{99}Mo - $^{99\text{m}}\text{Tc}$) and kits (e.g. Sn phosphate compounds) are delivered to the nuclear medicine facility by a commercial producer. The final product for administration to the patient is only partly manufactured by the commercial organisation and requires subsequent handling by the user.

'Home-made'

The classification 'home-made' radiopharmaceutical is reserved for products derived from raw materials, either radioactive or non-radioactive, within the hospital or institute. These include cyclotron-produced radionuclides, such as positron emitters, and laboratory-prepared pharmaceuticals, such as colloids.

Autologous labelled

Autologous radiopharmaceuticals are produced by the radioactive labelling of materials from the patient—for example, cells or metabolic compounds.

Additional information on radiopharmaceuticals can be found in the IAEA Technical Report Series No 194 by K Kristensen, *Preparation and control of radiopharmaceuticals in hospitals*, published by the IAEA, Vienna, 1979.

A dispensing laboratory in which radiopharmaceutical production takes place must therefore accommodate a fume hood and laminar flow cabinet in addition to bench space and storage facilities plus a wash basin and shower

facility for decontamination. However, in some hospitals there is more than one dispensing room and that for production of kit form, 'home-made' and autologous labelled radiopharmaceuticals is sited within the pharmacy department, whereas the other dispensing laboratory is within nuclear medicine or medical physics and handles ready-for-use radiopharmaceuticals. An example of a design for a dispensing laboratory in a small nuclear medicine department is shown in figure 11.4. The hand-held radiation monitor is provided so that the floors and benches in the laboratory can be surveyed for contamination. In addition, though, there should also be a radiation monitor which is *not* hand held near the laboratory door. This is to monitor hands and clothing before leaving the room. If a person were to be contaminated and picked up the monitor, this would only result in the monitor itself becoming contaminated.

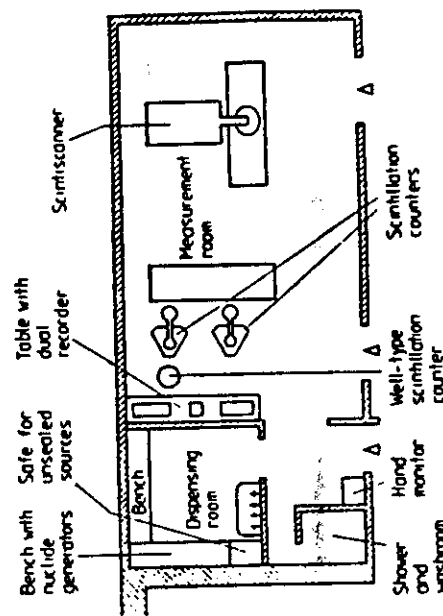


Figure 11.4 Dispensing room arrangement within a small department for diagnosis with unsealed sources. At the time of publication by WHO this was stated to represent the minimum requirements for a diagnostic clinic, which is also suitable for a physician's private practice. In the measurement room the single well scintillation counter will have a crystal similar to those shown in figure 11.1(b). The two scintillator counter *in vivo* probes can be used for thyroid uptake (figure 11.2) or renography. The scintiscanner (rectilinear scanner) would now be replaced by a gamma camera (from a WHO manual, Frost and Jammet 1975).

Storage safes in a dispensing laboratory will not be of identical design to those in a sealed source room (figure 8.12), since lead drawer inserts for needle and tube sources are not appropriate. Instead, shelves must be provided on which to store vials of radioactive liquid such as stock solutions from which material can be dispensed on request. These vials will be stored within their own lead pot, possibly that in which the source was delivered

(figure 10.1), and for security the vials should be locked away. Other lead shielding within the dispensing room, on benches and within fume hoods, can be constructed using interlocking lead bricks (figure 5.5) which can then be clad with stainless steel or a laminate so that contamination can easily be wiped off. L-shaped shields with lead glass viewing windows to avoid splashes to the face are essential within a dispensing room. The shape is as indicated in figure 8.13 but the thickness of lead protection required for

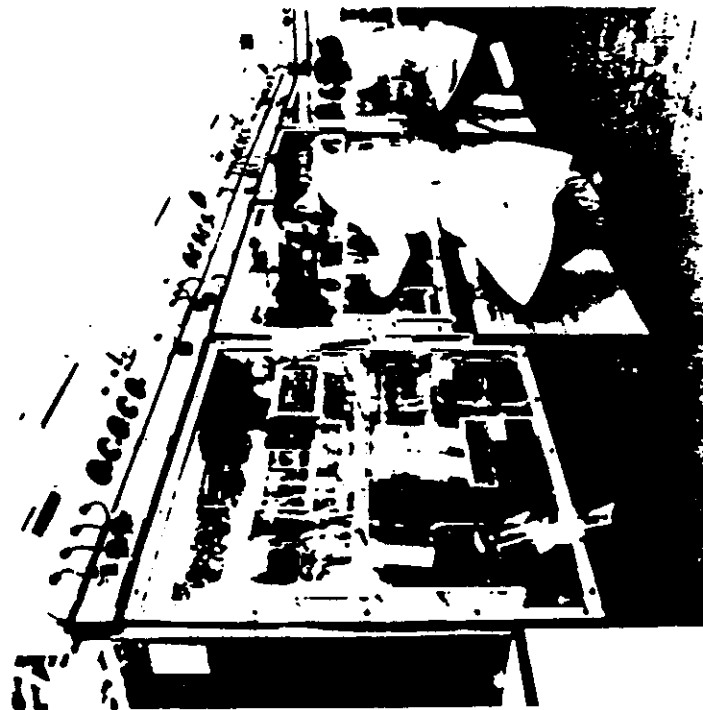


Figure 11.5 A slit box, class I, or 'air contained' glove box. This is operated through one or more slits, and when these are not in use they are closed by flaps and the air inlet is diverted through small pad filters. This ensures that the minimum contamination passes into the enclosure when not in use, while still maintaining air flow conditions. The slits can also carry slides on which are mounted ports and neoprene glove gauntlets. This class I type enclosure can be converted into a sealed class III type enclosure by changing the front panel. The differences in classes are that: I takes in air from the surroundings to provide air flow conditions in the enclosure through an open port; II is sealed and relies on the internal air circulation system to provide air flow, supplied and extracted through high efficiency particulate air filters. (Courtesy: Amersham International plc, Amersham, UK.)

handling ^{99m}Tc and ^{125}I sources is not as great as that for ^{137}Cs sources in a sealed source room. An L-shaped shield in a small protected bay within the measurement room can be useful for temporary storage of radioactive material (already in a lead shield) or for any last minute dispensing modifications. However, the major dispensing facility should not be within the measurement room.

Fume cupboards and laminar flow cabinets have already been mentioned, but there is also a third type of cabinet, a *glove box* (figure 11.5). This can be used to handle low activities of non-volatile substances, non-volatile since there is no ventilation. These are often used with alpha and beta emitting radioactive isotopes. If necessary, lead shielding can be incorporated into the glove box. It is also pertinent to note that when dispensing radioactive materials gloves should always be worn. Disposable surgeons' gloves are the most convenient, and the practice of wearing non-disposable rubber 'washing-up' gloves should be discouraged! Even if scrubbed after each use there is no certainty that ^{131}I contamination might not be transferred to a ^{99m}Tc dose.

Remote handling instruments have also been mentioned in relation to handling solid radioactive sources in a sealed source room (see §8.4) and figure 11.6 shows a selection of these instruments, including tongs, forceps, tweezers and bottle openers. Models can also be purchased which are attached through the arm to a ball and socket joint in the centre of an interlocking lead brick. In this manner, a remote handling tool can be built into a lead shield within the laboratory. These are useful when handling high activity sources.

As well as the use of lead shields, remote handling tools and disposable gloves, there are other good working principles within a dispensing laboratory. These include: no smoking, eating or drinking, leaving any



Figure 11.6 Selection of remote handling devices. (Courtesy: Buchler.)

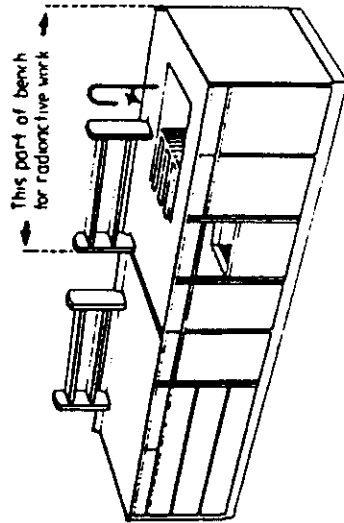


Figure 11.7 The allocation of work space to radioactive and non-radioactive work. Any sinks used for the disposal of radioactive liquids should be clearly labelled as such and should not be used as a normal wash basin for washing hands.

ingestion of radioactive materials impossible; clear division of work areas so that prospects of contamination are minimised (figure 11.7); regular monitoring of work surfaces for contamination using a swab which can be measured for any residual activity; and use of rubber bulb pipette fillers to avoid the pipette end being placed in the mouth and any accidental

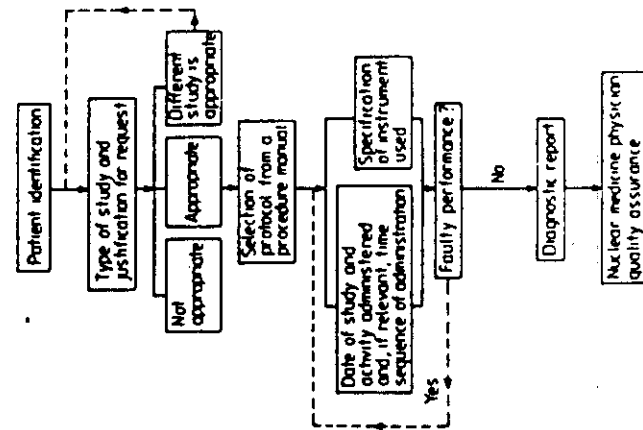


Figure 11.8 Specification of patient record requirements. (Modified from WHO 1982a.)

swallowing of a radioactive liquid. In addition, radiation workers on entry into the dispensing laboratory can change their normal white coats used around the hospital, for ones to be worn only in the laboratory. This minimises the possibility of spread of contamination. Mallinckrodt Nuclear of St Louis, USA, published in 1973 a booklet by Marshall Brucer, entitled *Radiation Protection Procedures in the Nuclear Medicine Laboratory or The technician's constant battle against radiation contamination*. Some of this advice is listed in table 11.1. Extracts from guidance notes for the UK published by the NRPB in 1983 are listed in table 11.2, and table 11.3 gives important information relevant to a radiopharmaceutical dose. This forms part of essential record keeping, the housekeeping of table 11.1, and figure 11.8 shows a specification of patient record requirements after WHO (1982a).

Table 11.1 Nuclear medicine radiation protection advice. (After Mallinckrodt Nuclear.)

In a *dispensing* room (or *hot* room) excessive exposure and contamination are possible during high-level storage and in the preparation of doses. Compulsive housekeeping, access restricted to qualified personnel and continuous monitoring are recommended.

In the *controlled* area outside the dispensing room, exposure from patients is transient and samples for counting are a low-level source of contamination. Good housekeeping, access restricted to necessary personnel and film badges for employees are recommended.

In the *uncontrolled* area around the boundary of the controlled area, all areas are not under radiation control. Routine housekeeping, unrestricted access and routine periodic monitoring of background are recommended.

Nuclear medicine physician quality assurance† is mentioned in figure 11.8, and in some countries, in addition to the records already described, there is a requirement on the physician to be licensed by a government body. One example is in the UK under the Medicines Act 1968 concerning the administration of radioactive substances to persons for purposes of diagnosis, therapy or research. Medical and dental practitioners wishing to make such administrations have since 1 July 1980 been required to apply for prior authorisation to the Department of Health and Social Security (DHSS 1979). The background to this requirement was the Council of the European Communities' Directive of 1 June 1976 (76/579/Euratom) which revised

† This involves an input of patient follow-up data including that on adverse patient reactions, and the correlation with other available surgical, pathological, clinical and anatomical information. This will then lead to an analysis of false-positive and false-negative diagnostic reports.

Table 11.2 Guidance notes for general procedures in laboratories and radioisotope departments (NRPB 1983).

- (i) It is essential that detailed local rules for handling unsealed radioactive substances are drawn up; they must be supplemented by careful training and instruction of staff at all levels.
- (ii) Working procedures should be designed to minimise the spread of contamination from the working area.
- (iii) No food or drink should be brought into the area, e.g. for storage in a refrigerator, nor open packets of cigarettes.
- (iv) There should be a ban on the use of handkerchiefs; an adequate supply of paper tissues should be provided to replace them.
- (v) Any cut or break in the skin should be covered before a person enters the area. Dressings should incorporate a waterproof, adhesive strapping.
- (vi) The walls, floor and ceiling and all apparatus in the area should be cleaned often enough to ensure that contamination is kept as low as reasonably practicable.
- (vii) It is essential that radioactive solutions to be administered are clearly labelled, indicating the radionuclide, chemical form and activity at a given date and time. The terms 'millicurie' and 'microcurie' (where still used) should be written out in full to avoid mistakes.
- (viii) To reduce the radiation dose to the patient, the use of a thyroid blocking agent should be considered if radio-iodine in certain forms, or more than 185 MBq (5 mCi) of technetium-99m, is to be administered.
- (ix) When radioactive gases or aerosols are administered it should be ensured that exhaled breath is conducted directly out of the building.

Table 11.3 Data relevant to radiopharmaceutical dose preparation records.

Pharmaceutical identity
Volume
Total activity
Concentration
Date and time of assay or calibration
Expiration date
Specific activity
Manufacturer's batch number
Where a stock volume is retained for use over a period of time, records for each dose dispensation should record:
Date and time
Patient/study
Decay factor
Volume
Activity
Volume administered
Volume remaining
Activity remaining

basic safety standards for health protection against the dangers of ionising radiation. The relevant Article 5(a) reads as follows:

Apart from the prohibitions provided by national law, and irrespective of the degree of danger involved, a system of prior authorisation must be applied in respect of:
the administration of radioactive substances to persons for purposes of diagnosis, treatment or research.

11.4 RADIOACTIVE DECONTAMINATION

It is to be hoped that radioactive decontamination in hospitals does not become a serious problem, but nevertheless, preparations must be made for all eventualities. One essential preparation is to provide readily available emergency equipment. A list of items which should be considered, in the opinion of DHSS (1972), is given in table 11.4. although it is recognised that the final choice depends upon the type of work being carried out. Recommendations for a decontamination kit have also been given by Sodex and Early (1981) of Cleveland, Ohio (table 11.5).

Table 11.4 Emergency equipment for decontamination procedures DHSS (1972).

- (i) Overshoes, protective clothing (including caps) and respirators or breathing apparatus.
- (ii) Decontamination materials for the affected area, including absorbent material for wiping up spills.
- (iii) Decontamination materials for persons.
- (iv) Equipment for preventing entry into the affected area, including warning notices.
- (v) Equipment for the handling, temporary storage, and disposal of contaminated articles.
- (vi) Portable monitoring equipment, including personal monitoring devices such as pocket dosimeters and film badges (drawn from current stocks as necessary).
- (vii) Sundry items such as adhesive tape, labels, torch, notebook and pencils, and simple first-aid equipment.

Contamination occurs when a radionuclide spreads beyond its normal place of confinement and this spread may occur through the air, by water, over floors etc. It may also affect individuals, staff or patients and could become fixed inside or outside the body. Decontamination procedures will vary with type of contaminated surface depending upon, for instance, whether the surface is a bench top or the human skin. Very abrasive

Table 11.5 Decontamination kit. (After Sodde & Early 1981.)

Item	Purpose of item
Warning tape and signs	Posting of the area
Plastic bags, small	Shoe covers, wet containers
Disposable gloves	Hand protection
Masking tape	Fastening shoe covers and the like
Forceps, tongs	Safe handling
Large plastic bags	For contaminated material
Sponges, 4 x 4	Sopping up
Paper towels	Blotting and drying
Radiac wash or detergent	Detergent
Scouring powder	Friction
Tags	Identification
Scissors	Cutting absorbent paper, other uses
Whatman No 1 filter paper	Taking swipes after decontamination
Chux	Covering area after decontamination
G-M survey meter	Monitoring

chemicals and ultra-hard bristle brushes for scrubbing will not be appropriate for skin. Both WHO in their manual *Unsealed Sources* (Frost and Jammet 1975) and NRPB (1983) guidance notes, emphasise that laboratory glassware and metal ware such as tools, trays and sinks, should be properly cleaned after use. NRPB (1983) recommend that glassware should be cleaned with an alkaline detergent, whereas WHO (1975) specifically mention chromic acid cleaning mixture for porcelain and glassware. Commercially available chemical concentrates devised as water-rinsable surface active cleaning agents and radioactive decontaminants are also generally available. These have been formulated specifically for laboratory, medical and specialised industrial cleaning applications. One such concentrate is Decon 90 which is also suitable for contaminated plastics.

A wise precaution, and one recommended by NRPB (1983) is for persons working with unsealed sources, or nursing patients to whom unsealed radioactive sources have been administered. They should wash their hands thoroughly with mild soap and water before leaving the working areas and especially before eating, drinking, smoking or the application of cosmetics. Particular attention should be paid to cleaning fingernails. Decontamination problems can be divided into three main areas:

Surfaces
Personnel
Linen.

Contaminated surfaces may be in the dispensing laboratory, or a dispensing bench in the gamma camera room, on the floor of the iodine-131 therapy room or other areas. All decontamination procedures should commence with wearing the appropriate protective clothing, e.g. rubber or plastic

gloves and, if necessary, boots. The radiation hazard must then be confined to prevent any further spread of the contamination. The spill should be monitored to try and ascertain the extent of the contamination activity and it should be also determined if any staff have been contaminated. Those not involved should remove themselves from the area. The contaminated surface should be washed and scrubbed with a decontaminant chemical, such as Decon-90, with the contaminant itself being taken up with paper towelling. Taking care not to spread the activity over any previously clean areas. Several washes and scrubbing may be necessary until the activity has been reduced to an acceptable level, say 0.36 MBq cm^{-2} , ($10^{-4} \mu\text{Ci cm}^{-2}$), which can be checked using a calibrated radiation monitor. This procedure can be adopted, for example, if a spill of radioactive urine from an iodine-131 therapy patient occurs. If a small area of bench in a dispensing laboratory is contaminated with a short-lived isotope such as technetium-99m (half-life = 6 h) then an alternative would be to cover the area with polythene sheeting and thin lead sheet specifically available for this purpose, label with the date and activity of the spillage, and leave to decay to an acceptable level. However, this is a lazy way of dealing with contaminated benches and floors. If, however, the problem is contaminated linen, either clothing or bed linen, and no special washing machine is available solely for decontamination purposes, then it is reasonable to store the linen in polythene bags, in a waste disposal storage room (see §11.6). These are kept there until decay has reduced the activity to a level at which the clothing can be returned to general hospital use. This is cost-effective in that it saves incinerating the clothing items, but in practice it can be a rather unpleasant task opening the polythene bags containing used bed linen after some time has elapsed.

When personnel contamination occurs this is usually on the skin of exposed parts of the body and is not extensive enough to need a shower. If, however, a shower is required, then care should be taken not to spread the contamination over a wide area through dilution. Use of hot water should also be avoided because it increases the circulation to the contaminated area of the body and enhances the absorption of radioactivity into the circulating blood. Warm water is recommended. Generally, however, the contaminated area, when this has been defined, should be well washed with soap and water, avoiding the use of abrasives, and this should be repeated at frequent intervals until the contamination is removed. An exception is when the skin is broken or when a wound is sustained in conditions where there is a risk of radioactive contamination. In this situation, the NRPB (1983) recommend that the injury should be irrigated immediately with copious amounts of water, contaminated then they should be irrigated with isotonic irrigant as soon as possible. If the hair is contaminated it should be washed in such a manner as to avoid spreading the contamination and pHisoHex or an equivalent

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shampoo should be used. Hair should only be shaved as a last resort since this increases the possibility of damage to the skin, but it may be cut to remove contamination.

Radiation protection advice given by Mallinckrodt Nuclear of St. Louis has already been quoted in table 11.1. In addition, presumably in relation to the US, they refer in cartoon format to three types of persons involved in nuclear medicine:

Radiation worker: trained to protect himself and others; film badge (and other meters) is required.

Radiation helper: any knowledgeable person; film badge only while in controlled area.

Supervisor: person with administrative authority; has key to executive washroom.

They also give advice as to the duties in an emergency in order of priority:

Duty priority	Radiation worker	Radiation helper	Supervisor
1st	Confine the hazard	Protect the worker	Protect others
2nd	Prevent spread	Call for help	Seal the area
3rd	Shield the source	Contain the source	Monitor personnel
4th	Call for help	Clean up the worker	Call for health physics consultation
5th	Clean yourself	Clean yourself	Report incident

As mentioned, among the duties of the supervisor is that any radiation incidents must be reported. Reporting mechanisms will differ among countries, as will the legal responsibility of the hospital or institute where an incident occurs. In the UK, all major radiation incidents must be reported to the Health and Safety Executive, whether in hospitals, industrial plants, power stations or on road or rail. There is also the NAIR (National Arrangements for Incidents Involving Radioactivity) Scheme for Great Britain which is administered by the NRPB. The handbook for NAIR details both administrative aspects and operational aspects, and in the latter are included details of police and fire service participation. However, accidents occurring in hospitals within the confines of radiotherapy and nuclear medicine departments are most unlikely to be so major that police and fire brigade services are immediately required. Far higher activities are used in other situations than in hospitals and it is for these that NAIR is normally required. Hospital involvement in NAIR is therefore more likely to be in an assistance role for outside incidents, particularly if a well equipped medical physics department exists within a district hospital. Indeed, hospital involvement in the NAIR scheme is often said to be primarily a question of

verifying that it is, in fact, a genuine incident involving radioactive sources being present. Notification of outside regulatory agencies, such as the Health and Safety Executive in the UK or the Nuclear Regulatory Commission, State Department of Health or Civil Defence in the US, is then the responsibility of the authorities in charge at the accident site.

11.5 MEASUREMENT LABORATORY

The measurement laboratory or measurement room in nuclear medicine can be either the laboratory where *in vitro* measurements are performed with equipment such as that in figure 11.1, or a room where *in vivo* measurements (that is, where the patient is present) are made. In both cases, care must be taken not to contaminate the measuring equipment by radioactive spills, and if a small area in the room is set aside for minor amounts of dispensing, then this area should be properly shielded and protective features such as an L-shaped shield (figure 8.13) incorporated. In principle, though, it is best to avoid, if at all possible, dispensing procedures in a measurement laboratory since, as well as the possibility of contamination, radiation from stored sources might also interfere in the measurement process.

Depending upon the layout of the nuclear medicine department in a hospital, sources for injection into a patient may have to be transported a long distance if the gamma camera scanning room and dispensing laboratory are sited in different parts of the hospital. Some lead protected transport carriers must therefore be available which, if the source is of high activity and in a vial, can be a simple design of lead pot with a long carrying handle, such as figure 5.14. If the necessary lead shielding is too heavy to carry the container by hand, then small wheels can be fitted and the source transported in this manner. However, for lower activities administered to patients in nuclear medicine diagnostic tests, a hand-held lead protected carrier is quite adequate. For therapeutic doses of iodine-131 though, heavier shielding is required. The radioactive dose for the patient is often transferred from the dispensing laboratory to the gamma camera room in the form of a syringe ready for use. Even if it is not transferred in this manner, the radioactive solution must eventually be transferred from the vial to the syringe, after which the patient receives their intravenous injection. During this procedure, the doctor or nurse administering the activity can receive a radiation dose to the fingers and hand unless a specially protected *syringe shield* constructed of lead, tungsten or lead glass, is used (figure 11.9). There are many designs of syringe shield commercially available and the most useful incorporate some sort of lead glass window through which the doctor or nurse can check the volume of the radioactive solution.



Figure 11.9 A heavy alloy syringe shield designed to provide radiation protection for the doctor or nurse giving the radioactive isotope injection for a nuclear medicine diagnostic test, such as organ imaging. (Courtesy: Gammashield Ltd.)

Finally, in a gamma camera room there will be a facility required for waste disposal of used radioactive syringes and syringe needles. A suitably labelled container is essential and the radioactive waste can be transferred at the end of each day to wherever the waste from the dispensing laboratory is stored. Waste from technetium-99m with its short half-life of six hours could usefully be separated from longer-lived radioactive waste such as that contaminated with iodine-131, gallium-67 or thallium-201 and therefore two suitably labelled containers would be best.

11.6 RADIOACTIVE WASTE DISPOSAL IN NUCLEAR MEDICINE DIAGNOSTICS AND IODINE THERAPY

The amount of radioactive waste from hospital use is only a very small fraction of the total waste generated. The bulk of the waste arises from the nuclear industry, such as that produced when spent fuel from nuclear reactors is reprocessed. Current public concern about the environmental pollution caused by radioactive waste is usually centred on national policy for waste disposal and alternatives such as turning liquid waste into synthetic rock for land burial or dumping waste into the ocean are at present just two of the points at issue. Within a hospital environment, the highest activity waste is usually solid waste such as iridium-192 wire following brachytherapy use (see §8.8). Whereas national disposal service facilities are required for this waste, it is very unusual for this service to be necessary for iodine therapy and nuclear medicine diagnostic waste. For these, local arrangements within the hospital can almost always cope with disposal by one of three methods:

(i) incineration;

- (ii) standard non-radioactive solid waste disposal method, i.e. dustbins;
- (iii) standard non-radioactive liquid waste disposal method, i.e. sewers.

The differences which occur national[†] will concern the permitted activities during a given period for wastes which can be disposed of by the above three methods. For incineration this will usually be defined as a total activity, for dustbin waste collection which will eventually be deposited in a local authority 'tip' the limiting factor may well be stated in activity per cubic capacity. The total permitted activity will therefore be calculated on the basis of the dustbin volume. For sewage disposal, via sinks, drains and toilets, the permitted activity may also be calculated on the basis of dilution, but will probably be stated as a total activity per month, or some such other period.

In the UK, certificates of authorisation for the disposal and accumulation of radioactive waste are issued by the Government Department of the Environment under the Radioactive Substances Act of 1960. Authorisation for accumulation of waste is necessary because all waste is not immediately disposed of. In some cases it is left to decay to an appropriately low activity before disposal. This is why a separate waste storage room, locked and with entry only to authorised personnel, is a necessity. Then not only can brachytherapy waste be housed but also iodine-131 and other waste. Since space is usually at a premium in hospitals, a small room solely devoted to waste storage is sometimes a problem to provide and is generally found located in basement or sub-basement areas. However, it is emphasised that electric lighting is necessary for these windowless rooms and users should not depend on torchlight. The Certificate of Authorisation after specifying the premises in the first paragraph, usually precludes waste accumulation and disposal of alpha-emitting radioactive isotopes and strontium-90 in the second paragraph. Example paragraphs 3–6 below consider:

- 3 Solid waste
- 4 Aqueous liquid waste
- 5 Organic liquid waste
- 6 Gaseous waste

and illustrate what the typical requirements[†] are in the UK.

- 3. *Solid waste:* The disposal of solid waste is authorised subject to the conditions specified in paragraph 7 of this Certificate and to the following conditions:

- (a) that the waste is disposed of by any of the following means, that is to say:
 - (i) by causing or permitting its removal as refuse by a waste collection authority or their contractors;

[†] Actual activity levels are not included since these (denoted by X in the text, where X can take different values wherever it appears) will vary among hospitals and each is a matter for discussion between the hospital and the Department of the Environment's Radiochemical Inspector.

(ii) by depositing it at, or causing or permitting its removal (by persons other than a waste collection authority or their contractors) for deposit, at, on or in a tip, dump or pit used for the deposit in substantial quantities of waste which is not radioactive waste;

(iii) by burning it on the premises and disposing of the residual ash by either of the means mentioned in sub-paragraphs (a) (i) and (ii) of this paragraph;

(b) that, where the waste is disposed of by either of the means mentioned in sub-paragraphs (a) (i) and (ii) of this paragraph, at the time of its removal from the premises:

(i) the waste is with refuse which is not radioactive waste;

(ii) the sum total of microcuries of all the radionuclides (excluding those which are decay products of others present) in any 0.1 cubic metre of the whole mass of the waste and refuse does not exceed X ;

(iii) the sum total of microcuries of all the radionuclides (excluding those which are decay products of others present) in any one article in the waste does not exceed X ;

(c) that, if the waste is disposed of by deposit at, on or in a place referred to in sub-paragraph (a) (ii) of this paragraph, it is not deposited in a part of that place in use for the deposit of radioactive waste only;

(d) that, if the waste is disposed of by burning it on the premises:

(i) in all the waste burnt on the premises in any one calendar month, the sum total of millicuries of iodine-125 and iodine-131, taken together, does not exceed X , the sum total of millicuries of xenon-133 does not exceed X , and the sum total of millicuries of radionuclides having a half-life of less than eight hours does not exceed X ;

(ii) the waste is burnt at such a place and in such a manner as to ensure that the gas or vapour arising from the burning is discharged into the open air at such points and in such a manner as to prevent, so far as is reasonably practicable, the entry of the gas or vapour into any part of any premises.

4 *Aqueous liquid waste:* The disposal of aqueous liquid waste is authorised subject to the conditions specified in paragraph 7 of this Certificate and to the following conditions:

(a) that the waste is disposed of on or from the premises by discharging it into a drainage system;

(b) that, in all the waste disposed of, on or from the premises by that means in any period of one calendar month, the sum total of curies of all radionuclides with a half-life of less than eight hours does not exceed X , and the sum total of millicuries of all other radionuclides does not exceed X .

5 *Organic liquid waste:* The disposal of organic liquid waste is authorised subject to the conditions specified in paragraph 7 of this Certificate and to the following conditions:

(a) that the waste is disposed of by either of the following means:

(i) by burning it on the premises and disposing of any residual ash in accordance with the conditions specified in paragraph 3 (a) of this Certificate;

(ii) by disposal to a person who is authorised under section 6(3) of the Act to dispose of radioactive waste of a description to which the waste belongs;

(b) that the waste contains no radionuclides other than carbon-14 or tritium;

(c) that in all the waste disposed of from the premises by either of the means specified in sub-paragraph (a) of this paragraph, in any period of six calendar months, the sum total of millicuries of carbon-14 and tritium taken together does not exceed X ;

(d) that each consignment of waste removed from the premises for disposal by the means specified in sub-paragraph (a) (ii) of this paragraph is accompanied by a Certificate signed on behalf of the Authority showing the estimated total activity of carbon-14 and tritium taken together contained in the waste at the time of its removal from the premises.

6 *Gaseous waste:* The disposal of gaseous waste is authorised subject to the conditions specified in paragraph 7 of this Certificate and to the following conditions:

(a) that the waste contains no radionuclide other than xenon-133;

(b) that the waste is discharged into the atmosphere through a ducting system at such points and in such a manner as to prevent, so far as reasonably practicable, its entry into any part of any premises;

(c) that the sum total of millicuries of xenon-133 discharged in any one week does not exceed X ;

7† The further conditions subject to which the disposal of waste is authorised are:

(a) that the Authority keeps, and retains for inspection by any person authorised by the Secretary of State in that behalf, records of disposal showing:

(i) the description of the waste disposed of and the names of and the sum total of millicuries or microcuries of all the radionuclides (excluding those

† Paragraph 7 which is referred to in the first sentence of paragraphs 3-5 is mainly related to record keeping.

- which are decay products of others present) contained in the waste at the time of its disposal;
- (ii) the means and date of its disposal;

(b) that, if the Secretary of State so directs, the Authority takes samples of the waste and of any other thing which may be specified by him and keeps such samples for such periods as he may direct for examination by or on behalf of any person authorised by him in that behalf.

The records referred to in paragraph 7 should demonstrate purchases and stock levels. These may be difficult to assess continually, but should be estimated every six months. When estimating liquid waste it is usually acceptable to consider that 30% of all administered technetium-99m doses and 30% of the therapy iodine-131 administrations are discharged into the sewerage system. There is usually no requirement to make a more accurate assessment of radio-iodine urine waste. For solid waste, good packaging prior to disposal in dustbins or an incinerator is important since clearly waste bags bursting in transit must be avoided. It is also important in the case of contaminated syringe needles to make sure they are packed in such a manner, perhaps in a sealed tin, that they are not capable of jabbing those handling the waste.

In the US the Nuclear Regulatory Commission (NRC) is the body that issues all classes of licences for non-exempt quantities of materials. Sections 20.301 to 20.304 and 20.106 of 10CFR (Title 10 Code of Federal Regulations) Part 20 refer to regulations for the disposal of solid waste, liquid waste and airborne dispersion of radioactivity. Incineration and burial are specifically prohibited except when permission is granted. The maximum amount of radioactivity which can be disposed of through a hospital's sewerage system is 1 Ci per year, provided that maximum permissible concentrations are not exceeded. Radioactive waste from nuclear medicine departments is therefore usually disposed of by either sewage, decay to acceptable levels by storage (for gaseous waste), venting to the outside, or by transfer to an authorised commercial disposal service. This is a method of choice if the activity concerned is large and the material is then packed in metal drums, which if it is liquid waste, is mixed with an absorber to prevent leakage†.

†Data on permitted radiation levels and labelling is given in 10CFR Parts 71-78 and also in Tariff No 13 of the Bureau of Explosives of the American Association of Railroads and in supplements to Tariff No 8 of Motor Carriers' Explosive and Dangerous Articles.

CHAPTER 12

PROTECTION IN DIAGNOSTIC RADIOLOGY

12.1 INTRODUCTION

It could be said that Röntgen himself started diagnostic radiology, not only by discovering x-rays, but also by taking the first x-ray picture of any part of the human anatomy, his wife's hand (figure 12.1). This was very quickly followed by anatomical radiographs taken in many countries with varying degrees of success. The orientation was also sometimes open to question as shown by the first x-ray of a heart (figure 12.2). It is taken from an 1896 textbook, and was printed upside down, as shown! Most of the earliest radiographs were of extremities, often demonstrating bony abnormalities or



Figure 12.1 The radiograph of Frau Röntgen's hand taken in 1895.

small foreign bodies. However, there were also examples of chest radiography, skull pictures (sometimes using Egyptian mummies) and even proven cases of false teeth swallowed. By 1897 the first whole body radiograph had been produced on a single plate (figure 12.3), although the exposure had to last 30 minutes. Fluoroscopy as well as radiography (see figure 1.9) was also in routine use from 1896; figure 12.4 shows one of the earliest tilting table designs by a French radiologist.

By 1910 some radiation protection at least was being used. Figure 12.5 shows a Siemens x-ray unit of 1909, the Blitz Apparat, plus a mobile lead-



Figure 12.2 The world's first cardiac radiograph 1896. This was published upside down when initially printed.



Figure 12.3 Whole body radiograph, 1897, from the pages of the *Archives of the Roentgen Ray*. The following are visible: hatpin, necklace, bracelet, rings, high buttoned boots with nail heels, and even a whalebone corset.

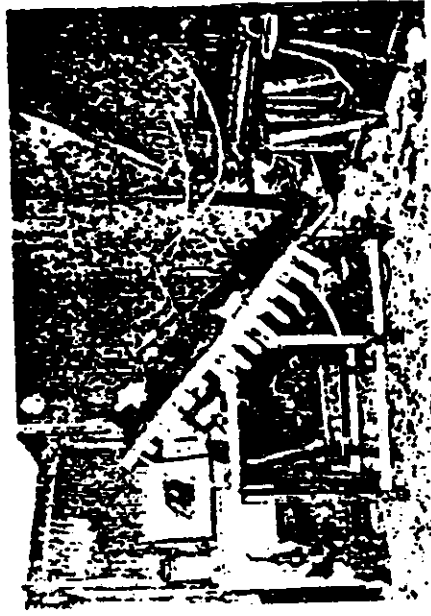


Figure 12.4 X-ray fluoroscopy using a tilting table, France, 1898.

ply screen which incorporated a lead glass window. A more modern version of this screen is still in use today, although it is now usual practice to incorporate a fixed protective cubicle in an x-ray room (see figure 5.4), for radiographers to stand behind during exposure.

X-ray diagnostic procedures can now be divided into different categories:

- Radiography
- Fluoroscopy
- Fluorography



Figure 12.5 Chest radiography using the Blitz Apparat, Germany, 1909. (Courtesy: Siemens AG.)

Radiography and fluoroscopy are shown schematically in figure 1.9. Fluorography is the permanent recording of fluoroscopic images, which used to be possible only with film but now also uses computer techniques. With the commercial systems now widely available a fourth classification of x-ray scanning can be added.

CT scanning is one of the two recent major advances in diagnostic x-ray equipment, the other being digital x-ray apparatus. Hence classification can also be according to:

Radiography—Conventional and Digital
Fluorography—Conventional and Digital

Alternatively, classification can be in terms of disease or anatomical site. The following list is given as an example:

Abdomen	Respiratory system
Obstetrics	Heart disease
Bone disease	Gastrointestinal tract
Joints	Hepatobiliary system and pancreas
Spine	Skull and sinuses
Bone trauma	Urinary tract

12.2 X-RAY SOURCES

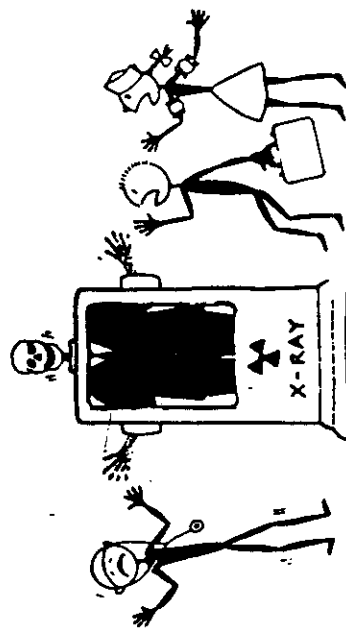
Radiation sources in radiotherapy (see chapter 7) include linear accelerators producing megavoltage energy x-rays and orthovoltage x-ray tubes typically producing 250 keV x-rays. In diagnostic radiology the x-ray energies do not exceed 150 keV and therefore radiation protection facilities and procedures, including the design of x-ray rooms, are very different. The only exception is the therapy simulator used only in the diagnostic mode.

An x-ray diagnostic image may be described as the shadow cast on a film or screen when a beam of x-rays traverses tissues of differing densities and atomic numbers. The greatest differential absorption for different atomic number tissues is at low x-ray energies where the photoelectric effect is predominant, as the latter depends on (atomic number)³.

Contrast, however, is not the only factor to be considered when producing radiographic and fluoroscopic images. Patient dose is also important. It should therefore be remembered that the low energy x-rays associated with good contrast also cause a high overall absorption and hence a high patient dose. Patient dose is reduced by increasing the x-ray beam energy, thus making the Compton effect the more predominant (see figure 3.1). In practice, a balance is struck between contrast and patient dose and many

diagnostic procedures are undertaken with x-rays between 70 keV and 110 keV.

Various international and governmental bodies have made recommendations relating to general radiation protection requirements for



diagnostic x-ray equipment. Table 12.1 gives an extract from the UK consultative document outlining draft guidance notes (NRPB 1983). The table details those items relating to x-ray tube housing, assembly and beam filtration.

Filtration preferentially removes the low energy x-ray photons which would have increased patient dosage without contributing to the x-ray image itself and is thus essential. The *inherent filtration* of an x-ray tube includes the thin glass window of the tube itself, the oil filling within the tube housing and the plastic cover in the housing which acts as the x-ray beam port. The inherent filtration is not sufficient under regulations and hence extra filtration known as *added filtration* is incorporated.

The World Health Organisation publication on x-ray diagnosis radiation protection in hospitals (Keane and Tikhonov 1975) includes a chapter on the choice of x-ray equipment from the radiological safety viewpoint and their commentary on filtration is:

For general radiography and fluoroscopy a fixed total filtration is recommended of 3 mm of aluminium. Although it has been suggested that various kinds of filtration should be used according to the task in hand, any change of filtration on a general purpose x-ray unit is highly undesirable. Only when an x-ray unit is used exclusively for one special technique may the filter be chosen specifically for that purpose. In mammography, for example, where soft radiation is specifically required, an aluminium filter 3 mm thick is inappropriate, but the thickness should not in any case be reduced to less than 0.5 mm. The

Table 12.1 Diagnostic x-ray equipment requirements for tube housing and assembly, and beam filtration† (NRPB 1983).

X-ray tube housing and assembly

(i) It is essential that the protective housing of a diagnostic x-ray tube is so constructed that, for every rating specified by the manufacturer for the tube in that housing, the leakage radiation at a focal distance of 1 m does not exceed 100 mR (equivalent to a free air kerma of 0.87 mGy) in one hour. In assessing compliance with this requirement it is adequate for measurements to be averaged over an area up to but not exceeding 100 cm².

(ii) It is essential that every x-ray tube assembly is marked to identify the nominal focal spot position.

Beam filtration

(i) It is essential that the inherent filtration of every x-ray tube assembly is permanently and clearly marked on the housing.

(ii) It is essential that every added filter is permanently and clearly marked with its filtration in mm Al equivalent.

(iii) There should be appropriate filtration of the x-ray beam, having regard to the requirement of the work. The filtration will include the inherent filtration of the x-ray tube assembly, added filters and filtration afforded by objects permanently intercepting the beam, e.g. the mirror of a light beam diaphragm or (in the case of undercouch tubes) the couch top. For normal diagnostic work, it is essential that the total filtration of the beam is equivalent to not less than the following:

(a) 1.5 mm of aluminium when voltages up to and including 70 kV are used;
(b) 2.0 mm of aluminium when voltages above 70 kV and up to and including 100 kV are used;

(c) 2.5 mm of aluminium when voltages above 100 kV are used.

(iv) In the case of tubes for general examinations which may be used for soft tissue procedures such as mammography, part of the filtration may be removable but it is essential that the total filtration is never less than 0.5 mm equivalent of aluminium. This is particularly important in the case of beryllium window tubes, the inherent filtration of which is equivalent to only about 0.05 mm of aluminium. If the total filtration is greater than 1.5, 2.0 or 2.5 mm (according to the voltage) the user should be able to remove the excess in order to optimise a particular examination technique.

(v) Compliance with the minimum recommended values may be checked by measuring the first (and if necessary also the second) half value layer of the x-ray beam at the particular operating conditions as an alternative to direct measurement and observation of thickness.

(vi) The x-ray beam should not be significantly attenuated between the patient and the image receptor by objects such as the couch top (in the case of overcouch tubes) or an ionisation chamber for automatic exposure control.

† These NRPB (1983) guidance notes for diagnostic x-ray equipment also consider beam size, image receptors, signals and markings, exposure factors, exposure switches, control of exposure duration, exposure measurement and protection against scattered radiation. In addition, there is a separate section devoted to dental radiography.

only other exception is a dental x-ray unit used exclusively for intra-oral radiography, when the total filtration may be fixed at 2 mm of aluminium.

Their recommendation of 3 mm of aluminium for general work is in excess of that given in table 12.1 by NRPB (1983) and can be regarded as having an added safety factor.

Kean and Tikhonov (1975) also provide useful advice on the rating of an x-ray tube, generator and power supplies and on tube head protection (i.e. tube housing) and collimation.

Rating of x-ray tube, generator, and power supplies

Although the x-ray equipment should be chosen with the medical purpose primarily in mind, one must also take account of the local power supplies. Ideally, electric power for an x-ray unit should be separate from that for other power equipment such as lifts, radio-therapy machines, and other x-ray units. Failure to allow for this can result in many retakes owing to a drop in mains voltage just at the instant of exposure. Where power supplies are particularly unreliable and it would be prohibitively costly to improve them, some thought should be given to the use of battery-operated or condenser discharge equipment, which gives relative immunity from power supply variations for short periods.

Wherever possible the power supply should be adjusted to suit the maximum possible load of the x-ray generator. It is unwise to install an x-ray tube head of lower rating than that of the generator since there is the danger that a tube of higher rating may be subsequently fitted as replacement without attention being paid to the increased radiation protection required. The maximum rating envisaged for the equipment on installation should be taken as the basis for all radiation protective measures.

Tube head protection and collimation

Although most manufacturers now offer tube heads with protection up to ICRP standards, it is always necessary to check that the fitting of a different type of collimator from that originally designed for the tube head does not reduce the standard of protection. One should ensure that there is at least a diaphragm very close to the tube window with an aperture designed to restrict the beam area to the maximum required by the subsequent diaphragms. A poor diaphragm will permit the emission of off-focus radiation, which not only produces poor image quality but also causes some radiation outside the confines of the direct beam. Occasionally, insufficient protection is provided around the diaphragm box itself. This will be revealed by the radiation survey, but

if the survey expert is readily available it may be worth while seeking his advice before choosing the equipment.

A practical point that is often overlooked is the level of lighting in which the equipment is to be used. For example, when the sun is shining into the room light beam diaphragms often fail to give a satisfactory indication of the field on the patient. A possible alternative to the light beam under these circumstances is a viewfinder device for beam alignment in which a picture of the patient is seen reflected through the diaphragms. With such devices the field of view must be adequate for the part being radiographed to be recognised. For most purposes rectangular diaphragms are to be preferred, but other types may be more suitable in dentistry and angiography, when radiographs are taken during fluoroscopy, and where compression is required for special shapes (e.g. mammography).

In all such cases, where cones are used, the shape of the cone should conform closely to the shape of the beam so that the operator can judge whether the beam will lie within the confines of the film.

Ward mobile machines with intensifiers for fluoroscopy require a spacer cone of adequate length to ensure that the focus-skin distance is not less than 30 cm under any circumstances, otherwise the skin dose becomes excessive.

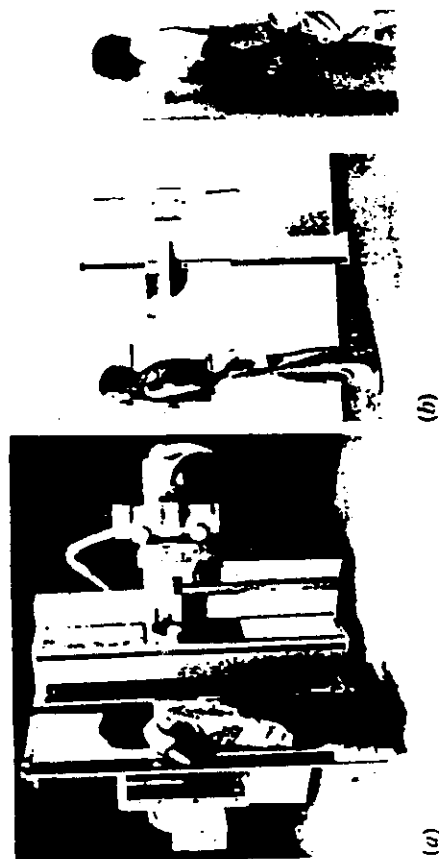


Figure 12.6 (a) Chest radiography using the Philips Diagnost 92 x-ray unit. (Courtesy: Philips Medical Systems.) (b) A Basic Radiographic System (BRS) designed to meet the needs of developing countries as specified by the World Health Organisation. In the illustration shown, a chest radiograph is being taken and the patient is shown wearing a lead rubber apron gonad shield. The radiographer is standing behind a protective screen which contains a lead glass viewing window. (Courtesy: Siemens AG.)

As examples of the typical conventional x-ray apparatus (not CT scanners or digital x-ray units) figure 12.6 illustrates chest radiography, figure 12.7, a fluoroscopy (screening) of the gastro-intestinal tract, and figure 12.8 a mobile x-ray unit.

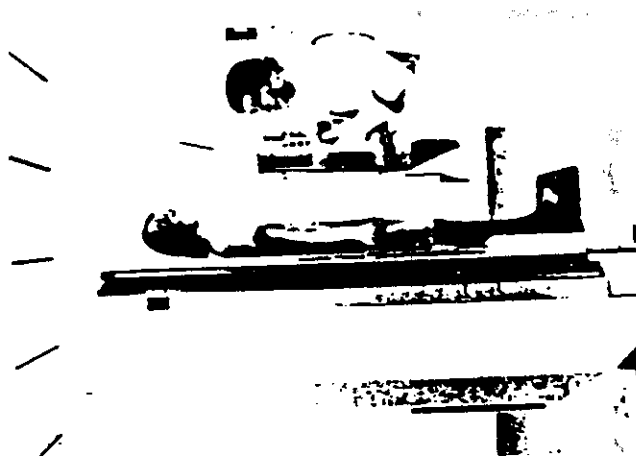


Figure 12.7 Siemens Sireskop 4 Tiltng tables are used for most general radiography purposes. The image intensifier is placed above the table and the x-ray tube below. The equipment and patient positioning for a barium meal examination of the gastro-intestinal tract using a Siemens Sireskop 4 in the fluoroscopic mode is shown here. Note the lead rubber apron strips and the radiographer's lead rubber gloves and lead rubber apron. (Courtesy: Siemens AG.)

X-ray tomography has been in existence for a number of years and its aim is to blur out overlying and underlying structures, hence keeping a selected plane of the body in sharp focus. In this technique the x-ray tube and film are moved about an axis of interest. The tomographic image in the anterior-posterior view can, for example, be of use in showing the kidneys, particularly the renal outlines and renal parenchyma, when there are overlying bowel shadows. Tomography may also be useful in chest radiography to demonstrate more clearly an indefinite pulmonary lesion or an abnormal shadow seen on a routine projection.

Computed tomography (CT) is very different from conventional x-ray tomography both in the equipment and in the radiographic images which are



Figure 12.8 The CGR Medical Supra 125 mobile x-ray unit. (Courtesy: CGR Medical Ltd.)

usually transverse cross-sections of the body (figure 12.9). The CT scanner (figure 12.10) uses a very narrow beam of x-rays entering the patient at different angles around the plane of interest. Reconstruction of the transverse image is undertaken by computer using complex mathematical techniques. A radiation dosimetry survey of CT systems from ten manufacturers (Shope *et al* 1982) reported that the range of single scan doses (maximum dose in the profile) ranged from less than 5 mGy (0.5 rad) to almost 100 mGy (10 rad) for a single scan. However, the survey contained several early designs of CT scanner and the current models can be expected to give doses of a few tens of mGy rather than approach 100 mGy.

The digital subtraction angiographic system (DSA) is the most recent innovation in hospital x-ray equipment and has applications in the imaging of blood vessels. As blood in the vascular system has very much the same density as background tissue, straightforward x-ray imaging will not reveal these structures. Contrast media containing iodine needs to be introduced into the vessel and some means are necessary to subtract the underlying structures from the image. Until recently the only method available has been film subtraction, in which an x-ray prior to the introduction of contrast media into the vessel is taken (the mask) and a series of films subsequent to the introduction of the contrast media are taken (the contrast). When the earlier image is subtracted from the later ones, structures which are constant

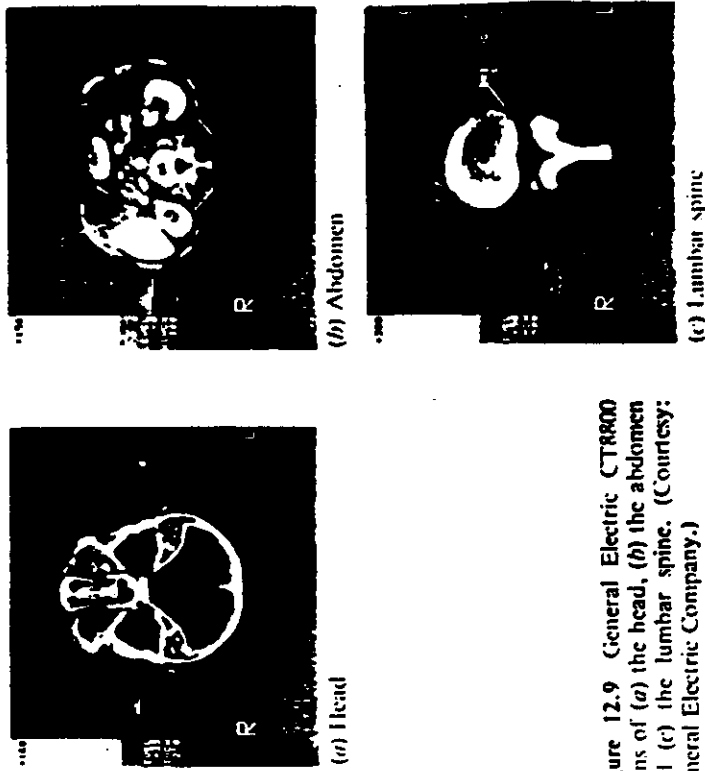


Figure 12.9 General Electric CT8800 scans of (a) the head, (b) the abdomen and (c) the lumbar spine. (Courtesy: General Electric Company.)

in both films can be removed, leaving the difference, which is the contrast media, in the blood vessels. As film has poor contrast sensitivity, contrast media is normally introduced directly into the artery under investigation and this can be a very invasive procedure. DSA systems use image intensifiers and

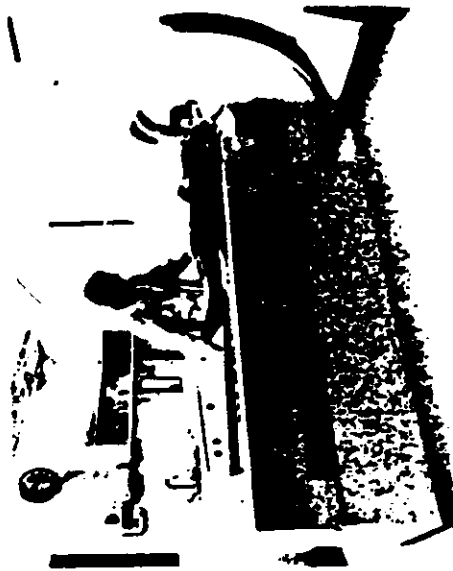


Figure 12.10 The General Electric CT8800 computed tomography system. (Courtesy: General Electric Company.)

high quality television cameras interfaced to a computer system to store a series of images electronically on a magnetic medium (figure 12.11). Frames acquired pre- and post-introduction of contrast media may be electronically subtracted in real time, thus achieving a very rapid subtraction technique. With digital systems, contrast resolution is very much better and images may be produced with less contrast media in the vessel under investigation (figure 12.12). This may permit an intravenous injection rather than an arterial one, and this reduces the procedural complexity. Hence less screening is required, resulting in a smaller radiation dose to the patient and the radiologist (Pavlicek *et al* 1982). These authors compared doses in conventional

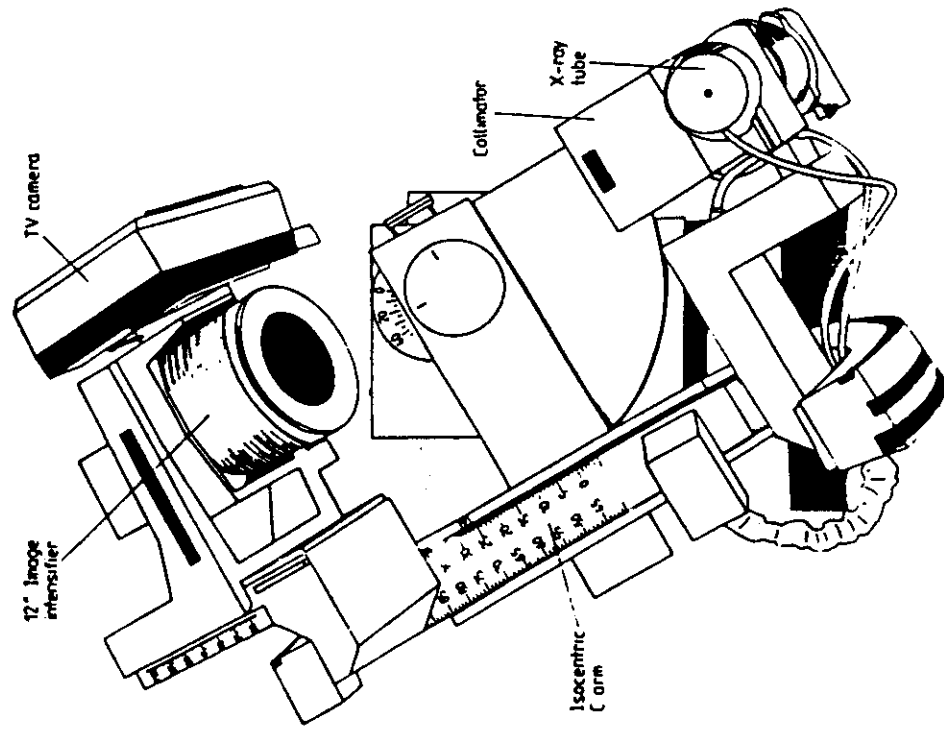


Figure 12.11 The Technicare DR960 digital angiographic system. The patient table would lie approximately halfway between the image intensifier and the collimator. (Courtesy: Technicare Ltd.)

film-screen angiography and DSA in 97 patients investigated for carotid disease. Their results indicated a twentyfold reduction in the radiation dose to bone marrow and lens of the eye and a tenfold reduction in thyroid dose with DSA. The physical basis for this reduction was the smaller x-ray field size required in DSA as well as the previously mentioned reduction in screening requirements.

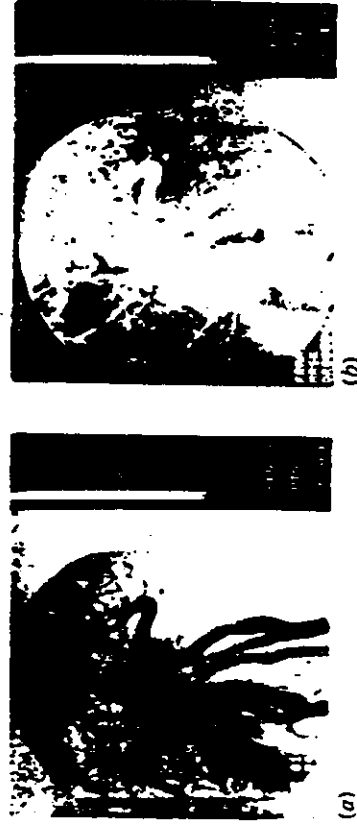


Figure 12.12 Digital subtraction images of carotid arteries, showing stenosis of the left internal carotid after an intravenous injection to the superior vena cava. (a) is the Contrast-Mask image and (b) is the Mask-Contrast image. (Courtesy: Technicare Imaging Ltd.)

12.3 X-RAY ROOMS

Since the maximum energy of a diagnostic x-ray unit is 150 keV, the protection features incorporated into an x-ray room are far less elaborate than in a deep or megavoltage x-ray therapy room (see §7.3). Some of the requirements have already been mentioned in earlier chapters, as have protective clothing for radiologists and radiographers (see figures 5.5, 5.6) and technical data on shielding. For example:

Tenth value thicknesses for various materials: table 3.3

Lead equivalence of various materials for 100 keV x-rays: figure 5.1

Lead equivalence of barium gypsum plaster: table 5.1

Lead equivalence of barium concrete, steel and brass: table 5.2

Transmission of x-rays (50–200 keV) through lead: figure 5.3

Wherever possible, diagnostic x-ray examinations are carried out in rooms designed specifically for that purpose. Sometimes, though, it is necessary to undertake the studies elsewhere using mobile equipment (see figure 12.8). In this case, radiation protection procedures need to be considered for each individual situation. As an example, the examination could be in a ward or an operating theatre while the patient is undergoing treatment with radioactive gold grains.

Lead is widely used for shielding at diagnostic energies because of its high atomic number ($Z = 82$) and thus a greatly increased probability of absorption by the photoelectric effect (table 3.1 and figure 3.1). Thus *weight for weight*, high atomic number materials are far more efficient absorbers than their low or medium atomic number counterparts. This is also true for deep x-ray therapy energies (see §7.3), but the cost and bulk of lead required sometimes prohibits its use and barium concrete is used as an alternative for the therapy rooms.

Protection of rooms must be designed to keep all doses to the staff and patients as low as reasonably achievable (the ALARA principle, which due to financial restrictions in practice often becomes the ALARP principle, as *low as reasonably practicable*). Also, it is necessary to ensure that no persons outside the room can receive a higher dose than that allowed by national regulations for members of the general public. Thus use made of adjacent rooms must be considered and adequate protection must be afforded to people working above and below an x-ray room. Structural walls may be constructed of a double layer of brick or concrete. This can in itself provide adequate shielding for some diagnostic x-ray energies (see figure 5.1 and table 12.2). Partition walls, though, probably will require additional protection. If the structure of the existing wall is unknown, then it is possible to measure experimentally the lead equivalence, such as with a calibrated americium-241 source (gamma ray energies in the range 26 keV–125 keV, half-life = 433 years) and a detector. Extra shielding, if necessary, can be added in the form of lead-ply (table 12.3), or barium plaster (see table 5.1). In the case of lead-ply panels, the joints are important and advice given by NCRP (1976) includes the following:

The joints between lead sheets should be constructed so that their surfaces are in contact and with an overlap of not less than 1 cm or twice the thickness of the sheet, whichever is greater. Welded or burned lead seams are satisfactory if the lead equivalence of the seams is not less than that required of the barrier.

The doors of diagnostic x-ray rooms should be lead lined with no radiation leakage around the edges. This can be avoided by lead-lined rebates or lead baffles where appropriate, depending on whether the door design is hinged or sliding. Consideration must also be given to windows and the areas which may be occupied beyond the windows. Radiographers often try their best to retain at least some natural light in an x-ray room wherever possible. This is very understandable but cannot be accepted if it contravenes protection regulations. An expensive solution is to install lead glass windows, but a more practical solution may be to limit the possible movement of the x-ray unit head and hence the radiation beam, if this is not going to interfere with the x-ray examinations.

Table 12.2 Lead equivalence of various materials for narrow beam x-rays. All data are for evaluating potential generators (use only as a guide for broad beams). Data taken from Table of BS 4094: Part 2: 1971 and are reproduced by permission of the British Standards Institution. In addition to the data in this table, BS 4094 also gives data for steel of density 7.9 g cm⁻³ and yellow brass (65% Cu, 35% Zn) of density 8.3 g cm⁻³.

Material	Mean density (g cm ⁻³)	Material thickness (mm)	Lead equivalent (mm) at applied kilovoltages
			50 75 100 125 150 200 250 300 400
Brick, yellow stock	1.6	100	114 4½ 0.7 0.9 1.0 0.9 0.9 1.2 1.3 1.3
Barium plaster or concrete	3.2	200	12.7 ½ 1.2 1.8 2.2 1.2 0.9 0.8 0.8 0.8
Portland cement base composition by volume			19.1 ¼ 1.9 1.2 1.2 1.3 1.3 1.3 1.3
parts coarse BaSO ₄			25.4 1 2.3 3.3 4.1 2.3 1.8 1.7 1.9 2.2
parts fine BaSO ₄			38.1 1½ 3.1 2.5 2.7 2.8 3.1 2.5 2.7 2.8 3.1
part cement			50.8 2 4.3 3.4 3.7 4.0 4.3 3.4 3.7 4.0 4.3
part coarse BaSO ₄			76.2 3 5.9 5.1 5.8 6.3 7.7 6.9 7.9 8.6 9.9
part fine BaSO ₄			102 4 6.9 7.9 8.6 9.9 10.3 13 16
part cement			127 5 152 6
Barium plaster	2.0	128	12.7 ½ 0.38 1.08 1.60 1.18 0.90 0.70
concrete base (British composition 1 lb)			19.1 ¼ 2.40 1.65 1.20 0.93 3.15 2.15 1.55 1.15
linker concrete	1.2	75	102 4 0.7 0.6 1.1 1.0 1.4 1.4 2.3 2.3 6.0 9.1
			152 6 1.6 1.4 2.1 1.9 3.3 3.0 4.1
			203 8 3.8 1.5 3.8 3.0 4.1
			254 10 4.1 3.3 4.1
			381 15 4.1
			508 20 4.1

Radiation warning signs are important and one should be displayed on each door to discourage the entry of non-essential persons (figure 12.13). The doors should always be closed during exposure and an illuminated sign such as a red light automatically switched on and displayed in a prominent position outside to signify when the x-rays are on.

(1) Image analysis equipment and the radiographer's control desk below a lead glass protective window are seen in figure 12.14. A panoramic view protective screen is shown in figure 12.15, constructed of half lead glass and half lead-ply. Several lead rubber aprons are seen on the left and two lead protected doors on the left and right. These doors each contain a radiation proof ventilation grille.

Within an x-ray room provision must be made for a protective viewing screen or cubicle between the patient and the radiographer's console (see also

Table 12.3 Protective barriers against (a) primary radiation for diagnostic x-ray installations and (b) against secondary radiation arising from fluoroscopy, without radiography. Data taken from Annex 4, Tables 1 and 2, of Keane and Tikhonov (1975). Reproduced by permission of the World Health Organisation.

(a)

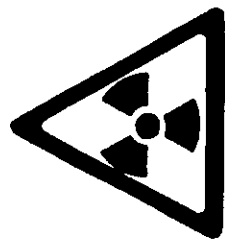
Maximum tube voltage (kV)	Distance from target (m)	Barrier thickness†	
		Lead (mm)	Concrete of density 2.35 g cm ⁻³ (mm)
100	2	1.8	150
	3	1.6	130
	5	1.2	100
125	2	2.1	170
	3	1.8	150
	5	1.3	110
150	2	2.2	190
	3	1.9	170
	5	1.4	130

†The values given in the table are suitable for a workload not exceeding 150 mA.min per week of radiography and should reduce the exposure at the stated distance to 10 mR in a week.

(b)

Maximum tube voltage (kV)	Distance from target (m)	Barrier thickness†	
		Lead (mm)	Concrete of density 2.35 g cm ⁻³ (mm)
85	1	1.2	130
	2	1.0	105
	3	0.8	85
100	1	1.35	110
	2	1.05	90
	3	0.85	70
125	1	1.4	110
	2	1.1	90
	3	0.9	70

†These values are suitable only for existing installations where the primary beam is trapped by the lead protection of the fluorescent screen or intensifier. For new installations and where radiography is possible the room shielding must be designed for primary radiation (see table (a)). This table is intended for fluoroscopy workloads not exceeding 300 mA.min/week and a maximum permissible level of 10 mR/week.



DO NOT ENTER
WHEN LIGHT IS ON

Figure 12.13 Radiation warning sign for an x-ray room door.

figure 5.4). This should have a sufficient lead equivalence to protect against scattered radiation and, if possible, for the x-ray beam to be directed towards the console, also enough protection against the primary radiation. The lead glass window should be positioned so that the door to the room is visible if anyone should enter as an exposure is about to begin. It should also, obviously, be possible to see the patient during the radiation exposure.

Protection features are different to a certain extent when the patient is being investigated by fluoroscopy (often termed *screening*) rather than by radiography. In this case the radiologist and maybe a radiographer or nurse will have to remain outside the protective viewing screen or cubicle (see figure 12.7). In addition to lead rubber aprons and gloves, added protection



Figure 12.14 (c) scanner room and radiographer's control desk. (Courtesy: Dr C Mackintosh and The London Imaging Centre.)

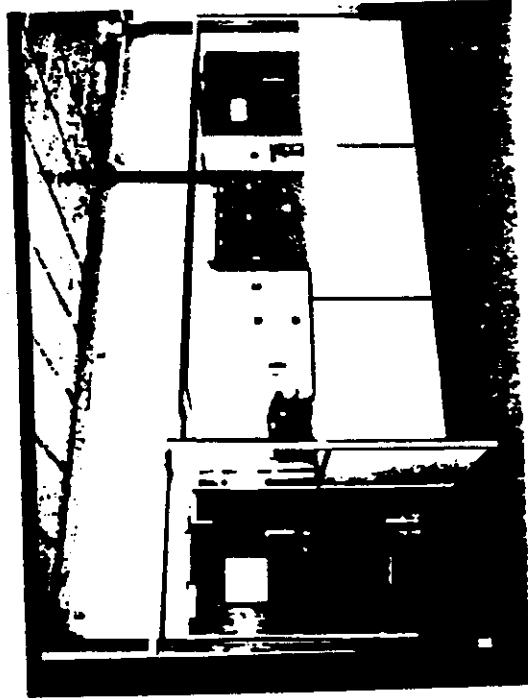


Figure 12.15 15 foot length panoramic protection screen at the Kings College Hospital X-ray Equipment Assessment Centre, London. (Courtesy: Premise Engineering Ltd.)

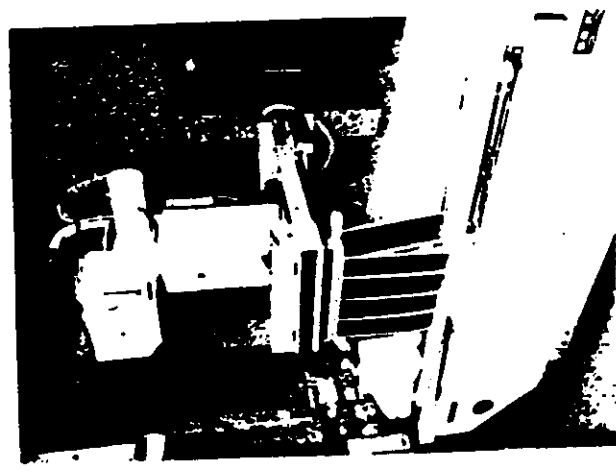


Figure 12.16 Protective lead rubber flaps in position for fluoroscopy when the tilting table is horizontal.

is provided by lead rubber flaps which are an integral part of the x-ray equipment. These flaps automatically fall into the correct position and are shown with the tilting table vertical (figure 12.7), and horizontal (figure 12.16).

As an example of recommendations on the structural aspects of a diagnostic x-ray room, table 12.4 gives data from UK draft guidance notes, NRPB (1983). As a further example, the WHO x-ray diagnosis publication (Keane & Tikhonov 1975) gives recommendations on efficient room layout as follows:

- (i) Inside the x-ray room the layout of equipment should be designed to avoid unnecessary movement around obstacles *en route* to the darkroom, to the patient, and to the protected control panel. The uninterrupted x-ray beam should not be able to fall on the darkroom wall and should not routinely point towards doors or windows. When members of the staff have to be present in the room for some particular examination it is good practice to place the protective shields near to the source of radiation rather than at a distance from it, since for the same protection a smaller shield area will then be required.

Table 12.4 Structural aspects and protection against scattered radiation for diagnostic x-rays (NRPB 1983). Adequate protection is defined by the NRPB as 'protection which is intended to ensure that doses received are as low as reasonably achievable (ALARA) and in any case do not exceed the dose limits which are appropriate for the category of person exposed'.

Structural aspects

- (i) If it is reasonably practicable and if clinical considerations permit, the work should be carried out in a room which provides appropriate shielding for all persons outside the room. This room will be referred to as an x-ray room. The approved code of practice does not define 'appropriate shielding' for a medical x-ray room but it is recommended that the shielding should be assessed or designed according to the method of Appendix 12 of ICRP publication 21. The shielding should ensure that, taking into account the maximum expected weekly workload, the dose equivalent in surrounding areas will not exceed $300 \mu\text{Sv}$ (30 mrem) in a week. This is a derived limit equivalent to three-tenths of the annual dose limit for workers and it should then be unnecessary to designate any surrounding area as a controlled area (though it may need to be a supervised area). If an individual member of the public is likely to spend any extended time in the vicinity (for example in a living room or a ward) the weekly design limit should be reduced to $100 \mu\text{Sv}$ (10 mrem) in a week. These recommendations are subject to the agreement of the radiation protection adviser whose advice should be sought at the planning stage and before a new or modified installation is used.
- (ii) In order to achieve appropriate shielding efficiently and economically, equipment should be installed in the x-ray room so that:

Table 12.4 Continued

- (a) where practicable, the useful beam can be directed away from adjacent occupied areas;
- (b) the residual useful beam and scattered radiation will be absorbed close to the x-ray image receptor (e.g. film or image intensifier) and patient. If the normal structural materials of the room do not then afford the required shielding, protective material should be applied to the floor, ceiling and walls, including windows and doors.
- (iii) To afford adequate protection to persons working in x-ray rooms the following features are essential:
- (a) all x-ray rooms to have sufficient space to provide safe accommodation for occupants;
- (b) protected areas to be provided for personnel at all control panels such that the radiation dose received there by a person not wearing protective clothing is not likely to exceed one-tenth the dose limits shown in table 6.2. Protection for such an area should normally be by means of protective cubicles or protective panels marked with their lead equivalent thickness;
- (c) where an x-ray room is used for more than one radiological procedure at a time, adequate protective measures (e.g. a protective panel separating parts of the room) to ensure that there is no significant additional exposure, either of one patient from radiography of another or of staff from examinations in which they themselves are not engaged.
- (iv) An x-ray room should not be so constructed that it is, or is likely to be, used as a thoroughway from one room or part of the establishment to another except to give access to a dark room when radiography is not in progress.
- (v) There is a general requirement to provide 'shielding appropriate to the circumstances'. This will include shielding which forms part of the x-ray equipment, shielding to attenuate the residual useful beam and protective panels which provide shielding against scattered radiation but not protective clothing, listed in the last part of table 12.3.
- (vi) In hospitals all x-ray examinations, except possibly mass miniature radiography, dental radiography and radiotherapy simulation, should preferably be carried out in a diagnostic radiological department containing one or more x-ray rooms, unless the condition of the patient makes it advisable for the examination to be carried out in a ward or in an operating theatre. This can be facilitated if entrances to radiological departments and doors of x-ray rooms are wide enough to allow beds from the wards to pass through and equipment so arranged that patients are subjected to the minimum disturbance.

Protection against scattered radiation

- (i) It is essential that all tables and stands which are used for fluoroscopy are provided with an adequate arrangement for protecting the operator and his assistants against scattered radiation from the patient and from materials between the x-ray source and the patient. When an under-couch tube is used, this may take the form of a protective 'apron' in which case it is essential that it is:
- (a) large enough; it should not be less than 45 cm wide and 45 cm long;
- (b) made of protective material having a lead equivalent of not less than 0.5 mm;
- (c) attached to the lower edge of the screen holder or intensifier support when the

Table 12.4 Continued

latter is vertical and to the operator's side of the screen holder or intensifier support when this is horizontal.

- (ii) Additional protective 'aprons' or fixed shields should be attached to both sides of the table when the screen/intensifier is horizontal and, if practicable, also to both sides of the stand when the screen/intensifier is vertical. The beam limiting device for under-couch tubes should extend as close as is possible to the back of the table or stand. When an over-couch tube is used and staff may possibly be close to the patient, the space through which the primary beam passes should be enclosed so far as is reasonably practicable. This may be achieved by a rigid canopy from which are suspended protective 'aprons'. The latter may be made of, for example, lead-loaded acrylic material which is transparent. A further protective 'apron' should be attached to the side of the table to protect the legs of a person who is close to it.

Protective clothing

- (i) Any person who is not adequately protected by the shielding referred to above must be provided with, and must wear, protective clothing. This will normally consist of suitable gloves and aprons which, however, are not designed to provide adequate protection from an unattenuated primary beam but only from primary radiation transmitted through the patient and from scatter.
- (ii) It is essential that gloves have a protective equivalent throughout both front and back (including fingers and wrist) of not less than 0.25 mm lead for x-rays excited at voltages up to 150 kV.
- (iii) It is essential that body aprons have a minimum lead equivalent of 0.25 mm for x-rays excited at voltages up to 150 kV.
- (iv) Each item of protective clothing should carry an identifying mark.
- (v) A suitable range of protective clothing should be provided in all x-ray rooms and for use with mobile and portable x-ray sets, but it is not required for mass miniature radiography in vehicles. Sizes and lead equivalent thicknesses (subject to the minimum lead equivalents specified above) and type of apron (i.e. protecting the front and sides of the body only or also the back) should be decided according to local circumstances and in conjunction with the radiation protection adviser.
- (vi) Suitable arrangements should be made for storing protective clothing when not in use. Aprons should not be folded but should be supported in a suitable manner, for example, by draping them over a rail of comparatively large diameter.
- (vii) Gloves and aprons should be examined visually at frequent intervals. They should be thoroughly examined by the radiation protection supervisor, or by a person under his supervision, at least every 14 months to ensure that the protection afforded has not been impaired as a result of cracks in the material and a signed report should be made of the examination. It may be decided to carry out a radiographic examination. Any defects in protective clothing found by the wearer must be reported immediately and examination records must be kept for two years.
- (viii) If the protective material of the gloves has a permanent cover, this cover should be bonded to the underlying material. Otherwise the gloves should have a detachable cover of nylon or similar material so that any cracks which might develop may be revealed.

(ii) When funds and facilities are severely limited there is always a temptation to install several pieces of equipment in one room. This involves particular hazards; for example, staff setting up a patient on one side of the room may be irradiated by exposures taking place on the other side. This may be prevented by having only one generator per room and by mounting warning lights on each x-ray tube head and the control panel of the generator. As soon as the rotating anode or the filament in one of the tube heads is energised, the appropriate light comes on, so that, if the wrong tube has been connected, a warning is given before the actual exposure is made. Adequate protective screens should be provided between each x-ray tube area.

(iii) For each special technique such as tomography, angiography, or plain chest fluorography, a separate room should be provided. Any x-ray room should be of adequate size for the full facilities likely to be needed (e.g. not less than $6 \times 4 \text{ m}^2$ for simple radiography at level 1). At all levels of radiological care separate record rooms, offices and waiting rooms should be provided. Physicians or radiologists reporting on films must not be in the room in which radiography is being carried out; separate viewing rooms that can be darkened should be provided. At levels 3, 4, and 5 it is desirable to have at least one patient preparation and recovery room for special procedures involving anaesthetics. As a general principle, protective screens should be provided for all the positions in which staff are required to be during exposures in the x-ray room.

Commercial suppliers of x-ray equipment will usually supply site planning guides on request and the 1979 guide for the EMI C scanner provided the following advice under the heading radiation protection:

- (i) It is the customer's responsibility to provide radiation protection, by ensuring the scanner room walls, ceiling, floor and doors are constructed of materials which meet local shielding requirements.
- (ii) The amount of protection required is expressed as 'the equivalent thickness of lead' expressed in millimetres.
- (iii) Minimum permissible protection is based on radiation scatter at one metre from the x-ray tube, requiring the equivalent thickness of 1.5 mm of lead.
- (iv) EMI will provide on request information regarding the equivalent lead protection required for the scanner room walls, ceiling, floor and doors.
- (v) The following points must be considered when determining the shielding required for a particular scanner room:

- (a) the Radiation Controlling Authority's method of specifying the level of protection required;
- (b) the size of the room in which the scanner unit is to be installed;
- (c) the frequency the scanner unit is to be used;
- (d) the purpose for which the area outside the scanner room is to be used.

(vi) Adequate radiation protection can be provided by using the following materials:

- (a) lead sheet in wooden cladding;
- (b) structural concrete;
- (c) brickwork;
- (d) brickwork plus barium plaster.

Lead sheet in wooden cladding. The wooden cladding will be required to support the lead sheet and protect the lead from accidental damage. A specialist installer will be required to overlap the butt joints of the panelled sections. The scanner room doors should have lead sheeting and it should be ensured that there is no radiation leakage around the door frames.

Structural concrete. This is erected by pouring cement into prearranged shuttering as used in the construction of steel framed buildings. Particular attention should be given to obtaining constant density throughout the mixture when set.

Brickwork. Brick walls already present may be used for protection provided they satisfy the equivalent thickness of lead required.

Brickwork plus barium plaster. Where existing brickwork does not satisfy 'the equivalent thickness of lead' required, barium plaster, of a thickness according to local regulations, can be applied to the brickwork.

Dental radiography is a special instance of diagnostic radiology with purpose built apparatus such as in figure 12.17. Recommendations for dental radiographic equipment are usually separated from those for diagnostic equipment such as in table 12.4, although those for x-ray tube housing and beam filtration are similar. However, many recommendations for beam size and distance control are very specific to dental work (table 12.5). NRPB (1983) also advise for location and installation

It is essential that the x-ray room is large enough to provide safe accommodation for those people who have to be in the room during examinations. Dental x-ray equipment operating up to 70 kV should be installed so that the person operating it can be at least 1.5 m from the x-ray tube and from the patient and well outside the useful beam. If the



Figure 12.17 (a) Positioning a Heliodont 70 Siemens dental x-ray unit preparatory to radiography. (b) Specialist dental x-ray unit, the Orthopantomograph 10, which is used to produce panoramic radiographic views as illustrated in (c). (Courtesy: Siemens AG.)

equipment operates at above 70 kV the operator should be able to stand at least 2 m away.

In addition, the answer to the following six questions (after Keane and Tikhonov 1975) will be informative when first assessing any dental radiography facility:

- Is a lead protected cone provided?
- Can the timer be reset without making an exposure?
- Is the hand-switch cable at least 2 m long?
- Is a protective apron provided for the patient?

Table 12.5 Recommendations for beam size and distance control for dental radiography equipment (NRPB 1983).

- (i) It is essential that equipment for radiography using an intra-oral film is provided with a field-defining spacer-cone which will ensure a minimum focal spot-to-skin distance of not less than 20 cm for equipment operating above 60 kV and not less than 10 cm for equipment operating at lower voltages. The cone may be a pointer cone or an open-ended cylindrical or divergent cone; the choice will depend on various considerations. It may be desirable to have two or more interchangeable cones for different radiological techniques; for example, a longer cone may sometimes be more suitable. The field diameter at the patient end of the cone should not exceed 6 cm; it is essential that it does not exceed 7.5 cm. When the same equipment is to be used with occlusal or extra-oral films, the beam size may be increased, for these films only, but should not exceed the size of the film.
- (ii) For panoramic tomography the beam size at the cassette holder should not exceed $10 \times 150 \text{ mm}^2$. The total beam area should not exceed the area of the cassette holder receiving slit by more than 20%.
- (iii) For other equipment it is essential that the maximum beam size is limited to the maximum required in practice. It is essential that equipment for cephalometry has a beam limiting device which enables the useful beam to be confined to the area of diagnostic interest and within the limits of the x-ray film selected.
- (iv) All beam limiting devices should, as far as is practicable, afford the same degree of protection as is required for the tube housing.

Are film processing facilities adequate and well maintained?
Are any local rules on display?

12.4 LOCAL RULES

Local rules are very necessary for all hospital departments, rooms, laboratories, wards and operating theatres involved with the medical applications of ionising radiation. X-ray rooms, though, are similar in many hospitals, unlike the layout of radiotherapy departments, sealed source rooms, nuclear medicine departments and dispensing laboratories (*hot labs*). It is therefore easier to formulate local rules and those suggested by Keane and Tikhonov (1975) are reproduced as the following tables:

- 12.6 x-ray room—radiography only;
- 12.7 x-ray room—radiography and fluoroscopy;
- 12.8 ward mobile radiography;
- 12.9 radiography of patients during their treatment with internal radionuclides or brachytherapy;
- 12.10 dental radiography.

These local rules are relevant not only to the staff but also to the patient.

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Table 12.6 Local rules for x-ray room—radiography only. (After Keane and Tikhonov 1975.) Reproduced by permission of the World Health Organisation.

- 1 Before making an exposure close the doors of the x-ray room.
- 2 Do not direct the x-ray beam at the windows of the room or towards the control panel or darkroom wall.
- 3 During radiography all staff must stand behind the protected control panel and may observe the patient through the lead glass window.
- 4 Gonad shields must be used on patients whenever appropriate, and the field must be adjusted to the minimum size consistent with adequate clinical diagnosis.
- 5 When films or patients require support, use *mechanical* supports whenever possible.
- 6 No patient should wait or change in the x-ray room while another patient is being radiographed.
- 7 If anyone is ever required to support a patient or film during an exposure, he must:
 - (i) wear a protective apron and gloves and avoid the direct beam by standing to one side and away from the x-ray tube,
 - (ii) record, in the notebook provided, his name, the date, the number of exposures, and the radiographic technique used.

Table 12.7 Local rules for x-ray room—radiography and fluoroscopy. (After Keane and Tikhonov 1975.) Reproduced by permission of the World Health Organisation.

- 1 Before making an exposure close the doors of the x-ray room.
- 2 Do not direct the x-ray beam at the windows of the room or towards the control panel or darkroom wall.
- 3 During radiography or fluoroscopy, all staff must *either* stand in the protective cubicle, observing through the lead glass window *or* wear protective aprons, keeping well away from the patient when not specifically required to come close. Protective gloves must be worn when handling the patient during fluoroscopy.
- 4 In conventional fluoroscopy the current must not exceed 4 mA at 100 kV. With image intensifiers the current should not exceed 1 mA at 100 kV. Examination time and field size should be kept to a minimum consistent with adequate clinical diagnosis.
- 5 Gonad shields must be used on patients whenever appropriate.
- 6 If films or patients require support, use *mechanical* supports whenever possible.
- 7 No patient should wait or change in the x-ray room while another patient is being radiographed.
- 8 If anyone is ever required to support a patient or film during an exposure, he must:
 - (i) wear a protective apron and gloves and avoid the direct beam by standing to one side and away from the x-ray tube,
 - (ii) record, in the notebook provided, his name, the date, the number of exposures, and the radiographic technique used.

Table 12.8 Local rules for ward mobile radiography†. (After Keane and Tikhonov 1975.) Reproduced by permission of the World Health Organisation.

- 1 The direct beam must not irradiate any person other than the one being radiographed.
- 2 When the radiographic exposure is being made, staff must stand as far away from the patient as possible (at least 2 m) and wear protective aprons.
- 3 Gonad shields must be used on patients whenever appropriate, and the x-ray beam size should be restricted by diaphragms or a suitable rectangular cone so as not to irradiate more of the patient than is necessary for diagnosis.
- 4 If anyone is required to support a patient or film during an exposure, he must:
 - (i) wear a protective apron and gloves and avoid the direct beam by standing to one side and away from the x-ray tube,
 - (ii) record, in the notebook provided, his name, the date, the number of exposures, and the radiographic technique used.

†One most important local rule is that the person in charge of the area where the exposure is to be carried out must be informed.

Table 12.9 Additional local rules for radiography of patients during their treatment with internal radionuclides or brachytherapy. (After Keane and Tikhonov 1975.) Reproduced by permission of the World Health Organisation.

- 1 Everything must be ready before the patient is sent for, so that the time he spends in the x-ray department is as short as possible.
- 2 Unused or unprocessed x-ray film must be kept at a distance from the patient.
- 3 The patient and the x-ray equipment must be positioned first of all, then the film cassette should be placed in position just before the exposure is made. The cassette must be removed to a safe distance (e.g. 3 m) immediately after the exposure.
- 4 Staff must stay at least 2 m from the patient except when necessary for setting up. The lead apron provides no protection against high-energy gamma rays; distance is the best safeguard.
- 5 Dressings on the patient must not be disturbed.
- 6 The patient should be sent back to the ward as soon as possible.
- 7 If any unforeseen difficulties arise (e.g. with new techniques), the radiologist should consult the radiation protection officer, who may refer the matter to the radiation protection adviser if necessary.

Table 12.10 Local rules for dental radiography. (After Keane & Tikhonov 1975.)
Reproduced by permission of the World Health Organisation.

- 1 The direct beam must not irradiate any person other than the patient being radiographed.
- 2 Whenever possible the dental film should be fixed in position, otherwise it should be held by the patient. It should never be held by the dentist or staff.
- 3 When making an exposure, the staff should stand as far away from the patient as possible to avoid the radiation that is scattered in all directions. If it is necessary to be as near as 1 m or if the workload exceeds 1800 mAs a week, a protective apron should be worn.
- 4 The patient should be protected by a protective apron (0.25 mm lead equivalent) large enough to cover the whole trunk.
- 5 The x-ray beam size should be restricted by suitable cylindrical cones to the minimum aperture appropriate to the particular examination.
- 6 Radiological examinations should not be made in the absence of clear-cut clinical indications. Extensive or repeated x-ray examinations of children or pregnant women should not be undertaken without considerable forethought.

12.5 PROTECTION OF THE PATIENT

In diagnostic radiology, radiation protection of patients must ensure that they only receive the minimum dose necessary. This involves not only quality assurance of radiographic and fluoroscopic systems (see WHO 1982b), but also the adoption of a rational approach to radiodiagnostic investigations (see WHO, Scientific Group 1983), which includes an assessment of whether an x-ray examination is justified for a given patient. For instance, the WHO Scientific Group (1983) stated:

- (i) Many x-ray examinations are made as a matter of routine, or without medical justification; these x-rays are not worthwhile.
- (ii) X-rays are of no benefit either to the asymptomatic patient, or in cases where other diagnostic methods are more efficient and cheaper.
- (iii) For physicians, the x-ray is a comforting ritual; radiologists should advise them whether it is likely to be useful.
- (iv) Over-used and misused x-rays are a major and costly source of exposure to ionising radiation.

It also made specific comments for chest, skull, obstetrics and abdomen investigations (table 12.11).

Persons with responsibilities for radiation protection of patients include: doctor requesting the x-ray examination; radiologist; doctor, other than a radiologist, who may supervise a radiological examination.

radiographer performing the radiographic examination
radiation protection supervisor (RPS)
radiation protection adviser (RPA)

and the BRPA (1980) has published useful advice to the above six groups in part 1 of its manual. Part 2 considers technical factors such as the physical characteristics, geometry and direction of the x-ray beam. ICRP publication 26 (1977) also contains relevant material on protection of the patient. For example, paragraph 206, incorporating the ten-day rule, refers to radiological examinations of women of reproductive capacity as follows:

Because of the risk of radiation injury to any embryo or foetus, the possibility of pregnancy is one of the factors to be considered in deciding whether to make a radiological examination involving the lower abdomen in a woman of reproductive capacity. Although such an examination is least likely to pose any hazard to a developing embryo if carried out during the ten day interval following the onset

Table 12.11 Commentary on justification for various diagnostic x-ray procedures. This information is taken from a WHO Scientific Group's information sheet aimed at the non-scientific press media, but nevertheless serves as a useful summary. (WHO Scientific Group 1981.)

<i>Chest</i>	Routine procedure Mass survey Admission to hospital	Chest x-rays are <i>not recommended</i> as a routine procedure in asymptomatic individuals. In unselected populations, mass radiography should be abandoned. Serves <i>no useful purpose</i> , especially for patients under 40, in areas with low prevalence of chest disease. <i>Unjustified</i> unless high local incidence of chest disease. <i>No indication</i> in absence of clinical evidence of chest disease.
	Pregnant women Prior to operation	
<i>Skull</i>	Minor head injury	<i>Not recommended</i> for sober adults in absence of clinical signs of fracture; but patient must be carefully watched. In children under 10, depends on clinical status.
<i>Obstetrics</i>	Pregnant women	<i>Only</i> in presence of very specific clinical indications. No routine use.
<i>Abdomen</i>	Intravenous urography	<i>Of no benefit as routine procedure in</i> —hypertension without evidence of renal disease —obstruction of the urinary tract by prostatic or urethral strictures —in gynaecology, hernia, infertility or child enuresis

of menstruation, attention should always be paid to details of radiological technique that would ensure minimisation of exposure to any embryo or foetus that may be present, whether or not the woman is known to be pregnant.

The most important investigations which would affect the radiation dose to the uterus (BRPA 1980) are: barium meal and enema, intravenous urography, cystography, cholecystography, lumbar spine, pelvis, hips, abdominal angiography, myelography and utero-salpingography. BRPA (1980) also state that the ten-day rule may be disregarded in the following situations:

- medical urgency;
- sterilisation of the husband or wife;
- adequate contraception;
- menstruation;
- denial of recent intercourse.

Table 12.12 Parameters to be checked on radiographic equipment. After WHO (1982b). Reproduced by permission of the World Health Organisation.
Key: A = essential; B = necessary for good practice; C = important; P = physicist or engineer; R = radiographer or technician. A = annually; S = semiannually; W = weekly; D = daily (or more frequently, as necessary).

Recom- mended priority	Item	Personnel category	Testing required			
			On installation	After repair	As necessary	W D
A	Tube potential (kV _p)	P/R	X	X	X	
A	Automatic exposure system	P	X	X	X	
A	Filtration	P	X	X		
A	Removable filters	R	X	X	X	X
A	Light localiser	P/R	X	X	X	
A	Grids	R	X	X	X	
A	Mechanical stability	R	X			
B	Radiation output	P/R	X	X	X	X
B	Timer	P/R	X	X	X	
B	Controls	P/R	X			
C	Meter zero	R				X
C	Touch top					
B	absorption	P	X	X		
B	Area exposure	P	X	X		
B	Focal spot size	P	X	X		

In addition there is now some discussion as to whether the 'ten-day rule' is actually appropriate and whether perhaps a new rule should be introduced (Detain 1984).

Table 12.13 Parameters to be checked on fluoroscopic equipment. After WHO (1982b). See table 12.12 for key. Reproduced by permission of the World Health Organisation.

Recom- mended priority	Item	Personnel category	Testing required			
			On installation	After repair	As necessary	A W
A	Tube and generator	P/R	X	X	X	X X
A	Automatic exposure rate control	P/R	X	X	X	X X
A	Field size and distortion	P	X	X	X	X
A	Beam collimation and alignment	P	X	X	X	X
B	Conversion factor	P	X	X		
B	Contrast ratio	P	X	X	X	
A	Grey scale test object	P	X	X	X	X
A	Limiting resolution	P/R	X	X	X	X X
A	Threshold contrast	P/R	X	X	X	X X
A	Minimum visible detail versus contrast	P	X	X	X	X

Quality assurance of equipment is of the utmost importance and involves checking parameters upon installation, after repair, routinely or as a result of reject analysis raising doubts about equipment performance. Tables 12.12 to 12.16 reproduce the WHO (1982) quality assurance recommendations for five categories of x-ray equipment:

- 12.12 radiographic;
- 12.13 fluoroscopic;
- 12.14 mammographic;
- 12.15 computer tomography;
- 12.16 dental.

In addition, WHO (1982b) also gives quality assurance recommendations for:

radiographic image recording and processing equipment;
conventional tomography;
Cineradiographic equipment.

Table 12.14 Parameters to be checked on mammographic equipment. After WHO (1982b). See table 12.12 for key. Reproduced by permission of the World Health Organisation.

Recom- mended priority	Item	Personnel category	Testing required		
			On installation	After repair	As necessary
A	Tube potential (kV _p)	P/R	X	X	X
A	Half-value layer (HVL)	P/R	X	X	X
A	Safelights	R	X	X	X
A	Screens	R	X	X	X
A	Film/screen contact	R	X	X	X
A	Plates (dark dusting)	R	X	X	X

Table 12.15 Parameters to be checked on computer tomography equipment. After WHO (1982b). See table 12.12 for key. Reproduced by permission of the World Health Organisation.

Recom- mended priority	Item	Personnel category	Testing required		
			On installation	After repair	As necessary
A	Precision	P/R	X	X	X
A	Uniformity	P/R	X	X	X
A	Accuracy	P/R	X	X	X
A	Contrast	P/R	X	X	X
A	Sensitivity	P	X	X	X
A	Spatial resolution	P	X	X	X
A	Artefacts	P/R	X	X	X
B	Patient exposure	P	X	X	X

Table 12.16 Parameters to be checked on dental x-ray equipment. After WHO (1982b). See table 12.12 for key. Reproduced by permission of the World Health Organisation.

Recom- mended priority	Item	Personnel category	Testing required		
			On installation	After repair	As necessary
A	Tube head stability	R	X	X	X
A	Beam alignment	R	X	X	X
A	Technique factor	P	X	X	X
A	Exposure reproduc- ibility	P	X	X	X
A	HVL†	P	X	X	X
A	ES†	P/R	X	X	X

†ES† = patient entrance skin exposure; HVL = half value layer.

In conclusion to this section on patient protection, a series of miscellaneous comments are listed in no special order of priority or importance.

One of the factors which determines the radiation dose received by the patient is the size and energy of the x-ray beam. The higher the energy the more penetrating the x-rays and consequently the lower the dose which is received by the patient. The highest keV that will give adequate image contrast should therefore be used. It can also be beneficial from time to time to reconsider what contrast is actually required for different techniques. In recent years, for example, more radiologists are finding that the flatter radiographs of chests taken at 120–140 keV provide more useful information than the traditional techniques at about 80 keV.

Different materials for tube targets and filters have been re-examined so that use can be made of the characteristic target radiation and the filter's absorption edges to produce the optimum spectrum. An example is the use of molybdenum for the x-ray tube targets used in mammography (figure 12.18). Low energy radiation is required for mammography to produce the required contrast between tissues with very similar atomic numbers. The characteristic K-radiation from molybdenum (atomic number = 42) has energies in the range 17.9–19.5 keV, which is most appropriate for mammography. The characteristic K-radiation from tungsten (atomic number = 74) is in the range 57.9–69.1 keV. The modern mammographic

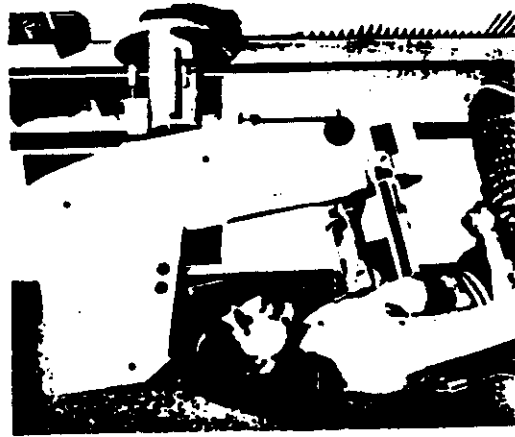


Figure 12.18 Radiographic equipment designed for use in mammography. The Mammomat B unit. (Courtesy: Siemens AG.)

x-ray tubes also have beryllium (atomic number ≈ 4) exit windows to ensure transmission of a high proportion of low energy x-rays.

The radiation dose is proportional to the beam size and hence this must be kept to a minimum. To assist in reducing the x-ray beam area to this minimum, it is essential that the light beam diaphragm is correctly aligned. This should be regularly checked. In all events, though, the beam should not have a dimension larger than the detector since any part of the beam which does not impinge on the detector does not provide any useful information. Films should, therefore, always have a clear frame around the edge of the image.

The radiation exposure required to produce an image depends on the sensitivity of the detector. The patient dose is therefore related to this sensitivity and is also dependent on the presence of any absorber in the x-ray beam path between the patient beam exit area and the detector. The film-screen combination is thus important in radiography, and the image intensifier in fluoroscopy. Intensifying screens have a thin phosphor layer (in the past, this has usually been calcium tungstate) front and back. These convert some of the x-rays to visible light wavelengths to which the film is particularly sensitive. The increase in sensitivity using calcium tungstate phosphor is limited by the effective thickness of the phosphor which produces acceptable resolution and also the thickness of phosphor through which visible light is able to travel. Larger crystals of phosphor transmit

more light in all directions so that light released at a depth in the phosphor will produce a relatively poorly resolved patch on the film. Finer resolution is obtained using smaller crystals and introducing dyes which absorb and scatter the visible light so that only a thin surface layer of phosphor is effectively used. Higher resolution is achieved at the expense of lower speed or sensitivity. Rare earth screens are several times faster than calcium tungstate ones although their image quality may be limited by quantum mottle caused by too few x-ray photons producing the image. Radiographic practice must therefore decide on an optimum balance between lower film quality but reduced patient dose for fast film screen combinations and better image quality but a higher patient dose for the finer detail film and screens. This can, for example, be to use the fine screens for extremities, such as from elbow to fingers and ankles and feet, and rare earth screens for other examinations. However, it should not be forgotten that there are exceptions, such as the use of non-screen film (which has a high silver content and is consequently more expensive than other films) which gives a high inherent contrast and is therefore good for soft tissue imaging. Radiography is no longer recommended as a tool for metallic foreign body location while alternative techniques are available. However, a practical point to remember if x-rays are used is that dirt on the screens prevents light from reaching the film and hence can simulate foreign bodies in skin, e.g. glass, wood, metal. With non-screen films in foreign body location work for areas such as the orbits, the dose to the patient may be too high to be acceptable.

Absorbers which attenuate the x-ray beam between the patient and the detector include the patient table or bed, grids used to remove the scatter and the cassette front. Different materials have been used for table tops and cassette front covers and the best in terms of physical strength and x-ray transmission properties are carbon fibre materials (Schmidt *et al* 1983).

Grids are designed to absorb a large proportion of the unwanted scattered radiation but they also absorb about half the primary beam. Hence care should be taken to ensure that grids are not used unnecessarily. As an example, grids may not be required when screening young children since they produce a smaller amount of scatter. They may also not be needed in pelvimetry where only a skeletal outline is required (Russell *et al* 1980). Air gaps may be used as an alternative to a grid in some techniques and consequently this practice will result in a dose reduction to the patient. When focused grids are used, care must be taken that the grid is properly aligned otherwise a larger proportion of the primary beam will be absorbed by the grid than is necessary. Since grids are used to reduce the amount of scatter reaching the film they are of most use during radiography of large or thick areas such as abdomens, skulls, spines and, in the case of obese patients, chests. For post-operative orthopaedic examinations, the grid is sometimes

removed and a tin filter is inserted. This reduces the dose to the patient but results in a poorer film quality. However, this is acceptable in this instance since the aim is usually only to check the position of joints and metalwork such as artificial hips.

Shielding is most commonly used for protecting gonads, although leaded spectacles may occasionally be used for shielding the eyes. Gonad shielding is important for women below the age of 50 and in all men, and should always be used unless it is likely to reduce the diagnostic information. However, gonad shields are difficult to position accurately for women and although the shielding is effective for the primary beam it is of little use for scattered radiation. In figure 12.19 the mean gonadal doses are shown for various examinations of men and women. These are the results of a survey in the United Kingdom by the NRPB (Wall *et al* 1980).

Reject analysis is an important method of monitoring the major reasons for spoil films and hence trying to reduce repeat radiographs in the future. Reasons for spoil films include: exposure, film processor and equipment faults, failure to adequately cover the region of interest, and patient movement. Before discarding the spoil films their source (e.g. x-ray room) and radiographer should be written on them. Any changes in trend in a reject analysis can be revealing. For example, an increase in exposure faults for one particular x-ray room means that the x-ray equipment requires checking for performance, but if the errors are due to patient positioning—then the staff require further training!

Equally important with spoil films are the excessive times sometimes used in screening examinations. Large variations in patient dose occur from hospital to hospital with these examinations and it can be instructive to attach a flat ionisation chamber to the x-ray tube collimator assembly, the diaphragms, to register the product of exposure and beam area. The total radiation energy absorbed by the patient can be calculated from this.

The terms *radiation protection supervisor* (RPS) and *radiation protection adviser* (RPA) have been mentioned earlier in relation to the BRPA (1980) manual of good practice in diagnostic radiology. The duties of the RPS, the relationship of the RPS to the RPA and the general responsibilities of the RPA are reproduced below from the BRPA (1980) manual. Although they refer to the UK, similar supervisory and advisory roles are of course necessary in other countries and the BRPA (1980) data provides useful guidelines.

Duties of the Radiation Protection Supervisor (RPS)

- (i) The RPS is the officer who carries out, or directly supervises the carrying out of, such radiation protection duties in her department as

The gonadal doses from 13 types of diagnostic examination have been measured at 21 hospitals throughout the country in preparation for a new assessment of the genetically significant dose to the population of Great Britain from diagnostic radiology. Thermoluminescent dosimeters, consisting of lithium borate powder contained in adhesive polythene sachets, were used for the measurements. They were attached to patients to monitor the testes dose directly or the entrance skin dose at the level of the ovaries. Skin doses were converted to ovarian doses using factors obtained by measurements in an anthropomorphic phantom exposed to a range of typical diagnostic x-ray fields.

The results indicate that for some types of examination there has been an increase and for others there has been a reduction in the mean gonadal dose delivered per examination since a similar survey was made 20 years ago. Individual gonadal doses for the same examination still ranged over three or four orders of magnitude throughout the country with distributions described by coefficients of variation that were no less than those found in the late 1950s. This large variability in patient exposure, together with the observation that examinations were satisfactorily conducted on children with a much higher degree of gonadal protection than that offered to young adults, indicates that many patients must be receiving doses that are unnecessarily high.

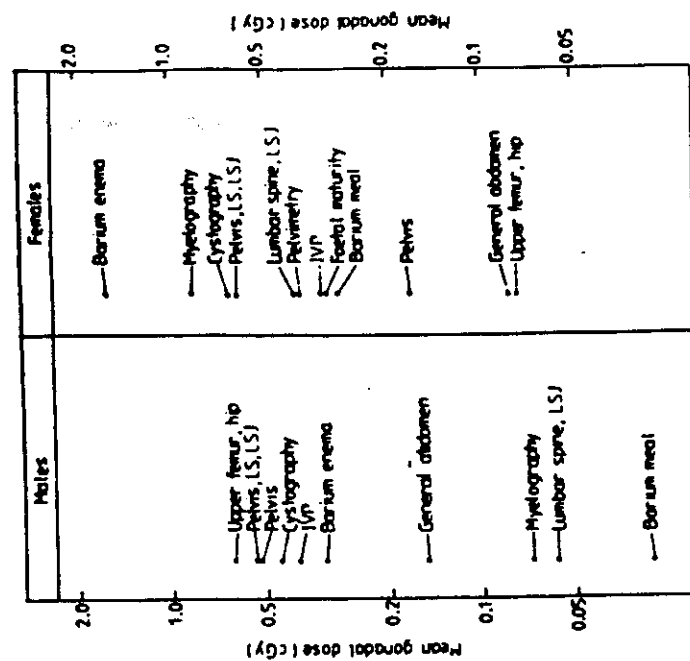


Figure 12.19 Mean gonadal doses for all examination types (except chest x-rays) included in the NRPB survey (1 cGy = 1 rad). The abstract given above to the report by Wall *et al* (1980) describes the survey. L.S. = lumbar spine; L.S.J. = lumbar sacral joint; IVP = intravenous pyelogram.

may be delegated to her. The RPS is usually a full-time radiographer who is engaged part-time on protection duties.

(ii) The RPS must make herself familiar with the more detailed requirements of regulations and supporting advisory literature relating to radiation protection in the work of the x-ray department. She should establish herself as the departmental focal point for information on radiation protection matters.

(iii) One of the main duties of the RPS is to ensure that a departmental radiation safety regime, established in conjunction with the RPA in agreement with the radiologists and departmental seniors, is effectively implemented. Although many of the requirements of such a regime will be concerned with protection of staff, radiation safety measures for the protection of patients should have high priority in the regime.

(iv) To be effective, such a safety regime requires acceptance by all departmental staff, and it is important, therefore, for the RPS to gain the willing co-operation of staff members in the observance of radiation protection measures.

(v) The main requirements of the departmental radiation safety regime must be incorporated in 'local rules' of good safety practice, copies of which must be made available to all members of staff of the department.

(vi) The RPS must be consulted when changes in the department are proposed which impinge on radiation protection requirements, and especially those affecting the safety of the patient. The RPS should herself recommend changes in procedures where such changes have been shown to be necessary for the improvement of radiation protection in the x-ray department.

Relationship of the RPS with the Radiation Protection Adviser (RPA)

(i) It is important that the RPS should establish a close working relationship with the RPA so that each may contribute their own special knowledge to the solution of radiation protection problems in the x-ray department.

(ii) In collaboration with the RPA and the Head of the department, the RPS must investigate and report on such radiation accidents and incidents as any of these officers feels appropriate or statutory regulations demand.

General responsibilities of the Radiation Protection Adviser (RPA)

(i) The RPA is responsible for giving general advice on the radiation safety of installations, equipment and procedures used in the diagnosis and treatment of patients. There will normally be a Radiation Safety Committee to which he reports.

(ii) In diagnostic radiology the RPA is not usually involved directly with the radiation protection of individual patients, although he must be available to advise on problems of protection in particular cases brought to his attention, or which appear to him to require his attention. Nevertheless, he is indirectly involved with the safety of patients in many aspects of his work.

(iii) The RPA is responsible for the prior examination of plans for new or modified installations or equipment, and for advising on their radiation safety. Before acceptance, the RPA in conjunction with the RPS is responsible for checking that the installations or equipment conform with accepted standards of radiation protection.

(iv) These duties of the RPA have an important bearing on the radiation protection of patients, since badly designed and radiologically unsafe installations and equipment usually lead to unsatisfactory work and additional irradiation of the patient, in particular from unnecessary repeat films.

Some duties of the RPA in the x-ray department

(i) The RPA, or his deputy, should make regular visits to premises where diagnostic radiology is undertaken, for discussions with the RPS, radiologists and other relevant members of staff, on all aspects of radiation protection, including protection of the patient. Where necessary, improved protective measures should be recommended.

(ii) The RPA, in conjunction with the departmental RPS, must examine and review new operational procedures, including techniques for the examination of patients, and advise on their radiation safety.

(iii) The RPA must also advise on the interpretation and significance of radiation exposures of patients and, where necessary, must initiate dose measurements, including measurements on patients in conjunction with the RPS and with the agreement of the radiologist concerned, in order to determine the radiation doses received by parts or organs of the patient's body or the dose to a fetus.

(iv) When a research project involving patients is under consideration the RPA should estimate the radiation doses likely to be received by each patient, or by single organs of the patient's body as appropriate, so that the research category may be established prior to an application for approval of the project being made to the appropriate Ethics Committee.

(v) The RPA is responsible for investigating, where appropriate, in conjunction with the departmental RPS, incidents involving inadvertent radiation doses to patients, and for making recommendations for the avoidance of such incidents in the future.

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PREFACE

The preparation of this manual came about in response to the USNRC report entitled *Radiation Protection Training For Personnel Employed in Medical Facilities* (NUREG-1134, U.S. Nuclear Regulatory Commission, May, 1985). It is a recognized fact that there exists a need to provide radiation protection training on a regular basis to those medical facility personnel who may, on occasion, in performing their duties come into contact with medical radiation sources. Of all the medical care personnel not specifically trained in methods of radiation protection, nurses run the single greatest risk of confronting a radiation source at some time during their career. This risk increases significantly for nursing staff working in oncology units, surgery, emergency care facilities, or special radiographic procedure units.

Though nurses constitute a special group within the broad spectrum of medical facility personnel, this is not to lessen the importance of adequate radiation protection training for security officers, orderlies, housekeeping, grounds personnel, and administrators. Accidents involving medical radiation sources make no distinctions of an individual's job classification. For this reason it is in the best interest of the medical facility and its personnel to provide a fundamental understanding of radiation, sources of radiation within the medical facility, methods of detection, biological effects, and basic principles of radiation protection.

It should be pointed out that the contents of this manual will provide, on certain topics, more than just the "basics" which might be required for ancillary personnel training sessions. However, the authors have attempted to provide a logical development of topics in an easily readable format without sacrifice of basic information pertinent to making additional decisions in practical situations in which radiation sources are involved. It is therefore our intent to provide the information which will allow you, as a member of your medical facility's personnel, to make those practical judgements to reduce radiation exposure to yourself, patients, your co-workers, and members of the general public.

Michael A. Thompson, Associate Professor
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Chapter 1

Medical Radiation Sources and The Need for Radiation Protection Training

The discovery of x-rays in 1895 by the German physicist, Wilhelm Conrad Roentgen, was perhaps the beginning of the development of radiation sources which would soon be employed for the benefit of mankind. Roentgen made his discovery in December of 1895 and produced the first x-ray images (of his shotgun and his wife's hand) during the same month. As early as February of 1896, x-rays were used on patients throughout the world to aid in surgery. Crude x-ray units were even used in field hospitals by the British in the Sudan in 1898. Since very little was known about the biological effects of radiation, these early x-ray units were used with no protective shielding for the patient, the physician, or others working in the area.

About this same time period, between 1896 and 1898, natural sources of radiation were discovered by the French physicist Henri Becquerel and the husband-wife team of Pierre and Marie Curie. Becquerel was credited with the discovery that radiation similar in nature to x-rays was emitted from uranium, and the Curies were credited with the discovery of two additional radiation emitting substances, namely polonium and radium. These elements in addition to others, today known as radioactive materials, have similarly found their way into the diagnosis and treatment of disease.

The great enthusiasm which followed these important discoveries was unfortunately followed by the appearance of a range of biological injuries which resulted from overexposure to radiation. Within a few months after Roentgen's discovery of x-rays, erythema (skin reddening) had already been noted in individuals who had not taken precautions with these new rays. And as the radiation dose received increased, so did the severity of the injuries sustained. Early radiologists who did not take proper precautions suffered severe radiation damage to the hands. This damage was manifest in the form of radiation dermatitis which in many cases ultimately developed into skin cancers. Even the famed discoverers themselves were not immune to these radiation induced injuries. Becquerel experienced radiation burns from carrying radium samples in his pockets. Marie Curie and her daughter, Irene, both died of what appears to be radiation-induced leukemia, and even Marie's husband, Pierre, developed leukemia though he died as a result of a carriage accident. Numerous cases of radiation induced injuries followed prompting investigations into the biological effects of radiation. International commissions were established, data collected, populations of exposed individuals studied, and recommendations were subsequently made in the light of the current knowledge available regarding radiation exposure.

Thus, the radiation which would be used in the diagnosis and treatment of diseases, such as cancer, proved to be a double-edge sword. The rays which would be used to cure could also initiate the cancer. However, the benefits derived from the use of radiation to assist in diagnosis and therapy did outweigh the hazards associated with its use, provided adequate protection measures were taken and knowledgeable users controlled its application. Thus, the need for radiation protection was established.

TYPES AND CHARACTERISTICS OF RADIATION

In general, radiation may originate from either natural sources (e.g., radioactive materials) or artificial sources (e.g., x-ray units). We shall consider each source individually and their medical applications.

1. Radioactive Materials

All atoms consist basically of three types of particles. These are:

- 1) electrons (e) - very light particles having an electrical charge of -1.
- 2) protons (p) - particles having a mass of approximately 2000 times that of the electron and having an electrical charge of +1.
- 3) neutrons (n) - particles having approximately the same mass as the proton but electrically neutral.

All atoms are electrically neutral, that is, having the same number of electrons as protons. The protons and neutrons, accounting for approximately 99% of an atom's mass, are concentrated in a dense central core called the nucleus while the electrons revolve about the nucleus in shells or orbitals.

It is the number of protons in the nucleus (known as the Z number or atomic number) which determine the identity of the element. Thus, changing the number of protons in the nucleus changes the identity of the element. From the nuclear viewpoint, more than one form of an element may exist - forms having the same number of protons (thereby maintaining the same chemical identity) but different numbers of neutrons. These different forms of the same element are known as isotopes. Three isotopes of hydrogen are indicated in Figure 1. Also used in this illustration is the A number or the mass number which represents the total number of protons and neutrons in the nucleus. This is indicated as a superscript in the illustration on the following page.

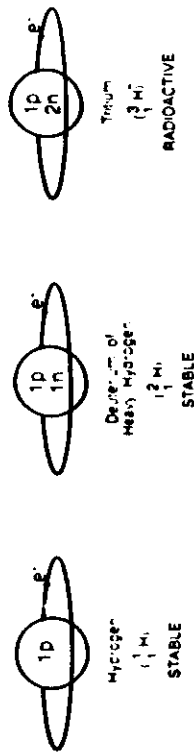


Figure 1. Isotopes of the Element Hydrogen.

From the illustration it is seen that all three are forms of the element hydrogen since each has the same number of protons in the nucleus. It should also be noted that the addition of neutrons to the nucleus of an atom may make that atom radioactive. To say that a nucleus is radioactive means that the nucleus will spontaneously emit radiation in an effort to alter its proton to neutron ratio. In this effort a nucleus may emit particulate (i.e., particles) and/or electromagnetic radiation (i.e., radiation like light but much more penetrating).

INSERT: RADIATION ENERGY UNITS

When discussing radiation protection, one must consider not only the type of radiation to which one is exposed but one must also consider its energy. The energy correlates to the penetrating ability or the distance the radiation will travel. The higher the energy, the more penetrating the radiation and the more precautions one must take in protecting oneself.

Radiation energy is expressed in units of electron-volts (eV) or more appropriately the kiloelectron-volt (keV) or million electron-volt (MeV)

$$1 \text{ MeV} = 10^6 \text{ eV} \quad (10^6 = 1,000,000)$$

$$1 \text{ keV} = 10^3 \text{ eV} \quad (10^3 = 1,000)$$

Particulate radiation may be in the form of:

- 1) Alpha Particles - particles carrying an electrical charge of +2; consists of two protons and two neutrons; approximately 8000 times more massive than the electron



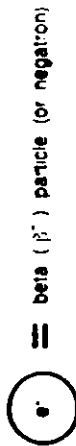
Range In Air: Approximately 1 cm per MeV of energy (for most naturally occurring alpha emitters, this is about 4-8 cm).

Range in Tissue: Of the order of microns.

Best Method of Protection From This Type of Radiation: Use distance; simply move away from the alpha emitting source.

Additional Notes: Rarely used in medical applications due to its low penetrating ability; though energies may be relatively high, low penetrating ability of alphas result from high loss of energy over short distances travelled due to electrical interactions (the amount of energy lost per unit of distance travelled is known as the linear energy transfer [LET] - thus alpha radiation is high LET radiation).

2) Beta Particles (also known as negatrons) - particles identical to orbital electrons except in that they are emitted from the nucleus of a radioactive atom; very light in mass and carries an electrical charge of -1.



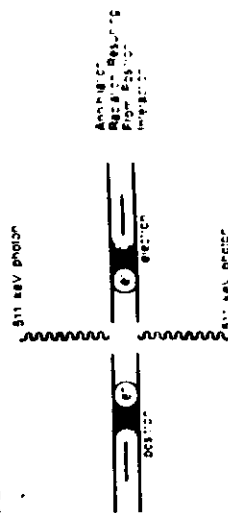
Range in Air: Approximately 12 feet per MeV of energy.

Range in Tissue: Up to several millimeters depending upon energy.

Best Method of Protection From This Type of Radiation: Distance can always be used with all radiation sources to reduce your radiation exposure; if shielding is to be used with beta emitters, shielding should not be lead since x-rays (known as bremsstrahlung) are produced when betas strike the shielding material; in place of lead, plexiglass, cardboard, particleboard, or plastics should be used; betas have lower LETs than alpha radiation.

Additional Notes: Beta radiation may be used to reduce fluid accumulation in the serosal cavities resulting from metastatic carcinoma. For this use the most commonly used source is radioactive phosphorus ($P-32$). Beta radiation is also widely used in the treatment of thyroid carcinoma. For this application the source of choice is radioactive iodine ($I-131$). These are probably two of the more common therapies utilizing beta radiation. When the beta radiation source is within the patient, there is virtually no beta radiation emitted from the patient's body. This is due to the low penetrating power of betas in tissue. However, attending personnel must remain cautious due primarily to the fact that most radioactive materials may emit more than one type of radiation. As an example, though $P-32$ emits beta radiation only (i.e., $P-32$ is a "pure beta emitter"), $I-131$ emits both beta and gamma (gamma radiation is identical to x-rays except for its origin; therefore, gamma radiation is much more penetrating than beta radiation). Thus, one must take precautions to shield against the more penetrating of the two types of radiation emitted, namely the gamma component.

3) Positrons (also known as positive beta particles) - particles having many of the same general properties of electrons except that their electrical charge is +1; when positrons interact with electrons in matter (which usually occurs within a distance of 1 mm or less in tissue), the electron and positron annihilate each other to produce two 511 keV photons (photons indicates radiation like X and gamma radiation, therefore very penetrating radiation); the two photons produced travel in directions totally opposite to each other (see diagram below); this radiation produced is known as annihilation radiation.



Range in Air: Of the order of mm depending upon energy.

Range in Tissue: Possibly up to a mm depending upon energy.

Best Method of Protection From This Type of Radiation: When using shielding, one should not be as concerned regarding the positron radiation but should concentrate efforts to shield against the 511 keV photon annihilation radiation. Adequate shielding would consist of lead (or other appropriate shielding) of approximate thickness of $1'' - 2 \frac{1}{2}''$.

Additional Notes: Though positron emitters are not in common use at the present time, it does appear that this type of radiation will come into more prominent use in nuclear medicine in the near future in positron emission tomography (PET) studies.

Electromagnetic radiation (also known as photons) is the most common form of radiation used in medicine. Both gamma rays and x-rays are electromagnetic radiation. The only real distinction between the two is their origin - gamma rays are emitted from the nuclei of radioactive atoms, while x-rays are emitted from sources other than nuclei, such as x-ray machines (discussed later in the chapter):

4) Gamma Rays (γ): High energy electromagnetic radiation emitted from radioactive nuclei; identical in nature to light but much more energetic (i.e., much more penetrating); unlike particulate radiation (i.e., alpha, beta, or positrons), gammas have neither mass nor electric charge; tends to lose their energy in matter by methods other than electrical interactions (discussed in next section).

Range in Air: Up to meters depending upon energy.

Range in Tissue: Up to meters depending upon energy.

Best Method of Protection From This Type of Radiation: Distance from the radiation source remains one of the best methods to reduce radiation exposure. Decreasing your time spent near the source of radiation will also greatly reduce your exposure. When these are inappropriate, adequate shielding (e.g., 1 1/2" - 2" thick lead shields) should be used.

Additional Notes: Gamma radiation is emitted by most of the medical sources of radiation which utilize radioactive materials (e.g., I-131 radioiodine patients, Cs-137 brachytherapy sources, Co-60 teletherapy sources, etc). When considering proper shielding one must remember that when working with radioactive materials:

1) radiation may consist of particles (i.e., alphas, beta, or positrons), electromagnetic energy (i.e., gamma rays), or both (i.e., particles and photons); shielding should be chosen to protect the individual from the most *potentially harmful* radiation emitted.

2) radiation is emitted *continuously* from this type of radiation source; it cannot be "turned off" - therefore when not in use, these sources must be kept in *secure, shielded* areas.

ACTIVITY AND HALF-LIFE:

Before the second type of medical radiation source is discussed, two additional concepts which apply only to radioactive materials must be considered. The greater the quantity of radioactive material present in a radiation source, the greater the quantity of radiation emitted from that source. The quantity of radioactive material present in a source is indicated by its *activity*. The greater the activity, the greater the amount of radioactive materials present, and the greater the amount of radiation emitted from that source.

Activity may be indicated in units of Curies (Ci) or a newer unit, the Becquerel (Bq), and their multiples and submultiples. Some of the more common activity units used with medical radiation sources are indicated below:

1 megacurie (MCi) = 1,000,000 Ci	1 gigabecquerel (GBq) = 1,000,000,000 Bq
1 kilocurie (kCi) = 1,000 Ci	1 megabecquerel (MBq) = 1,000,000 Bq
1 millicurie (mCi) = 1/1,000 Ci	
1 microcurie (μ Ci) = 1/1,000,000 Ci	1 Becquerel (Bq) = 1 dps (disintegration per second)

where:

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

or

$$1 \text{ mCi} = 37 \text{ MBq}$$

The Curie and its multiples have served as the units of activity for many years. The Becquerel is a much smaller unit in comparison to the Curie. Listed on the following page, are a variety of medical radiation sources and their representative activities in both systems of units.

Common Medical Radiation Sources and Their Corresponding Levels of Activity

Radiation Source	Activity in Ci Units	Activity in Bq Units	Comments
Cobalt Tele-therapy Source (Radiation Therapy)	10,000 Ci	3.7×10^{15} GBq	Radiation produced by these levels of activity can be potentially lethal if not controlled by qualified personnel.
Typical Dose Administered to Radioiodine Therapy Patient (Nuclear Medicine)	150 mCi	5.55 GBq	Special precautions must be taken to reduce exposure from radiation emitted from these levels of activity.
20 mg Ra eq.* Brachytherapy source (Radiation Therapy)	50 mCi (Cs-137)	1.85 GBq	Sources of this level of activity must always remain shielded when not in use. Take precautions to reduce radiation exposure.
Typical Activity Administered for Brain Scan (Nuclear Medicine)	20 mCi	0.74 GBq	Can produce relatively high levels of radiation exposure; take normal precautions.
Typical Activity Administered for a Liver Scan (Nuclear Medicine)	3 mCi	111 MBq	Use normal precautions with a radiation from this level of activity.
Typical Activity Contained in BACTEC Culture Vials (Clinical Laboratories)	2 μ Ci	74 KBq	Relatively low level of activity; not considered a dangerous level for medical radiation sources; take normal precautions.

*Activity levels of brachytherapy sources are commonly expressed in units of milligrams radium equivalent (mg Ra eq.), a historical method of designation of sources strength (or activity) originating from the time period when radium was the primary radiation source for brachytherapy. Today Cesium-137 (Cs-137) has replaced radium for most practical uses. 1 mg. Ra eq. = 2.5 mCi of Cs-137.

The activity of a radiation source does not remain constant but tends to decrease as time passes. This is known as *radioactive decay*. Different radioactive materials decay with different characteristic times known as their *half-life*. The half-life is that time period required for a radioactive material to decay to 50% of its original activity. Several half-lives for common medical radiation sources are shown in the table below.

Half-Lives of Common Medical Radiation Sources		
Radioisotope	Use	Half-Life
^{99m} Tc (technetium)	Nuclear Medicine	6 hrs.
¹⁹⁸ Au (gold)	Radiation Therapy	2.7 days
²⁰¹ Tl (thallium)	Nuclear Medicine	3.1 days
¹³¹ I (iodine)	Nuclear Medicine	8 days
³² P (phosphorous)	Rad Therapy/Nuc Med	14.3 days
¹²⁵ I (iodine)	Nuc Med/Rad Therapy	60 days
¹⁹² Ir (iridium)	Radiation Therapy	74.2 days
⁶⁰ Co (cobalt)	Radiation Therapy	5.3 yrs.
¹³⁷ Cs (cesium)	Radiation Therapy	30 yrs.
²²⁶ Ra (radium)	Radiation Therapy	1600 yrs.
¹⁴ C (carbon)	Clinical Labs	5730 yrs.

To clarify the concept of half-life, the following example is given.

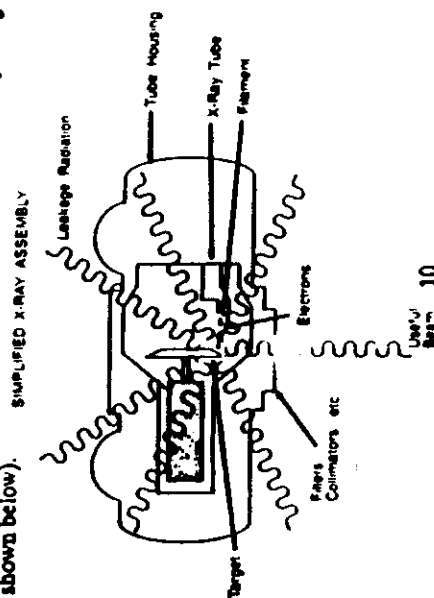
Example: If 100 mCi of ^{99m}Tc is the initial activity of a radioactive source, trace the activity which remains over a 24 hour period.

Elapsed Time	Activity Remaining
0 hr.	100.00 mCi
6 hrs.	50.00 mCi
12 hrs.	25.00 mCi
18 hrs.	12.50 mCi
24 hrs.	6.25 mCi

Since the half-life of ^{99m}Tc is six hours, then the activity remaining is decreased by 50% each six hour period that passes. As the activity decreases, the amount of radiation emitted from the source also decreases. The amount of radiation emitted from certain medical sources drops quite rapidly (e.g., nuclear medicine's ^{99m}Tc which has a half-life of six hours) while other sources appear to remain fairly constant (e.g., radiation therapy's ^{137}Cs sources which have a 30 year half-life). Half-life must therefore be considered in determining how rapidly radiation levels will drop for a given medical radiation source.

II. X-Ray Units

Perhaps the most common radiation source within a medical institution is the x-ray unit. X-ray units are found in emergency rooms, operating rooms, dentist's offices, radiology departments, radiation therapy departments and, on many occasions, portable units are brought directly to a patient's room. Additional special procedures such as cardiac catheterization, mammography, fluoroscopy, and computed tomography (CT) utilize x-rays produced by an x-ray tube. X-rays are produced when fast moving electrons slam into a positively charged target within the x-ray tube. The electrons, being negatively charged particles, are attracted to the positively charged target (see diagram shown below).



The energy (and therefore, the penetrating power) of the x-rays are determined by the speed of the electrons as they strike the target. The speed, and therefore the energy of the resulting x-rays, is controlled by varying the voltage across the tube using the high voltage power supply. By increasing the voltage, one increases the energy or penetrating ability of the x-rays produced.

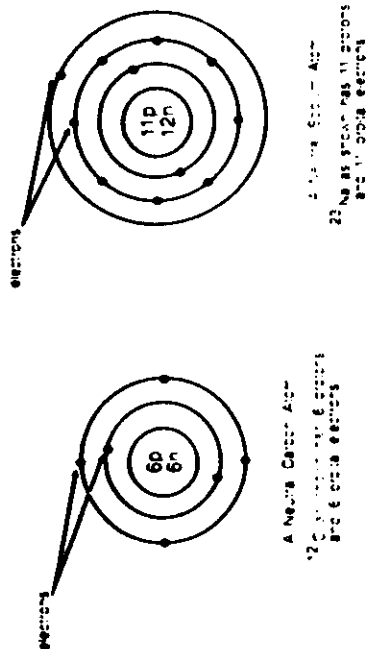
The energy of the x-rays produced is determined by the kilovoltage (i.e., 1000's of volts or kV) across the tube. The kilovoltage used directly translates into keV energy units (discussed in previous section). Thus, x-rays produced using a voltage of 80 kilovolts (i.e., 80 kV) will have a *maximum* energy of 80 keV. The actual energy of the x-rays produced will range in energy from near zero keV up to a maximum energy of 80 keV. Most x-rays used for diagnostic procedures utilize energies between 60 keV and 100 keV.

X-rays are electromagnetic radiation (i.e., photons) identical in nature to the gamma radiation emitted from radioactive sources. The only actual difference between x-rays and gamma rays is their origin — x-rays originating from x-ray units and gamma rays originating from radioactive atoms. The penetrating power of each is determined by their energy expressed in units of keV.

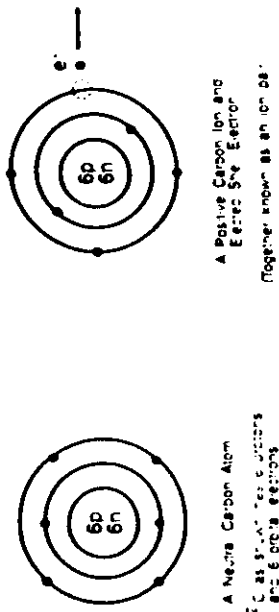
One important difference to note between these two distinct radiation sources: the radiation emitted from a radioactive source is emitted *continuously* and decreases with the passage of time according to its *half-life*; radiation emitted from an x-ray unit, utilizing an x-ray tube, is emitted *only* when the x-ray tube is energized (i.e., no radiation is emitted when the unit is switched off). The radiation emitted by both sources is emitted in *all directions* unless the source of radiation is contained within specially designed shielding devices.

RADIATION INTERACTIONS WITH MATTER

What happens when radiation strikes matter such as shielding material or human tissue? What does the radiation do that produces harmful effects if one is overexposed? In order to attempt to answer these questions, a closer look must be taken of the methods by which radiation interacts with individual atoms of which matter is composed. From previous sections we recall that atoms, consisting of a nucleus and orbital electrons, are electrically neutral. That is, an atom has the same number of protons (+) and electrons (-). See Figure below.



If an electron is removed from one of the orbitals the atom is no longer electrically neutral. It now has one more positive charge than negative charges and is now called a positive ion. The electron which was removed and the remaining positive ion are called an ion pair. See Figure below.



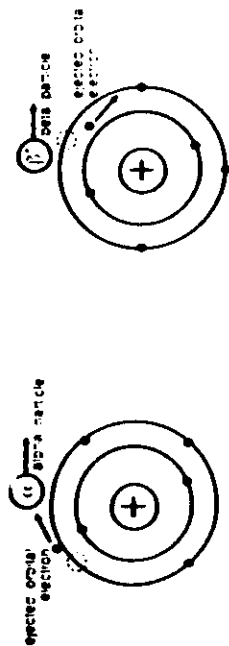
Energy is required to "free" or "eject" an orbital electron from an atom. Negatively charged electrons are held in their orbitals by the electrical force of attraction between themselves and the positively charged nucleus.

Radiation, whether it be particles or electromagnetic radiation, possesses energy. Radiation which has sufficient energy to eject a shell electron from an atom is classified as ionizing radiation. It usually takes about 33-35 eV to create an ion pair in air. Thus, any radiation which has energy in excess of 33-35 eV is considered as ionizing radiation. Since all medical x-ray machines (both radioactive sources and x-ray units) have energies of the order of keV or MeV, all emit or produce ionizing radiation.

The exact mechanisms by which ion pairs are created depends upon the type of radiation involved. These mechanisms will be considered separately.

I. Charged Particle Radiation

Charged particles (i.e., alphas, betas, and positrons) tend to lose their energy as they travel through matter by the creation of ion pairs. As the particles pass near or through a neutral atom, electrons are removed primarily by electrical forces of attraction or repulsion between the particle and an orbital electron. See Figure below.



Creation of Ion Pairs as Charged Particles Travel through Matter

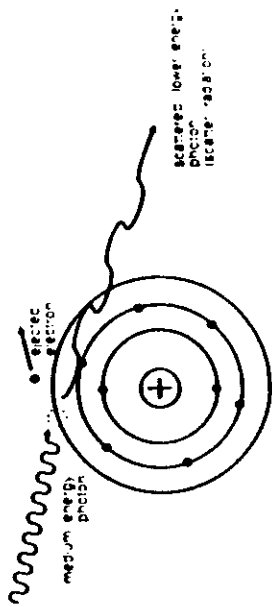
II. Electromagnetic Radiation (Photons)

Since photons (i.e., gamma or x-rays) are not electrically charged particles, they cannot create ions by electrical interactions. Instead, photons interact directly with orbital electrons. The energy carried by the photon, upon ejection of the orbital electron, may be partially absorbed and scattered or totally absorbed.

A. Partial Absorption and Scattering

This method of interaction is characteristic primarily of medium energy photons (most nuclear medicine and diagnostic x-ray procedures utilize photons of these energies).

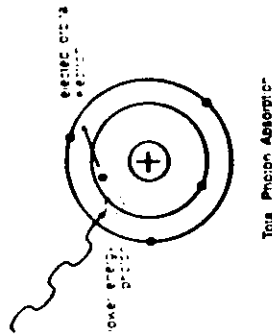
The photon usually interacts with an outer shell electron. The electron is ejected and a lower energy photon is emitted, usually travelling in a direction different from the original photon (i.e., scattered). See Figure below.



Partial Absorption of a Medium Energy Photon and Resulting Scatter Radiation.

B. Total Absorption

This method of interaction is characteristic of lower energy photons. The photon usually interacts with a more tightly bound inner shell electron. All of the energy of the photon is absorbed by the atom when the electron is ejected. See Figure below.



Special Note: Medium energy photons may first undergo partial absorption, resulting in a lower energy scattered photon. This lower energy scattered photon will then undergo a total absorption interaction. Thus, one must take special precautions to protect oneself from scatter radiation since there is a greater chance of total absorption of these lower energy photons.

Therefore, whether the radiation is particulate or electromagnetic in nature, if it possesses sufficient energy, it will create ions as it passes through matter by one of the methods described previously. The number of ion pairs it creates per unit of distance travelled is known as the specific ionization (SI). This is closely related to the linear energy transfer (LET), defined earlier as the amount of energy lost by the radiation per unit of distance travelled. Generally, the higher the LET (i.e., more energy lost per unit distance travelled), the higher the specific ionization (i.e., the more ion pairs created per unit distance travelled). Alphas and betas have generally higher LET's and higher SI's than gammas or x-rays.

On a relative scale, if gamma and x-rays are assigned a relative specific ionization of one (1), a comparison to other forms of radiation is shown below.

Type of Radiation	Relative Specific Ionization
Gamma & x-rays	1
Betas (β^-)	100
Positrons (β^+)	100
Alphas (α)	2500

Thus on a relative scale, betas are roughly 100 times more ionizing per unit distance travelled than X or gamma radiation. There are other factors which must be taken into account for this statement to be completely accurate, but the table provides a ready reference of relative ionizing ability. These concepts will be used again in Chapter 4 on biological effects of radiation.

For most medical facilities the primary locations of radiation sources are:

1. Radiology - utilizing x-ray units for diagnostic x-ray examinations.
2. Radiation Therapy - therapeutic uses of radiation in the form of radioactive materials (e.g., brachytherapy implants and teletherapy) and x-ray units.
3. Nuclear Medicine - use of radioactive materials in all physical forms (i.e., solids, liquids, and gases) for diagnostic and therapeutic procedures.

Each of these areas will be discussed separately in order to present the problems and precautions unique to each regarding their radiation sources.

GENERAL RADIATION PROTECTION CONCEPTS

Prior to discussing methods of detection, biological effects, and the three areas of medicine which utilize radiation sources, several basic methods of radiation protection which have general application to *all* radiation sources will be explained. The purpose of instruction in radiation protection is to provide you with methods to reduce your radiation exposure to *as low as reasonably achievable* (known as the ALARA concept) while allowing you to perform your duties as a health care professional or as a member of the health facility staff to the highest possible standards.

Regardless of the type of radiation source, your own radiation exposure can be reduced by applying the principles of time, distance and shielding.

I. Time

Radiation exposure can be reduced by minimizing the time spent near or in the vicinity of the radiation source.

II. Distance

Radiation exposure can be reduced by moving farther away from the radiation source.

III. Shielding

Proper shielding can be used whenever available and/or practical to reduce radiation exposure.

Any one or combination of the above can be used with **any** radiation source to reduce radiation exposure. These should be committed to memory for their widespread applicability. Each of these concepts will be referred to again as specific radiation sources are considered.

PHYSICAL FORM OF MEDICAL RADIATION SOURCES AND TYPE OF HAZARDS ASSOCIATED WITH EACH

Medical radiation sources which utilize radioactive materials may be in the form of either sealed or unsealed sources. These will be considered separately.

I. Sealed Radiation Sources

Sealed sources are those radioactive sources contained or encapsulated in metal, plastic, or other appropriate material in such a way that the probability of possible leakage of the radioactive material inside is minimal. The primary hazard associated with these sources is that of irradiation (i.e., radiation exposure only). The primary users of sealed radiation sources are radiation therapy departments.

II. Unsealed Radiation Sources

Radioactive materials in liquid or gaseous form are known as unsealed sources. These types of sources produce not only irradiation but also the possibility of contamination. Contamination implies that the radioactive material can be spread from one point to another if precautions are not taken.

The primary users of unsealed radiation sources are nuclear medicine departments.

In addition, radiation sources are classified as external radiation hazards if they present a radiation hazard to individuals in their near vicinity. If there is a significant probability of radiation injury as a result of the radiation source being taken internally (e.g., by means of ingestion, inhalation or through open wounds or cuts), then the source is known as an internal radiation hazard. For example, an x-ray unit represents an external radiation hazard while radioactive iodine ($I-131$) may be classified as both an external (i.e., because it emits energetic gamma radiation) and an internal radiation hazard (i.e., if taken internally it tends to concentrate in thyroid tissue where it will emit its beta and gamma radiation).

IMPORTANT CONCEPTS OF CHAPTER ONE

1. The need for radiation protection education came about as a result of recognition of biological damage sustained by many early investigators and users of radiation sources.

2. The most commonly used medical radiation sources are radioactive materials and x-ray units.

3. In regards to radioactive materials:

a. All atoms are electrically neutral, consisting of electrons, protons and neutrons.

b. Isotopes are different forms of the same element having the same number of protons but different numbers of neutrons.

c. In designating an isotope such as:



53 = Z number = number of protons

131 = A number = number of protons and neutrons

d. The radiation emitted from a radioactive nucleus may be particulate (i.e., alphas, betas, or positrons) or electromagnetic (i.e., photons such as gamma rays).

e. The penetrating ability of radiation is determined by its energy expressed in units of eV, keV, or MeV.

f. Alpha and beta radiation are not as penetrating as gamma radiation.

g. When positrons interact with electrons in matter, two energetic photons are produced (annihilation radiation).

h. The radiation emitted from radioactive sources cannot be "turned off" but does decrease with a characteristic time known as the half-life.

i. The greater the activity of a radioactive source, the greater the amount of radiation emitted from that source.

Chapter 2

Units of Radiation Measurement

When one is exposed to radiation, it does not mean that detrimental biological effects will manifest. When radiation levels are kept low and on an infrequent basis, the chances of observing clinical symptoms of radiation overexposure are minimal. However early users, unskilled in methods of radiation protection, did show signs of overexposure to the radiation with which they worked. Thus, a need existed to develop methods of detecting and measuring levels of radiation in an attempt to establish guidelines for radiation protection purposes. Not only was the quantity of radiation to which one was exposed important but also the time period over which it was delivered. In addition, certain types of radiation tended to be more damaging than others. Each of these factors needed to be included in the development of a system of radiation units. In this chapter these units will be explained with practical examples. It is important to understand these units, unique to radiation measurements, for they are used with detection devices (e.g., geiger-counters, pocket dosimeters, etc.), establishment of time limits for medical personnel working with radiation patients and personnel dosimetry records (i.e., records of an individual's radiation exposure history).

The following quantities and associated units have been defined by the International Commission on Radiation Units and Measurements (ICRU) in order to standardize their usage throughout the world. The basic quantities described are *exposure*, *absorbed dose*, and *dose equivalent*. Each will be considered separately.

I. Exposure

When one walks into a room where there is an unshielded radiation source, the individual has been exposed to the radiation emitted from the source. Quantitating the amount of radiation to which the individual has been exposed is the first step in predicting the potential biological effects, if any, on the individual.

As discussed in the previous chapter, the radiation with which we are most concerned is ionizing radiation - radiation which has the ability to create ions in the medium through which it passes. The unit of exposure, known as the Roentgen (R), is defined in terms of the amount of ionization produced by the radiation as it passes through a known quantity of air. The formal definition also restricts the Roentgen to X and gamma radiation of energy less than 3 MeV. For most practical applications of medical radiation sources, the penetrating radiation used will be X or gamma rays within this energy range.

4. In regard to x-ray units:

- a. X-rays are produced when high speed electrons strike a tungsten target inside an x-ray tube.
- b. The energy (i.e., penetrating power) of the x-rays produced can be varied by altering the voltage on the x-ray tube.
- c. When not in use, an x-ray unit does not emit radiation.
5. Regardless of its origin, radiation having energy in excess of 33 eV is classified as ionizing radiation since it has sufficient energy to eject electrons from atoms within the material through which it travels.
6. The linear energy transfer (LET) indicates the energy lost per unit distance travelled by the radiation.
7. The LET is closely related to the specific ionization (SI), the number of ion pairs created per unit distance travelled by the radiation.
8. As photons (i.e., X or gamma rays) travel through matter, they are either partially absorbed and scattered or totally absorbed.
9. Scatter radiation is of lower energy which increases its chances of total absorption on its next interaction in matter.
10. Radiation exposure may be reduced by using time, distance, and shielding.
11. Sealed radiation sources are used primarily by radiation therapy departments for purposes of medical irradiation. There are essentially no contamination problems associated with sealed sources.
12. Unsealed sources are used primarily by nuclear medicine departments for diagnosis and therapy. In addition to radiation hazards there is also the possibility of contamination with this type of source.
13. External radiation hazards refer to sources which emit energetic, penetrating radiation which can present a hazard to individuals in the vicinity of the source.
14. Internal radiation hazards refer to sources which can produce biological injury if taken internally.

Generally it should be remembered that the greater the amount of radiation being emitted from a radiation source, the greater will be the exposure produced by that source. Exposure rates are perhaps the more commonly made measurements. Exposure rates indicate the exposure obtained during a specific period of time, such as "per hour".

The Roentgen represents a relatively large unit of radiation exposure. Though the exposures or exposure rates may be high from certain types of medical radiation sources, a smaller submultiple of the Roentgen, the milliroentgen (mR), is more commonly used. The relation between the two units being:

$$1 \text{ Roentgen} = 1000 \text{ milliroentgens} \\ \text{or} \\ 1 \text{ milliroentgen} = 1/1000 \text{ Roentgen}$$

Thus, exposure rates might be expressed as R/hr or mR/hr. Given the exposure rate measurement and the interval of time, exposure can be determined.

Example: The exposure rate measured at the bedside of a radiation implant patient is determined to be 20 mR/hr. If a nurse stands at this location for 10 minutes to administer medication, what exposure does the nurse receive during this time period?

Exposure	= Exposure Rate	X Time
= 20 mR/hr	X	10 min.
= 20 mR/hr	X	10/60 hr
= 3.3 mR		or 0.0033 R

Special Notes: It is important to realize that exposure rates will vary with their location from the radiation source. Exposure rates will increase greatly as one moves closer to the source. Similarly, one will notice a marked decrease in moving away from the source. Thus, a radiation exposure rate measurement is valid only at the location at which it was measured.

Once the exposure received has been determined, one must then estimate the amount of radiation energy actually absorbed. All the radiation energy which passes through a medium (e.g., an individual's body) is not necessarily absorbed. A fraction of the incident radiation may be totally absorbed, partially absorbed (e.g., scattering events), or penetrate completely. This leads to the next quantity to be considered.

II. Absorbed Dose

Given the amount of radiation to which one has been exposed (i.e., the exposure in Roentgens), the fraction of radiation energy absorbed depends primarily on the energy or penetrating ability of the radiation and the composition of the medium through which the radiation passes.

These factors are taken into account in a quantity known as an f-factor. When the appropriate f-factor is multiplied by the exposure in Roentgens, the absorbed dose is obtained. That is:

$$\text{Absorbed Dose} = \text{Exposure} \times \text{f-factor}$$

The most commonly used unit of absorbed dose is the rad (an acronym for radiation absorbed dose). The rad represents a specific quantity of energy absorbed per gram of medium. An international unit of absorbed dose, the Gray (Gy), is currently making its appearance in radiation protection literature. It too represents a specific quantity of energy absorbed however per kilogram of medium. The relation between these two units are:

$$1 \text{ Gray} = 100 \text{ rads} \\ \text{or} \\ 1 \text{ rad} = 1/100 \text{ Gray}$$

Example: A patient receives an exposure of 20 Roentgen from 80 ke V x-rays. If the f-factor for soft tissue and 80 ke V photons is 0.9 rads/Roentgen, determine the patient's absorbed dose.

$$\text{Absorbed Dose} = \text{Exposure} \times \text{f-factor} \\ = (20 \text{ R})(0.9 \text{ rads/R}) \\ = 18 \text{ rads}$$

Example: Express the above absorbed dose in units of Grays.

Using the knowledge that 1 Gray = 100 rads, then

$$\text{Absorbed Dose} = 18 \text{ rads} \times 1 \text{ Gray}/100 \text{ rads} \\ = 0.18 \text{ Gray}$$

Once the quantity of absorbed radiation energy has been determined (i.e., the absorbed dose in rads or Grays), the potential biological effect on an individual should be relatively easy to predict. However, since there are many types of radiation (i.e., alpha, beta, positrons, gamma, and x-rays) and their energies vary, it was soon discovered that certain types of radiation tended to have the potential to be more biologically damaging than others. This potential for greater biological harm had to be incorporated into, especially, those units which would be used for radiation protection standards. These factors were included into the quantity known as the dose equivalent.

III. Dose Equivalent

The effects of radiation depend not only upon the amount of energy absorbed, but also upon the distribution of that energy within the medium. As explained in chapter one, the various types of radiation do tend to distribute their energy differently in the medium through which they travel as indicated by the differences in their LET's and SI's. The degree of biological damage incurred as a result of radiation exposure is closely linked to the radiation characteristics (i.e., energy of the radiation, LET and SI) and physiological conditions which exist within the exposed individual. These latter conditions would require review on an individual basis whereas the former are somewhat easier to generalize.

In order to incorporate these radiation characteristic differences and their close association to varying degrees of potential for biological harm, the unit of dose equivalent the rem (acronym for roentgen equivalent in man), was formalized. To obtain the quantity known as dose equivalent, the absorbed dose is simply multiplied by the appropriate quality factor, QF. Quality factors are assigned to the various types of radiation according to LET and SI. These relationships and a summary of assigned quality factors are shown in the tables shown below.

Relation Between Specific Ionization, Linear Energy Transfer and Quality Factor*

Average Specific Ionization (IP/μm)	Average LET (KeV/μm)	QF
100 or less	3.5 or less	1
100-200	3.5-7.0	1-2
200-450	7.0-23	2-5
450-1500	23-53	5-10
1500-5000	53-175	10-20

*From Recommendations of the International Commission on Radiological Protection.

Quality Factors For Different Radiations*

Type of Radiation	QF
X rays, γ rays, β particles with $E_{max} > 0.03 \text{ MeV}$	1
β particles with $E_{max} \leq 0.03 \text{ MeV}$	1.7
Neutrons and protons $\leq 10 \text{ MeV}$	10 (30 for irradiation of eyes)
α particles from natural radionuclides	10
Heavy recoil nuclei	20

*This data should be used only for purposes of radiation protection.

To make this somewhat easier, by far the most common type of radiation utilized for medical diagnosis and therapy is X and gamma radiation. For this type of radiation the quality factor is one.

It should also be noted that if the absorbed dose is expressed in units of Grays, the resulting dose equivalent, obtained after multiplication by the appropriate QF, will be expressed in the unit known as the sievert (Sv). The relationship between the sievert and the rem is:

$$1 \text{ sievert} = 100 \text{ rems}$$

$$\text{or}$$

$$1 \text{ rem} = 10 \text{ millisieverts (mSv)}.$$

The relationships between the various quantities and their respective units are relatively simple and are summarized below.

1. Exposure measured in units of roentgens (R)
2. Absorbed Dose = Exposure x f-factor (rads or grays) (roentgens) (rads/roentgen or grays/roentgen)
3. Dose Equivalent = Absorbed Dose x Quality Factor (rems or sieverts) (rads or grays)

For the dose and energy of radiation most frequently used in medical diagnosis and therapy, the following approximation can be made:

Exposure in roentgens	=	Absorbed Dose in rads	=	Dose Equivalent in rems
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These relationships will now be applied to a practical situation involving a radiation therapy patient.

Example: A brachytherapy patient has 60 mg. Ra eq. of Cs-137 (a gamma emitting source) temporarily implanted for treatment of cervical cancer. A measurement of exposure levels at the patient's bedside yields a reading of 40 mR/hr. If it takes a nurse 15 minutes to administer medication to this patient,

a) determine the exposure received by the nurse:

$$\begin{aligned}\text{Exposure} &= \text{Exposure Rate} \times \text{Time} \\ &= 40 \text{ mR/hr} \times 15 \text{ min} \\ &= 40 \text{ mR/hr} \times 15/60 \text{ hr.} \\ &= 40 \text{ mR/hr} \times 1/4 \text{ hr.} \\ &= 10 \text{ mR (i.e., 10 milliroentgens)}\end{aligned}$$

$$\begin{aligned}\text{Note: } 10 \text{ milliroentgens} &= 10 (0.001 \text{ Roentgens}) \\ &= 0.01 \text{ Roentgens}\end{aligned}$$

b) determine the nurse's absorbed dose:

$$\begin{aligned}\text{Absorbed Dose} &= \text{Exposure} \\ &= 10 \text{ millirads} \\ &\text{or } .01 \text{ rads}\end{aligned}$$

c) determine the nurse's dose equivalent:

Since the radiation emitted from Cs-137 is gamma radiation and the QF for gamma radiation is 1, then

$$\begin{aligned}\text{Dose Equivalent} &= \text{Absorbed Dose} \times \text{QF} \\ &= .01 \text{ rads} \times 1 \\ &= .01 \text{ rems or 10 millirems}\end{aligned}$$

IMPORTANT CONCEPTS OF CHAPTER TWO

1. Radiation exposure is measured in units of Roentgens (R) or milliroentgens (mR).
2. Radiation absorbed dose, defined as

$$\text{Absorbed Dose} = \text{Exposure} \times f\text{-factor}$$
is measured in units of rads or Grays.
3. Radiation dose equivalent, defined as

$$\text{Dose Equivalent} = \text{Absorbed Dose} \times \text{Quality Factor}$$
is measured in units of rems or Sieverts.
4. The quality factor for X and gamma radiation is one.
5. For the radiation most frequently used in medical diagnosis and therapy the following approximation can be made:

$$\text{Exposure in Roentgens} = \text{Absorbed Dose in Rads} = \text{Dose Equivalent in Rems}$$
6. Dose equivalent units (i.e., rems and Sieverts) are used for radiation protection purposes only.

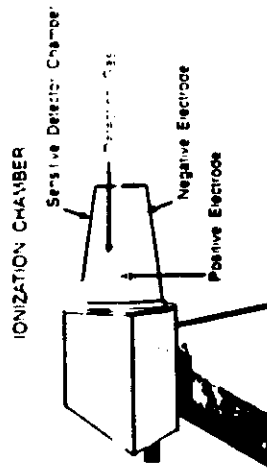
Chapter 3

Radiation Detection Equipment

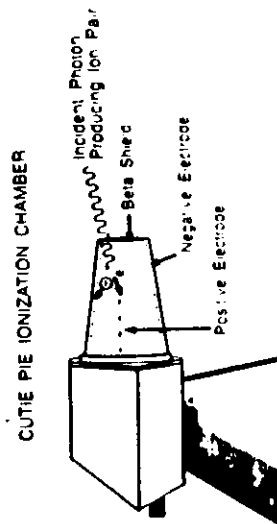
We, as humans, have no natural sense of detection for ionizing radiation. It cannot be seen, heard or felt. An individual could receive a lethal dose of radiation and not actually realize it until classical symptoms of radiation overexposure began to manifest themselves over a period of time. Thus when working with radiation sources it is important to know the radiation exposure levels in order to assure your safety and the safety of others in the area. In order to detect ionizing radiation, a wide variety of sensitive instruments are used. In this chapter three types of instruments commonly found in the hospital setting or at least available to radiation therapy wards will be considered. Their individual strengths, weaknesses and specific precautions in their use will also be discussed.

1. The Ionization Chamber (or "Cutie Pie")

Both the ionization chamber and perhaps the most common detection instrument, the Geiger counter, detect radiation by the collection of ions. As indicated previously, ionizing radiation, such as the X and gamma radiation used in a variety of medical procedures, produces ion pairs in matter. In the portable ionization chamber the radiation is allowed to penetrate a specifically known quantity of gas (usually helium or argon) within the sensitive volume of the detector. (See the figure shown below)



As the ion pairs are created within the sensitive volume, the charges migrate toward positive and negative electrodes within the chamber. This movement of electric charge constitutes what is known as an *electric current*. The amount of current produced is dependent upon the number of ions created which, in turn, is dependent upon the amount of radiation to which the chamber has been exposed. (Chamber components are shown in the figure below)



The amount of current produced per unit of time is measured by a meter within the instrument to indicate measurements of *exposure rate*, expressed either in units of R/hr or mR/hr.

Upon first observation of the scales found on this survey instrument, one becomes immediately aware of the wide-range of exposure rate levels which can be measured. Exposure rates ranging from 1 mR/hr to 1000 R/hr can be made with most instruments of this type.

It is this type of detection instrument which is most commonly used in determining radiation exposure rate levels for room surveys of patients receiving radiation therapy. These instruments, however, are relatively insensitive to low levels of radiation and should not be used to detect areas of radioactive contamination.

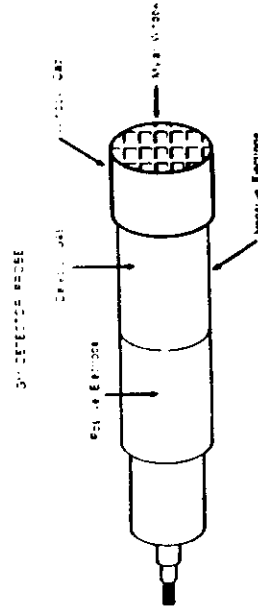
Usually these instruments tend to be rather expensive and will most likely be used only by radiation protection personnel for therapy patient room surveys. The results of these room surveys will then be used to determine time limits for nurses, staff and visitors. There may be occasions, however, when a member of the nursing staff attending a radiation therapy patient may be called upon to make these measurements. There are several items which should be called to the attention of anyone operating an ionization chamber in order that accurate and meaningful measurements be obtained:

5. After all measurements have been completed, turn the selector knob to the "OFF" position and store the instrument in a safe and secure location appropriate for an expensive and delicate instrument.
6. The instrument should be calibrated by a qualified individual *at least on an annual basis* to assure instrument accuracy.

II. The GM Survey Meter (GM Detector or Geiger Counter)

The GM detector is perhaps the most well known of all radiation detectors primarily because of its portability, ease of use, and relatively low cost. As its name implies, it is a "detector" for most common forms of ionizing radiation. It is not an instrument to be used if accurate determinations of exposure rates are necessary. It is, however, a good instrument for detection of contamination (e.g., I-131, P-32, and Tc-99m) and sealed therapy sources (e.g., Cs-137, Ra-226, Co-60, Ir-192, Au-198, and I-125).

Like the ionization chamber, the basis of radiation detection in the G-M is also the production of ions by radiation as it passes through a gas. The gas used within this type of detector is usually helium, argon, or neon. The gas is housed within the detector probe (i.e., the G-M tube itself) which consists of positive and negative electrodes and the detector gas. The gas is maintained within the tube by a thin Mylar "window" (See diagram shown below) located usually at the end of the probe. The window is very thin to allow penetration by weakly penetrating radiation such as alpha and beta. *Great care must be taken not to puncture this thin window with sharp objects when using the detector probe.* If the window is punctured, the GM probe must be replaced prior to further use.

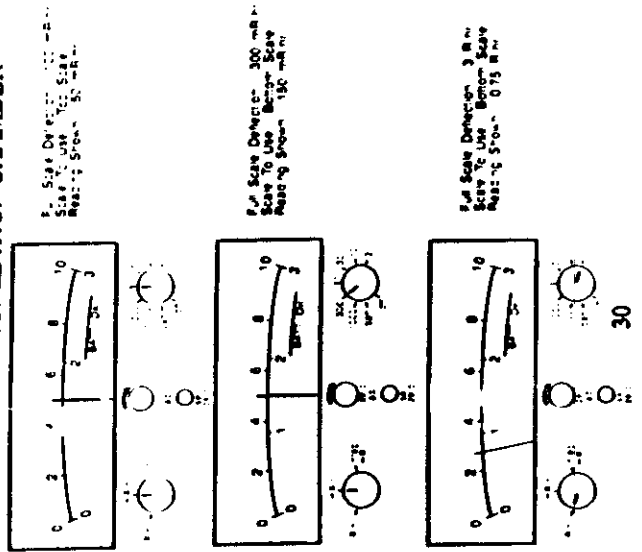


1. The instrument's batteries should always be checked using the "battery check" prior to operation. Batteries should be checked every *two to three months* and replaced if need be.
2. The chamber must also be properly "zeroed" using the "zero adjust" dial before actual measurements are made.
3. After zeroing, the "function" knob is used to select the appropriate function for which the instrument is to be used (Note: Since exposure rates are the most commonly made measurements, the function knob will most commonly be turned to "mR/hr" or for higher radiation sources, "R/hr").
4. After the appropriate function has been selected, the scale selector is then used to determine the scale to be used for full scale deflection (i.e., 3, 10, 30, 100, 300, or 1000).

See diagrams shown below indicating instrument settings and resulting sample readings.

NOTE: If exposure rates exceed 1000 mR/hr, the function selector should be changed from mR/hr to R/hr and the scale selector changed from 1000 back to 3. Higher scales may be chosen to obtain higher readings if necessary.

SAMPLE READINGS - CUTE PIE IONIZATION CHAMBER



As ionizing radiation enters the gas filled chamber of the detector probe, ion pairs are created. Negative ions (i.e., the ejected electrons) move toward the positive electrode. This movement of charge produces an electric current. The rate at which this current is produced is dependent upon the intensity of the radiation to which the probe is exposed. The electrical signal produced within the instrument yields a reading expressed usually in units of mR/hr (i.e., milliroentgens per hour, units of exposure rate). The GM is basically an instrument for the detection of radiation. It, however, cannot detect all types of radiation. Specifically, it cannot be used to detect low energy alphas and betas (e.g., low energy beta radiation emitted from H-3 cannot penetrate the thin window of the probe to be detected, even C-14 must be in sufficient concentration to be detected with many GM detectors).

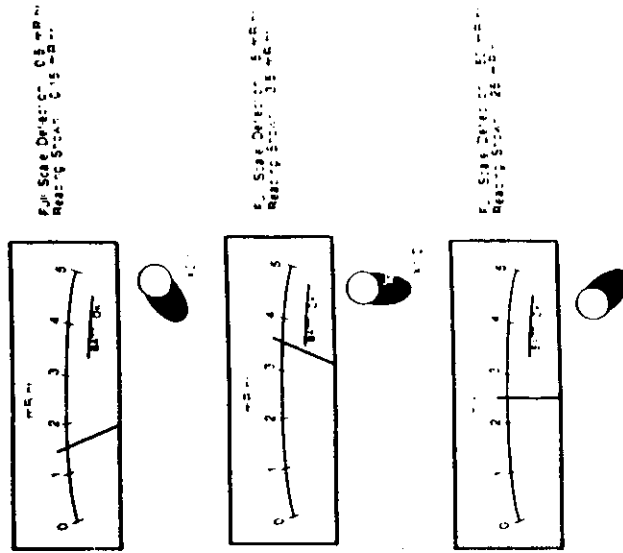
The GM is primarily a survey instrument used for the detection of low level radiation. Though its scales usually indicate units of mR/hr, it is not the instrument of choice if accurate determination of exposure rates, such as the calculation of nurse and visitor time limits, is required. Most GM detectors have at least three (3) scales which can be used. These scales are usually indicated by "X 0.1", "X 1.0", and "X 10". The lowest scale is considered to be the most sensitive and should be used for the detection of low level contamination. As radiation levels increase, higher scales may be chosen for use.

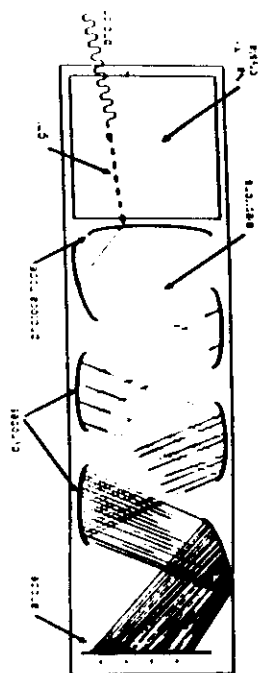
Proper use of the GM detector for the location of contamination or other sources of radiation should include each of the following:

1. The instrument's batteries should always be checked using the "battery check" prior to operation. Batteries should be checked every two to three months and replaced if needed.
2. The most sensitive scale (e.g., the lowest numerical scale) should be chosen initially for survey use. If radiation levels cause the needle indicator to be deflected full scale, then the next highest scale should be used. Higher scales are chosen in this same manner. One should recall that the higher the exposure rate measurement obtained, the greater the amount of radiation emitted from the source and the greater the care that should be taken.

3. Once the appropriate scale has been chosen with the selector switch, the scales are read as indicated by the diagrams shown below.

SAMPLE READINGS - GM DETECTOR





This detector is effective in the detection of low energy X and gamma radiation (e.g., I-125) as well as medium and higher energy radiations. Like the G-M, it usually has several scales of operation (see previous section on G-M Detectors), usually in units of milliroentgens per hour (mR/hr). Scales are read in exactly the same manner as with the G-M.

Due to the increased efficiency of these instruments in the detection of X and gamma radiation, they are generally of great use in the location of lost or misplaced radiation sources. Once the general area of the lost source has been determined with this detector further refinements of exact location can then be determined with a G-M detector.

Before using a portable scintillation detector, several important aspects regarding its proper care and use must be noted:

1. Batteries should always be checked *prior* to use with the "Battery check". If the detector needle does not register in the "Battery o.k." region of the scale, batteries should be replaced prior to use. *Batteries should be replaced every two to three months to assure proper operation.*
2. Unlike the previously discussed detector, the portable scintillation detector utilizes a crystal in the detector probe. As a result, *special care must be taken to protect the probe from mechanical jarring* (such as dropping or striking the probe against hard surfaces). In addition, *the probe must not be subjected to rapid changes or extremes in temperature*. Such actions can produce crystal fractures which will produce instrument malfunction.

Special Note: When working with the G-M detector, as with other types of radiation detectors, one should note the normal fluctuation which occurs on the most sensitive scales when *no radiation sources are in the near vicinity* of the detector. This is a result of *normal background radiation*. The needle of most G-M detectors will fluctuate between 0 and about 0.1 mR/hr as a result of normal background radiation and *not* due to the presence of any source of radiation.

4. The G-M detector may be used to detect radiation from Cs-137, P-32, Tc-99m, I-131, Ra-226, Co-60, Ir-192, and Au-198 sources but should *not* be used to detect radiation from H-3 sources since the radiation emitted from these sources does not have sufficient energy to penetrate the thin end window of the detector probe. The G-M detector may be used to detect I-125 and C-14 when in sufficient quantities though the efficiency of detection is relatively low.
5. When using the G-M detector, the detector probe should be placed approximately 1" above the surface to be checked for possible contamination (e.g., hands, feet, soles of shoes, furniture surfaces, etc) from liquid radiation sources or to locate other sources of radiation such as small brachytherapy sources. Care should be taken when using the detector probe *not to touch the probe to a possibly contaminated surface or to puncture the thin, end window of the probe with sharp objects*. (Note: If the end window is ever accidentally punctured, the detector probe must be replaced before reuse of the instrument.)
6. The instrument should be *calibrated* by a qualified individual *at least on an annual basis* to assure instrument accuracy.

SCINTILLATION DETECTORS (PORTABLE)

Whereas G-M detectors are useful in the detection of *most* commonly used medical radiation sources, the probe used must be rather close to the source of radiation in order for detection. A much *more sensitive* detector, used especially in the detection of X and gamma ray emitting sources, is the portable scintillation detector. This type of radiation detector looks and operates in much the same way as the G-M detector with the exception of the detector probe. The probe for this detector is somewhat larger than that of the G-M but does not utilize a detector gas. The probe of this instrument consists of a sodium iodide (NaI) crystal which upon interaction with X and gamma rays, produces small flashes of light known as scintillations. Though too faint to be detected with the unaided eye, the flashes of light are detected by a light sensitive electronic device known as a photomultiplier tube (or PMT) which converts these flashes of light to electrical pulses which causes deflections of the needle on the detector scale.

3. Appropriate scales are chosen with the scale selection dial in the same manner as described with the G-M detector (see G-M Detector section). Scales may be in units of mR/hr (i.e., milliroentgens per hour) or cpm (i.e., counts per minute). Regardless of the units, the higher the numerical values obtained with the instrument, then
 - a. the closer one is to the radiation source, or
 - b. the greater the amount of radiation being emitted
 or both. This is generally true for all types of radiation detectors including G-M's and ionization chambers.

3. When using any of these instruments, especially an ionization chamber or G-M, to detect possible contamination (such as on one's feet or hands), detector readings should be made away from known radiation sources (such as radioactive patients). Readings should be made approximately 8-12 feet away from the patient's room. If readings are made too close to the patient or the patient's room, one will obtain higher readings as a result of penetrating radiation emitted from the patient (This is especially true for I-131 therapy patients and brachytherapy patients. Each of these patients is discussed in the patient section of this manual.
4. Nurses and other medical staff personnel should take time to familiarize yourself with the proper use of the detection equipment available for your use at your medical facility.
5. All instruments should be handled carefully and stored in secure, easily accessible locations when not in use.

4. Due to the increased sensitivity of the scintillation detector for X and gamma radiation, it is generally useful in detecting radioactive contamination which might result from most liquid radiation sources used in medicine (e.g., Tc-99m, I-131, I-125, Ga-67, I-123, etc).

In addition these detectors may be used to locate sealed sources (i.e., solid radiation sources with which there is minimal chance of radioactive contamination though radiation is still emitted) which might have been lost or misplaced. This detector could be used to locate such sources as I-125 "seeds", Cs-137 brachytherapy sources, radium needles, etc. One might wish to use this type of detector to locate the general area in which a source might be lost (e.g., in a laundry area, trash bin, or operating room) then use a less sensitive instrument, such as a G-M detector, to actually "pinpoint" the location of the source.

5. When not in use, the detector should be turned to the "OFF" position and stored in a secure but readily accessible location.

Several additional notes in regards to radiation detection equipment:

1. All detectors should be calibrated periodically by trained personnel with an appropriate radiation source to assure instrument accuracy. Instruments are usually calibrated by a hospital's radiation safety office or health physicist. If neither are available, one should contact the company who makes the particular survey instrument for this service.
2. Batteries should be checked periodically (approximately every three to six months) and should not be left in an instrument indefinitely. Corrosion and/or rupture of batteries within an instrument can be very costly in terms of both money and loss of instrument use.

IMPORTANT CONCEPTS OF CHAPTER THREE

1. Three (3) relatively common types of radiation detectors and their general principle of operation are:
 - a. Ionization Chambers - collection of ions produced in a detector gas
 - b. Geiger-Mueller (GM) Detector - collection of ions produced in a detector gas
 - c. Scintillation Detector (Portable) - the production of scintillation (i.e., flashes of light) in a sodium iodide crystal
 2. All radiation detectors are not equally sensitive in the detection of radiation.
 3. Ionization chambers are most widely used for determining exposure rate (i.e., mR/hr) measurements when greater accuracy is required (e.g., in the determination of time limits for visitors, nurses, and staff attending a radiation therapy patient).
 4. Ionization chambers are not the best instruments to use in the detection of low level radioactive contamination.
 5. Ionization Chambers may be used to detect x and gamma rays and high energy beta radiation.
 6. GM detectors are useful in the detection of most radiation sources and low-level radioactive contamination.
 7. GM detectors should not be used to determine exposure rate measurements where accuracy in measurements is required.
 8. GM detectors may be used to detect x and gamma rays and medium to high energy beta radiation.
 9. Scintillation detectors are more sensitive detectors of x and gamma radiation than the GM detector or ionization chamber.
 10. Scintillation detectors are useful in the detection and subsequent location of lost radiation sources.
- Special Note: All of the detectors discussed, including the GM detector, cannot detect the low energy beta radiation emitted from radioactive C-14 used in BACTEC vials.

GENERAL PRINCIPLES TO REMEMBER FOR ALL RADIATION DETECTORS:

1. Batteries should be checked prior to using any radiation survey instrument.
2. Detectors should be handled carefully when in use.
3. Radiation survey instruments should be calibrated periodically by qualified personnel.
4. Batteries in all survey instruments should be replaced every three to six months to assure proper operation and reduce the chance of instrument damage by corrosion.
5. Instruments should be stored in a secure but readily accessible location when not in use.

Chapter 4

Biological Effects of Radiation

Introduction

A basic understanding of the physiological impact of absorbed radiation is critical to a nurse's function as an intermediary between the patient and the physician. Your attitudes influence the patient's attitudes. If you influence the patient by your positive attitude, there is a positive reinforcement that the treatments or procedures being performed are in fact safe to both you and the patient. A basic understanding of the underlying mechanism of radiation injury enables a nurse to employ all of their professional skills developed in situations where radiation was not involved to benefit a patient when radiation is involved. Finally, gaining a basic understanding of the mechanisms of radiation injury will provide assurances of safety to both yourself, other staff members and to the visitors within the hospital. All too frequently nurses are left to explain why children or potentially pregnant visitors must be restricted from routine hospital visitations.

Radiation safety is a relative point on a continuous scale of radiation exposure whose location is determined by:

- the actual absorbed dose
- the probability of injury from that dose
- the willingness to accept the risk of injury
- regulatory limits determined by society as a whole

The actual location of radiation safety standard along the dose axis is modified by a number of conditions which include:

- occupational versus a population dose
- the level of knowledge of radiation safety procedures
- protective or preventive interventions which may effectively reduce the actual absorbed dose
- the biological endpoint which is being described

The biological endpoint is extremely important. The biological endpoint may really have two different points of reference. The first may be the risk of that endpoint to the individual (somatic effect) or second it may be the risk to future generations (genetic effect).

SUBCELLULAR EFFECTS OF RADIATION

To understand the biological effects of radiation a short review is necessary in cell biology. First it must be remembered that some 80% of the total body mass is composed of water. Water is the solvent of biological systems. You may also recall that the properties of water are extremely unique because of hydrogen bonding among water molecules, and it provides a unique solvent in which is distributed the remaining 20% of the organic constituents, e.g., proteins, carbohydrates, nucleic acids or lipids. Furthermore it should also be remembered that the internal organization of individual cells is not random. Individual cells are composed of an external cell membrane and have suspended within them subcellular organelles such as the endoplasmic reticulum, ribosomes, mitochondria, lysosomes, Golgi complex, and most importantly the cell nucleus. Each of these structures also have a unique composition of carbohydrates or lipids or nucleic acids. The precise composition and structure are intimately involved with the physiological function required.

I. Direct Action

The amount of intracellular and extracellular water is very important to continued function of cells. Recognizing the importance of water, early investigators in the field of radiation biology elaborated a theory called Target Theory. The target theory is a biological concept in which certain essential molecules ("targets") must be inactivated ("hit") to result in a lethal event. Given the constituents within a cell there were two basic mechanisms that were described. The first is a direct effect in which the ionization occurs directly within the essential target molecule which subsequently inactivates that target molecule. In today's science we largely accept DNA as being the most essential target within mammalian cells for continued reproductive integrity of individual cells. This is due to its function as the repository for all genetic information required for function and survival of a cell. The actual nature of the damage to DNA can be described as follows: DNA is a double stranded helical molecule that has on each strand a defined sequence of nucleic acids, each base providing an important additional component to the genetic code. Because the structure of DNA is a double strand, radiation may effect either one or both of the strands of DNA. If radiation injury occurs in a single strand of the DNA, repair mechanisms normally found within cells may correct and restore the strand breakage. The exact nature of this repair is still largely incomplete. Certainly, two outcomes to any repair to DNA can be envisioned: one is that the repair is perfect and there is no evidence of radiation injury; alternatively, the repair is imperfect or leaves an area unrepaired such that the genetic sequence in that area of the DNA strand has been altered. Even a single base change is defined as a mutational event. Misrepaired areas of DNA are small and frequently undetected and therefore sublethal in nature. This is most likely due to the vast amount of redundancy within the DNA and the fact that not all components of individual molecules are essential to their function. The other possible alternative following radiation interaction is that double strand breaks

may occur within the DNA. Repair of these lesions is highly unlikely since there is no complementary strand of DNA which can be used as a template to repair the damaged strand of DNA. Therefore, at a minimum, there is a loss of genetic material with every double strand break within the DNA. This form of damage also ranges from sublethal in nature to lethal depending on the actual location within the genetic sequence that is being affected.

Overall the radiations which are encountered clinically will interact most frequently with single strands of DNA rather than with double strands of DNA. These types of radiation are termed low LET or Linear Energy Transfer radiations. Examples of these would be x-rays in diagnostic radiology, photons in x-rays in radiation oncology, and photon emissions from nuclear medicine procedures. Therefore it is important to stress that the majority of all radiation interaction in DNA are a repairable event and that many of them are repaired perfectly. After all it must be remembered that we as a species have evolved and lived on earth in an atmosphere of radiation for millions of years. Although we have changed as a species, we in fact are still here. It is important to remember that depending on where you live in the United States or around the world, you may be exposed to a 100 millirem of radiation per year and therefore up to 8 rem or 8000 millirem during your overall lifespan. Lastly it must also be reiterated that interaction of radiation with DNA is a very low probability event. Low LET radiations interact randomly with an absorber; therefore, they will interact most frequently with the substance or substances that are present in the greatest concentration. On this basis DNA is not the most abundant substance within the cell and therefore would not be interacted with very efficiently. The most abundant substance within the cell is water. There are some 1.2×10^{24} water molecules for every molecule of DNA within cells. Therefore it is far more likely that radiation would interact within the water within a cell than within the organic constituents suspended within that water. This leads to the second main part of the Target Theory or the indirect action theory.

II. Indirect Action

The indirect action theory states that an ionization occurs in something other than an essential target molecule within the cell and that this non-essential substance within the cell somehow dissipates its energy to the essential molecule within the cell. In the case of water we describe these events in terms of the radiolysis of water. During the radiolysis of water, an ionization occurs within a given water molecule, and by definition an electron is liberated. The aqueous or hydrated electron which has been liberated associates itself with a nearest neighbor, again another molecule of water. The result within the cell is a positively and negatively charged water molecule. These two molecules decompose rapidly to form the corresponding ion and a free radical. A free radical is a substance which is characterized by an unpaired spin electron within an orbital. The absence of this spin electron makes a free radical highly reactive and they last only a brief time as an individual entity. The actual

duration is less than a second and frequently is on the order of a microsecond or less. The most damaging of the free radicals created within water is considered to be the hydroxyl free radical. The hydroxyl free radical is also very important in the bioenergetics of cells under controlled situations. Passage of radiation through a cell and its random interaction within the intracellular water may create free radicals in locations which are inappropriate. Furthermore, once the energy has been absorbed or transferred from an incoming radiation such as an x-ray or photon to a cellular structure, this energy can now be dissipated among other cellular structures. The free radicals, being highly reactive, will either donate or capture an electron rapidly within the microsecond of their existence. This may occur within other water molecules or it may occur within organic constituents within the cell such as proteins or lipids or it may occur within the DNA of the cell. All of the reactions of course are possible due to all surfaces with the mammalian cell being hydrated. The yield of each of the free radicals will vary depending on the temperature conditions, the amount of oxygen within the cell and the pH. Interactions of the free radicals can also result in strand breakage within the DNA or crosslinks between groups within the DNA. They may also damage side chains of proteins which may affect their secondary and tertiary structure and therefore, function (e.g., enzyme activities). Free radicals may also interact with lipids to form peroxides of unsaturated fatty acids. These may provide leakage areas within membrane barriers such as the mitochondrial or cell membrane. Indirect action probably accounts for more than 90% of all radiation injury. Again it must also be stressed that although the initial damage may be through the indirect pathway, the ultimate expression of cell lethality due to the inability to divide would be damage to the DNA. If the damage sustained results in immediate lethality of a cell then the probabilities would increase that membrane damage had occurred which resulted in permeability changes to the cell and caused an inflow of calcium which dramatically altered the cell's ability to function under normal conditions.

CELLULAR RADIOSENSITIVITY

The initial concepts of cellular radiosensitivity were first elaborated around the turn of the century by Bergonie and Tribondeau. They stated that three basic characteristics made a cell more radiosensitive:

- cell has to be primitive or undifferentiated
- it has to divide rapidly
- and also should divide for a long period of time

Subsequently other investigators (Ancel and Vitebmurger) said that all cells had the same inherent radiosensitivity but the expression of that damage may be dependent upon the conditions the cell was exposed to immediately before or after radiation. During the intervening years we have also learned that this variable to the time of expression of damage is very important in understanding radiosensitivity.

Strictly defined, classical radiosensitivity is the rate of response for a given endpoint following irradiation (i.e., the sooner the biologic response is observed, the more radiosensitive the endpoint must be).

I. Cell Cycle

At the turn of the century two basic mechanisms of cell death were thought to exist: mitotic death and interphase death. A mitotic death is one in which a cell dies during mitosis versus an interphase death in which the cell dies in some other phase of the cell cycle, that is G-1, S-phase, or G-2. As techniques became available individual phases of the cell cycle were tested for radiosensitivity. It was found that the mitotic or M phase of a dividing cell population was the most sensitive phase of the cell cycle for lethal radiation injury. The mechanism of this lethal event is still largely unknown. A variety of reasons have been elaborated to include:

1. M phase is the shortest phase of the cycle
2. DNA exists in a supercoiled or highly condensed physical and supercoiled structure
3. That the enzymes responsible for repair may not be present during that phase of the cell cycle

There is probably some combination of all of these suggested mechanisms. Strand breakage may occur to the chromosomes or the supercoiled structure of DNA but because of the supercoiling, there may be inability of the repair enzyme to find the site of actual damage or breakage of DNA if the enzymes were present, and there is some speculation that the enzymes and DNA precursors are extremely low in concentration at that time. Because of the brief duration of the M phase there would be no chance to go back and synthesize more proteins to institute that enzymatic repair. This difference in sensitivity may be as much as a factor of 40 compared to other positions around the cell cycle. The most radioresistant phase of the cell cycle is the S phase or Synthetic phase of the cell cycle and the converse of the reasons given for the sensitivity of mitosis will apply to the resistance of S phase; i.e., it is the longest phase of the cell cycle, the DNA is in a linear configuration and actually exists as a sequence of single strand, broken fragments that will ultimately be polymerized during the S phase. And lastly there are optimum concentrations of precursors and the enzymes to actually synthesize DNA during this period of the cell cycle.

II. Temporal Component

Important as well is the frequency with which cells divide and how long they must continue to divide. The more frequently cells divide, the greater the cell turnover factor per unit time. Therefore the more quickly noticeable a loss of new cell production would be noted (hypoplasia). Again these basic principles relate back to

the original characteristics of radiosensitive cells. A basic issue however would be what about cells which died later because they divided more slowly. Are they less radiosensitive? Using the classical definition the answer would be yes; however, common sense would tell us that if an equally devastating effect may be measured six months from now rather than today, then we should change our definition of the relative point of radiosensitivity.

Appearance of damage from radiation injury is frequently seen during irradiation with a therapeutic intent. Examples of the differential appearance of radiation damage can frequently be seen with radiation therapy patients. Clearly there are a variety of tumors that occur within the human body which have different degrees of responsiveness to radiation therapy. Those tumors which respond rapidly have frequently been termed radiosensitive tumors such as a lymphoma. However other tumors which show the evidence of radiation injury much later after therapy has been completed have been termed radioresistant tumors. The dichotomy presented then is for an equal number of cells being killed in each tumor mass to result in the disappearance of the tumor--one was more sensitive than the other because it did it faster. Today's standards and definitions may find a new temporal timepoint being associated with them. A classic example is the whole body lethality of radiation which displays a prominent temporal timepoint associated with the onset of symptoms and lethality. This describes the systemic effects of radiation exposure when the radiation is delivered across the total body and done in a brief period of time.

RADIATION SYNDROMES

The survival time of an organism following whole body or total body irradiation is expressed as the mean or average survival time. This timepoint infers the mechanism of death, specifically, the organ which failed and therefore resulted in death of the organism. Certainly there are variations among species as well as between various members of the same species. The lethal dose to 50% of individuals exposed or the LD 50 dose has been compiled for a number of species. In man it is frequently stated that the LD 50/60 is 350 rads. Obviously this number would have associated with it a standard deviation, plus or minus. The value itself should be taken in context with a variety of syndromes which can be elicited following total body irradiation.

Doses of radiation in excess of 100,000 rads may result in a syndrome which is termed molecular death. This syndrome is characterized by symptoms of convulsions and coma. Death occurs within minutes to hours of the exposure. These dose levels would not be encountered in any medical situation. These would be associated with nuclear warfare or accidental exposures in such facilities as a Plutonium reprocessing plant.

II. Genetic Effects of Irradiation

1. Male Reproductive Tissues

The genetic effects of radiation are seen most profoundly in radiation effects upon reproductive tissues. Obviously the nature of the expression of radiation injury would differ between male and female because of the difference in the mechanism of cell production of germ cells in male and in the female. In the male, mature sperm are the result of a continuous cell renewal process. Cells which are dividing have been previously stated to be more radiosensitive than those which are not rapidly dividing. Therefore the first evidence of radiation injury within the testes would be the absence of the dividing cell pool within type B spermatogonia. However, the long term effects of irradiation are evident in the genetic mutations found within mature, non-dividing sperm. The expression of that damage obviously is to future generations. Again the dichotomy arises between direct cell kill and genetic alterations as a measure of radiosensitivity. Cell kill of type B spermatogonia may require doses as low as 25 - 30 rads to reduce their number to 50% of pre-irradiation values. Absorbed doses as low as 3 rads may result in a detectable decrease in the number of mature sperm. Much higher doses in the area of 600 - 1000 rads would be required to insure long term infertility. It takes approximately 3 months following an exposure to radiation for the sperm present at the time of irradiation to be cleared from the system. Therefore it is frequently recommended that following a significant exposure to the testes on the order of 1 - 5 rads that it may be appropriate to delay conception for approximately 6 months to one year.

2. Female Reproductive Tissue

Female reproductive tissue is not composed of a continuous cell renewing system. Instead a fixed number of primary oocytes can be found within the ovaries, the approximate number is one million. After birth the oocytes mature into secondary oocytes and polar bodies or a mature follicle. The secondary oocyte completes division upon fertilization. In the human this division starts at ovulation. As a result of this division we have the egg or ovum and three polar bodies formed at each cycle of menses. In the human female a single dose of 50 rads to the ovaries will cause infertility, however a minimum dose of 400 rads or a fractionated dose of 1500 rads over 15 days would produce permanent sterility in most women. Low level radiation exposure to the oocyte may be filtered out by the process of meiosis which occurs in the final division in the formation of the ovum and the three polar bodies. The reductive or meiotic division may filter out damaged copies of DNA. Additionally the actual process of embryogenesis may be so complex that only the most viable and healthiest of the DNA copies will go on to form an entire fetus. It has long been recognized that spontaneous abortions are associated with a greatly increased mutation frequency within the aborted fetus. The assumption being that only the most healthy copies of DNA would be competent to complete an entire new organism.

Doses as low as 1500 rads may cause central nervous or CNS syndrome. This syndrome is characterized by hyperexcitability, incoordination, ataxia, respiratory distress, stupor, coma, vasculitis, meningitis, encephalitis, and brain edema. The time to death from CNS syndrome is approximately 1 - 3 days and, like the molecular death syndrome, is universally lethal.

At dose levels between 250 - 1500 rads a gastrointestinal death may be induced. The symptoms from a gastrointestinal death are characterized by nausea, vomiting, diarrhea, GI bleeding, and severe electrolyte loss. The time to death during a gastrointestinal syndrome is approximately 5 - 14 days. The mechanism of GI syndrome is a failure to replenish mucosal lining cells within the bowel (a continuous cell renewal system). The shorter the time to death, the higher the radiation dose. Even within the gastrointestinal syndrome 50% of the individuals exposed to a 750 rad dose of radiation would survive beyond 14 days. However, they would not survive indefinitely.

Doses of radiation absorbed between approximately 200 - 600 rads would result in hematopoietic death which would result within approximately 30 - 60 days. The mechanism of death and the symptoms induced are due to bone marrow aplasia, hemorrhage, and infection. Even within this category survival is still probable. Below doses of 200 rads survival is highly probable but symptoms can still occur. Symptoms of the prodromal syndrome may include skin erythemas and blisters, a desquamation of sublethal but total body radiation - immunosuppression, carcinogenesis, and long term genetic mutational effects.

SUBLETHAL EFFECTS OF TOTAL BODY IRRADIATION

1. Immunosuppression

The degree of immunosuppression following whole body radiation exposures will be dose dependent. It would also be dependent on the total volume of lymphoid tissue irradiated if the radiation exposures were not whole body. Long term immunosuppression may result from doses of approximately 200 rads, although doses much higher than this are required to insure permanent immunosuppression for the conditions of bone marrow transplantation. The recovery of the immune system is dependent upon two factors: 1) the recovery of bone marrow progenitor cells which give rise to both T and B lymphocyte precursors and 2) the extent of radiation injury to peripheral lymphatic structures. During the recovery period individuals would be susceptible to bacterial and viral infections and may provide the greatest management problems for the health care professional in the event of nuclear warfare.

3. Carcinogenic Aspects of Irradiation

Carcinogenic is another long term side effect of radiation exposure. Although the mechanism of cancer induction is not yet known, two broad categories of hypothesis have evolved. The first hypothesis is that there is some genetic alteration within the DNA such as the addition of a viral genome or the deletion of genes from the DNA. Once this genetic alteration occurs then changes may develop in the growth control mechanisms and cancer cells may accumulate. The other broad hypothesis is genetic activation which represents a theory in which cancer arises from either the activation or repression of normal genes within the DNA. This importantly implies that cancer may be a reversible disease process through genetic modulation.

The most sensitive cancer thought to be induced or influenced by ionizing radiation is leukemia. The risk of leukemia is thought to be approximately 15 - 25 excess cases per million people exposed per rad across their lifespans. That is approximately 1 in 100,000 people exposed to 1 rad would get a radiation induced leukemia. Other cancers associated or thought to be radiation induced include skin cancers, thyroid cancers, breast cancer, and gastrointestinal tract cancers. It should be stressed that no individual cancer can be indisputably known to be induced by radiation. Once a cancer is formed, it may be identical to a spontaneously occurring type of cancer, i.e., there is nothing pathognomonic about a radiation induced neoplasm versus the same neoplasm which arose spontaneously.

The dose response relationship between absorbed radiation dose and the increased risk for cancer induction is highly controversial. To provide greatest safety, a linear dose response curve is assumed within the low dose region. Therefore, we assume that for every increment in dose absorbed there is an increased risk of cancer formation. Again it must be stated that for the purposes of protection and safety standards the assumption is that the risks are linear at the low dose region and these risks are determined from a back extrapolation of much higher exposure levels from such populations as Hiroshima and Nagasaki, fractionated exposures from patients with rheumatoid spondylitic arthritis, the early American radiologists, multiple fluoroscopic tuberculous exams, and postpartum mastitis patients among other groups. Until we know the exact influence of various dietary factors and lifestyles for the risk of cancer in addition to radiation, exposure linearity is probably the safest assumption to make. Interestingly, the incidence of radiation induced neoplasia tends to correspond to the frequency with which those same tumor occur spontaneously.

RADIATION EXPOSURE STANDARDS

It therefore becomes very important to understand the total dose levels that are permitted within the work atmosphere as well as to the general public. The importance of this comes not just to the individual who is exposed to radiation but also to future generations. With this in mind a series of concepts have developed over the last three

decades involving concepts of maximum permissible dose (MPD) and of maximum permissible concentrations (MPC). These concepts are based upon the belief that there should be some maximum limit which is established, and if these limits are not exceeded there will be no adverse effects such as carcinogenesis and genetic alterations. In reality, the MPD represents the best educated guess to arise from existing literature, reviewed periodically, and updated if necessary. Since the first standards were issued during the mid-1950's, the overall MPD has decreased in various categories during these years. MPD has also been referred to as the lower limit of totally acceptable radiation standards which further stresses the importance of minimizing exposures.

Stochastic versus Non-stochastic Effects

The principal objective in assigning MPD standards is to achieve and maintain appropriately safe conditions for activities involving human exposure to ionizing radiation from occupational and medical or dental exposures such that 1) we prevent non-stochastic effects from occurring, 2) limit the probability of stochastic effects considered acceptable to the individual and society as a whole, and 3) insure that the practices of radiation exposure within the society are justifiable i.e., a risk benefit analysis must be undertaken. As previously mentioned, the principle effects are those which may be somatic or of importance to the given individual or hereditary, those problems to future generations. In the category of stochastic effects, these are effects which there is a probability of occurrence regardless of whether or not radiation is involved. Occurrence is a function of the probability of the event and the severity is not dose related. These are considered to occur as a function of dose without a threshold level. Examples would include carcinogenesis and hereditary effects. Non-stochastic effects, those for which the severity of the injury varies with the radiation dose involved and vary according to the particular tissue injury under consideration such as cataracts of the lens of the eye or impaired fertility. These events are likely to follow a threshold dose concept, i.e., there may be doses below which these effects are not detectable and therefore there are no detrimental health effects with regards to protection standards. Obviously we must prevent the preventable in terms of the non-stochastic effects (those that are strictly dose related), and we must try to limit the occurrence of stochastic effects which may increase in probability of occurrence with increasing dose of radiation.

Another concept which is frequently mentioned but rarely defined adequately is the concept of detriment. Detriment is defined as a mathematical expectation of harm incurred from exposure to ionizing radiation in a population. It must include both the probability and the severity of the effect. The impact from these kinds of concepts would be as follows: the average maximum lifetime risk for all cancers within the general population due to the exposure and radiation standards that are presently in force would be 125 excess cases of cancer per million people exposed per rem. For the radiation occupational work force exposed to the maximum amount each year

across the working lifespan, an increase of 100 excess cancer cases per million people exposed per year would result. The average risk factor for fatal cancers rather than all cancers is approximately 1 in 10,000. This is to reflect that the majority of tumors which are induced are, in fact, non-fatal cancers.

One of the overriding principles and guiding cornerstones of protection standards is the ALARA principle. ALARA is an acronym which stands for As Low As Reasonably Achievable. The concept is an extension of the original NCRP recommendations to keep all radiation exposures at a level as low as practicable and below the maximum permissible dose. Title 10 of the Code of Federal Regulation, part 20, the term As Low As Reasonably Achievable means that we take into account the state of technology and the economics of improving the relationship of benefits to the public health and safety and other social and socioeconomic considerations in the derivation of protection standards. Today these concepts of ALARA are applied to almost every aspect of radiation such as shielding, shipping containers, actual amount permitted in therapy, and diagnostic uses of radiation. Ultimate decisions regarding regulatory standards are given to our governmental bodies such as Congress, the Bureau of Radiologic Health, the Nuclear Regulatory Commission, the Environmental Protection Agency, Occupational Health and Safety Agencies, as well as individual State Departments of Health. These protection standards govern the amount that you as a worker are permitted to be exposed to. These are the reasons why fingerings, pocket dosimeters, or film badges are handed out to nurses for their duty shift when a patient on their floor has either received radioactive materials or has radioactive sources placed within the body.

FETAL EFFECTS OF RADIATION

One of the greatest worries about radiation to both the general public and to those who are occupationally exposed is the fear that radiation may damage a developing fetus. This is regardless of the amount of radiation or the length of exposure working with radiation. Many times the worries are well founded while many more times the concerns are really based on wives' tales and a vast amount of ignorance. The major considerations when a woman finds out that she was irradiated during the early stages of a pregnancy, which was unrecognized at the time, is will the baby be normal? What they really want to know is will the baby be deformed at birth. The answers to these questions either implied or stated about fetal effects of radiation must be detailed in terms of two basic parameters: 1) the time post-conception that the irradiation occurred and 2) the total dose of radiation that was sustained. Even when all of this information is known the answers are frequently equivocal. The most crucial question becomes if the baby has no malformation, will it continue to be normal?

At doses less than 10 rads the most significant and probably the only effect on the embryo will be the induction of genetic effects i.e. chromosome aberrations or gene mutations or both in some cells to produce a mosaic individual. A mosaic in terms of fetal effects would be that varying proportions of cells contain the genetic alteration whereas varying proportions would also be normal. The consequences of the somatic mosaicism though real would be expected to be subtle and that they would not be recognizable at birth. The earlier during pregnancy or gestation that genetic effect has occurred, the greater the proportion of cells that would share that genetic alteration. This leads to one of the very first effects that can be measured during gestation. Irradiation of a preimplantation embryo has the greatest probability of causing preimplantation death. At the time of implantation approximately 100 cells constitute the entire developing embryo. If a genetic alteration is sustained during this period the outcome may be lethal to the developing fetus. Since pregnancy is not known at this time, the apparent effect may be a failure to become pregnant. Although the genetic damage may be sustained prior to implantation, the continued development and growth in utero may be severely inhibited or prevented because of the genetic mutation. The same dose of radiation sustained later in pregnancy, when more differentiated cells are present, may not carry the same biologic impact. Although the outcome of the irradiation of an early developing embryo has a very significant impact, namely preimplantation death, clinically it becomes less obvious when the impact is to the individual. This is largely because pregnancy is unrecognized at this time. Implantation occurs approximately day 10 in humans whereas the first menstrual period is missed approximately 14 to 15 days after conception, therefore the risk of preimplantation death really occurs before pregnancy is known.

Following implantation the next major event to occur is the development of the primitive embryonic tissues which will give rise to all organs and internal and external structures of the fetus. Shortly following implantation, differentiation of ectoderm and endoderm begin. Ectoderm gives rise to the neural tissue by approximately day 18. This primitive neural tissue or neural plate will give rise to the central nervous system and the peripheral nerves. As you might expect, it is only during the fetal development period that the nervous system continues to grow and divide. Division within the central nervous system is complete by age 2 and therefore is less susceptible to the same injuries by radiation. The other major tissue, the endoderm, will give rise to the major organs of the body. A combination of these two tissue types interact to form all of the recognizable structures of the heart and arm and leg buds during early fetal development by day 27. The third and last primitive tissue differentiates the mesoderm. Mesoderm will give rise to the lining of the body cavities and blood forming organs. Again during this particular time, major organogenesis is occurring. Irradiation during this time period has its greatest effects on organogenesis. These effects are usually seen at birth as organ abnormalities many of which are not compatible with post-natal survival. This continued sensitivity to radiation for organ abnormalities persists for approximately day 10 to day 42 post-conception. Again, it

must be reiterated that pregnancy is not known or detectable until well into this particular period of growth.

Many of the organ abnormalities are associated with damage to the neural tissue and most may be attributed to the lethal effects of radiation on the neuroblast, the dividing component of the central nervous system. The reason why the majority of all organ abnormalities are associated with the CNS may relate to two basic conditions: 1) this is the only time the central nervous system divides such that damage sustained in that tissue will not be compensated for by future divisions or to dilute out the nature of the damage and 2) it may also be that an intact and functioning neural tissue, although primitive, may be extremely important in the formation of organ structures within the body. Following the first 6-7 weeks of gestation, the same organ abnormalities and risks of pre-natal death are greatly diminished.

After approximately day 45 all major organogenesis has been completed, and now the process of creating more bulk to each individual organ is the major or principal finding in each organ. Now the same dose of radiation, rather than preventing the development of a given organ, may simply give rise to a brief degree of hypoplasia within that organ which may be compensated for by proliferation from surviving normal cells. Therefore the same dose that earlier in pregnancy may have caused pre-natal death for an organ abnormality following the first six weeks will now give rise to a different set of events. The major risks during the fetal stage age include: 1) the risk of cancer induction in years after birth; 2) mental retardation due to damage of the developing nervous system, i.e., the neuroblast; and, 3) growth retardation of growing bones. The increased risk of cancer induction due to in utero radiation exposure is difficult for some individuals to accept. The reason for this is that the latency period for induction of the most sensitive cancer thought to be induced by radiation (i.e., leukemia) would be approximately 5-7 years. This latency period also coincides with the peak of incidence of spontaneously occurring leukemia.

The incidence of leukemias are increased in children who were irradiated in-utero. This has been seen in a number of studies in both England as well as the follow-up of the Hiroshima and Nagasaki bomb blast victims. In each study the types of leukemias that are induced were acute lymphatic leukemia and stem cell leukemias in young children. These are also the same cellular types of leukemias that are found in greatest predominance without the influence of radiation. Although still controversial, many experts would regard that the risks of leukemia would increase by a factor of 1.5-2.0 as a result of 1-5 rads being delivered to the developing fetus. Although the quantitative data are not available, the conservative assumption would be that a linear response curve or no threshold dose would be appropriate to assign risk of developing leukemia following irradiation during this sensitive growth phase.

The second major effect during the fetal period is even more controversial, i.e. mental retardation. It is extremely hard if not impossible to document and quantify the intelligence potential of the developing fetus prior to the time of irradiation. Therefore any decrement in mental function is difficult to attribute to a single event of irradiation. The overall control of neural function is probably polygenic in nature, meaning that it requires more than 1 gene sequence and more than 1 cell type. There is extensive communication among cells. It certainly must be accepted as a possibility that radiation can irreversibly damage and kill developing neuroblasts. The functional loss of a neuroblast or its subsequent progeny may be unpredictable since we are unable to know *a priori* its potential. Currently only those extreme cases of severe mental retardation, without any other identifiable interferences from dietary, hormonal or genetic effects from either parent, can be attributed to the effects of radiation. In these cases they are very large doses in excess of 100 rads.

The last effect previously mentioned during this particular stage and throughout development would be growth retardation. As with the case of mental retardation, growth retardation involves a cell kill phenomena within a very sensitive developing tissue. Long bones during physical development are increasing both in length and in width in a very complex process of deposition of new bone and eroding both in length and diameter of the bone. Stunting or scoliosis of bones may occur when radiation is differentially absorbed across the growth plate of long bones. The side which has more surviving cells continues to grow and curve the bone toward the direction where more cells were killed. Again these kinds of effects are rare within the literature but certainly are possible due to the lethal actions of ionizing radiations.

To summarize fetal effects, it would be unfair to suggest that in the absence of any radiation dose that a parent can be guaranteed a normal and uneventful pregnancy. A variety of studies suggest that even in the absence of radiation exposure that approximately 2-3% of all newborns will have a malformation detectable at birth, plus an additional 3-5% may show an abnormality by approximately age 7. Therefore no one can guarantee that you will have a normal child. The second major fundamental factor to stress is that we can only define probabilities of injury to a given pregnancy based on the total dose as well as the time post-conception it was absorbed. These probabilities have two outcomes to an individual—either we're right or we're wrong. In this kind of very primitive risk benefit analysis one must weight a variety of psychological, sociological, and potentially economic factors in the decision process as to whether or not the probability of injury is a major influence in this particular pregnancy. Obviously radiation is not the only perturbation during fetal development. A significant positive impact has been achieved by increasing the nutritional status of mothers during the gestation period. This may be an important factor following irradiation. How extensively will the diet that the mother follows influence the effects of the radiation on the developing fetus? Likewise what hormonal stresses are placed on a developing fetus based on severe psychologic and economic constraints relevant

to the family effect normal fetal development, and in turn, how would this effect a pregnancy following irradiation? Could the parents deal with the probability that this child may potentially be retarded? A variety of decision guidelines have been used over the years to make recommendations to patients concerning the impact of the given dose of radiation in their particular pregnancy? During the first 6 weeks of pregnancy doses of 25 rads or greater are associated with a very high probability of inducing an organ abnormality, detectable at birth. Many of these abnormalities may not be compatible with post-natal survival. At this level of risk a strong recommendation for a therapeutic abortion of this particular pregnancy is indicated. At doses between 10 and 25 rads during the first 6 weeks of pregnancy the risk of organ abnormality is still very substantial and may also give rise to the same effects as 25 rads. In these cases the recommendation to parents should be that an organ abnormality is a possibility and to consider how they would view an abnormal child, i.e., could they accept the potential problems in this pregnancy. Doses of 5 - 10 rads during the first 6 weeks of pregnancy do not immediately infer that a therapeutic abortion should be performed. Between doses of 5 - 10 rads a complete history should be taken to determine the extent of other co-factors which may influence normal development in this particular pregnancy. Such factors as difficulty in becoming pregnant, incidence of still births and malformations among siblings who have had children, the amount of cancer in siblings, a variety of other dietary considerations, as well as lifestyle including such things as smoking and alcohol habits should be evaluated. If these co-factors suggest an increased probability for an organ abnormality or other problems in this particular pregnancy, then the recommendation would be weighed more strongly toward a therapeutic abortion. If these co-factors are found to be negative for this particular pregnancy or the radiation dose is between 1 - 5 rads then the recommendation to the patient may be to take a "wait and see" kind of position. At doses less than 1 rad, the risks to an individual pregnancy do not justify any drastic intervention. Although we can never be totally sure that one rad would have no effect in that particular pregnancy, the probability of defining that effect in a single pregnancy would be virtually impossible.

For those individuals who are occupationally exposed to radiation as part of their daily activities, more stringent and restrictive conditions are placed on the amount of radiation exposure allowed. The reasons for this position is that because of their increased probability of being exposed during an early stage of pregnancy, greater safety margins should be assumed to protect the developing embryo which is viewed as a non-occupationally exposed individual with regards to radiation safety standards. The maximum amount of radiation dose that can be absorbed throughout the entire gestational period for a radiation worker is 500 millirem or 0.5 rem. The assumption for permitting these exposures are: 1) the dose is being accumulated in a gradual fashion throughout the entire gestational period, and 2) that every safety precaution is being taken to insure that the dose is kept as low as possible.

Once again it must be reiterated that we cannot guarantee a "no risk" pregnancy. Many people would opt to take early medical leave to insure that the dose is kept low to the developing fetus. It is important though to reiterate and review the data that was presented earlier that the most severe and damaging effects of radiation in a pregnancy are sustained prior to the time that a pregnancy is detectable. Therefore early medical leaves really do not increase your probability of having a normal child. The most appropriate way to reduce any potential harm from radiation is to follow the defined radiation safety standards and the principles and practices that are recommended. Again the assumption of ALARA should be followed as strictly as possible to keep the dose as low as reasonable achievable.

It is equally important to reinforce a very basic concept that it is your right to continue working although pregnant in the areas of radiology, nursing or any potential occupation where you might be exposed to radiation. Your employment cannot be terminated until you have reached a 0.5 rem limit. The decision to take early medical leave is one of the employee's not the employer's. The employer must try to accommodate an employee by attempting to find a position that would insure the lowest possible exposure as the 0.5 rem level is being reached. The employer may need to double badge an employee and change the film badges out on an every two week basis rather than every four week basis to maintain the most current exposure history. It may also mean that other employees in the unit be requested to take the increased duties in higher dose areas such as emergency procedures, special procedures or work within the radiopharmaceutical area within nuclear medicine. Other accommodations may include polling other employees to accept assignment in the higher dose areas while the pregnant employee works low dose areas such as a chest film unit or other areas within the department. Ultimately it is the responsibility of the employer to dismiss a pregnant individual and prevent them from exceeding the 0.5 rem limitation, but again this must be done very carefully to insure that the rights of the individual to obtain a living are not infringed.

SUMMARY

The important effects of radiation can be summarized as follows: 1) radiation may affect most easily those cells which are dividing, 2) the principal effects of radiation are genetic alterations which may affect an individual cell during that potential cell cycle or may subsequently impair the cell's ability to survive, 3) most cells die during mitosis during a later division and therefore the effects of radiation are thought to be cumulative in that radiation damage has a delayed impact to an organism, and 4) probably the most sensitive phase during development of our species is during the fetal and embryonic stages. During this time very low doses of radiation, less than 10 rads, may exert an influence on a developing embryo or fetus.

It is important for nurses and other health care professionals, not routinely associated with radiation in the work place, educate themselves as to the proper safety procedures, precautions, and standards that they must follow. Nurses must carry out their role of caring for patients and must also insure that unnecessary risks from radiation exposure are not taken. Finally, neither role can be compromised due to ignorance.

IMPORTANT CONCEPTS OF CHAPTER FOUR

1. The immediate biological effects of radiation are dependent upon the total dose absorbed by the body:
 - a. these effects occur at doses much greater than permitted in the routine hospital environment.
2. The total dose of radiation absorbed is determined by dose rate x time. Therefore, the total dose absorbed will be reduced by:
 - a. duration of exposure - preplan activities around patient containing radioactive materials
 - b. distance from the source - inverse square law (dose rate decreases by $1/d^2$)
 - c. shielding - use leaded aprons, gloves, glasses, thyroid shields
3. The long term effects of radiations (e.g. genetic risks, carcinogenesis) increases initially in a linear manner with increasing dose, but their severity are unrelated to the total dose absorbed.
4. Ionizing radiation interacts in a random fashion in cells therefore only probabilities of injuries exist. These probabilities may change in a variety of ways with respect to dose delivery - dose response curves.

5. Monthly film badge exposure reports are for the employee and reflect the safety of standard practices in the environment.

a. Reports must be posted for your inspection.

b. Badge must be worn in the most likely area that will be exposed.

c. Wear only the badge assigned to you

Chapter 5

Personnel Dosimetry - Methods and Interpretation of Results

Personnel dosimetry refers to the measurement of an individual's radiation exposure (i.e., in milliroentgens) and the resulting *dose equivalent* (i.e., in millirems, or centisieverts) [See Chapter Two for description of these units] assigned to that individual depending upon the type and energy of radiation to which the individual has been exposed. As a health care professional, your work may include the caring of a radiation therapy patient which would require the need to monitor your radiation exposure obtained during your working hours. There will be occasions in which you may work with patients who have undergone *diagnostic* nuclear medicine tests where radiation exposure levels to attending personnel are much lower and thus monitoring is not required. Whether you are assigned a personnel dosimetry device is usually determined by the radiation safety officer of your facility.

The most commonly used personnel dosimetry devices include:

1. film badges
2. thermoluminescent dosimeters (TLD's)
3. pocket dosimeters

Each of these will be discussed separately, indicating proper care and individual strengths and weaknesses. Before each type is considered, several important points should be made to all individuals wearing personnel dosimetry devices regardless of type:

1. Dosimetry devices should be worn only by the individual to whom they are assigned.
2. Dosimetry devices should be worn only when on duty and at the institution which provided the dosimeter.
3. Dosimeters should not be worn during medical or dental x-ray procedures ordered by your personal physician or dentist.
4. When not being worn, dosimeters should be stored in a safe, secure location away from known radiation sources.
5. Great care should be taken not to lose your dosimeter or leave it attached to clothing to be cleaned.
6. Should you lose your dosimeter, notify your radiation safety officer to obtain a replacement before continuing to work with radiation sources.

devices, is proportional to the amount of radiation to which badge and wearer has been exposed.

These dosimeters may be assigned to individuals for short periods of times (e.g., for the duration of an individual therapy) or for an entire working period of up to three months. The time periods for which dosimeters are assigned will be determined by the institution's radiation safety officer.

Several advantages of TLD's include the following:

1. TLD's are relatively insensitive to normal variations in humidity and temperature.
 2. TLD's are generally very sensitive to low radiation doses and respond over a broad exposure range.
 3. Lithium fluoride crystals used in TLD's are very similar in absorption characteristics to human tissue, making them almost *tissue equivalent*.
 4. TLD crystals may be reused.
- Care should be taken with TLD's (in addition to those precautions previously mentioned for all dosimeters) not to expose them to extremes in heat since this could possibly cause the dosimeter to read lower than the actual acquired dose.

POCKET DOSIMETERS

The pocket dosimeter finds its primary use in emergency situations where an *immediate* reading of the radiation exposure to an individual is necessary. Whereas other dosimeter devices require that they be returned to the supplier for processing, the pocket dosimeter can be read directly and at the location where it is being used.

The pocket dosimeter consists of a simple electrical charging device which, when fully charged, moves a thin quartz fiber across a scale calibrated in units of radiation exposure (i.e., roentgens or milliroentgens). The unit is contained within a pen-type housing which can be clipped on the uniform or into the pocket of a lab coat. When exposed to penetrating ionizing radiation (i.e., X or gamma rays), the charge on the fiber is neutralized and the fiber migrates across the scale according to the amount of radiation to which the device has been exposed. This reading will then provide an immediate estimate of the radiation dose received by the wearer. Immediate readings can be obtained by direct viewing of the dosimeter scale through the eyepiece. Typical scales and several indicated readings are shown on the following page.

7. All efforts should be made to return personnel dosimeters to your radiation safety officer at the designated times for processing.

Each type of dosimeter most commonly used at medical institutions will now be considered.

FILM BADGES

Film badges are perhaps the most common type of personnel dosimeter utilized. This type of dosimeter makes use of the fact that photographic film tends to *darken* upon exposure to ionizing radiation. The degree of darkening is then directly related to the amount of radiation to which the film has been exposed. Fresh, light-tight packs of film are placed within special plastic holders usually at the beginning of each new month. Film packs exposed to ionizing radiation during the past month are usually returned to the institution's radiation safety officer for processing.

Film badges are most widely used to monitor *whole body radiation exposure* and thus should be worn attached to the clothing at *approximate sternum level* unless directed otherwise by your radiation safety officer.

In order to assure accuracy of exposure readings obtained with this type dosimeter, the following precautions (in addition to those previously mentioned) should be taken:

1. film badges should not be exposed to extreme heat.
2. film badges should not be exposed to excessive moisture or humidity.
3. film packets should be processed within a short period of time post-exposure.
4. film packets must be correctly oriented within the plastic badge holder when fresh packets are inserted.

THERMOLUMINESCENT DOSIMETERS (TLD's)

Thermoluminescent dosimeters (TLD's) are usually assigned to individuals whose contact with radiation sources results in radiation exposures which would not be expected to result in a radiation overexposure over a three month period (i.e., a calendar quarter). TLD's may be used to measure whole-body exposures (i.e., a body badge) or hand exposure (i.e., finger ring). TLD's consist of plastic holders which contain a small crystal of lithium fluoride. This crystal has the property that when exposed to ionizing radiation, energy is absorbed by the crystal. When the crystal is heated (or "annealed") the energy absorbed is re-emitted in the form of light. The amount of light emitted, which can be quantitatively measured by sensitive measuring

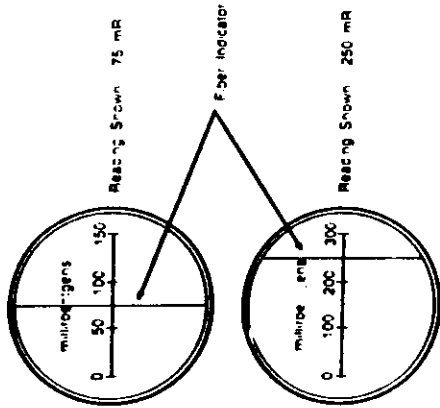
dose limit was defined by the International Commission on Radiation Protection (ICRP) as:

"The permissible dose for an individual is that dose, accumulated over a long period of time or resulting from a single exposure, which in the light of present knowledge, carries a negligible probability of severe somatic or genetic injuries; furthermore, it is such a dose that any effects that ensue more frequently are limited to those of a minor nature that would not be considered unacceptable to the exposed individual and by competent medical authorities. Any severe somatic injuries (e.g. leukemia) that might result from exposure of individuals to the permissible dose would be limited to an exceedingly small fraction of the exposed group; effects such as shortening of life span which might be expected to occur more frequently, would be very slight and would be likely to be hidden by normal biological variation. The permissible doses can therefore be expected to produce effects that could be detectable only by statistical methods applied to large groups."

This basically states that realizing that radiation is a double-edged sword, having both the power to harm and to heal, that if radiation doses received while performing your duties are maintained at levels not exceeding MPD's, there is a negligible probability, in light of current knowledge, of severe somatic or genetic injuries. All efforts, however, should be made to use the basic principles of radiation protection to keep your radiation exposure As Low As Reasonably Achievable (ALARA) yet never sacrificing the care of the patient.

Maximum permissible doses (MPD's) have been established by the International Commission on Radiation Protection (ICRP) and accepted by the U.S. Nuclear Regulatory Commission (USNRC). These MPD's are established for:

1. Different categories of individuals
for example,
 - a) Occupationally Exposed Individuals
i.e., those individuals whose work brings them into frequent contact with radiation; such individuals include x-ray techs, nuclear medicine techs, radiation therapists, radiation therapy nurses, and nurses tending special patients receiving radiation therapy; this class of individuals will always have personnel dosimeters assigned to them by the Radiation Safety Officer of the institution
 - b) Non-occupationally Exposed Individuals
i.e., those individuals who do not frequently come into contact with radiation sources, e.g., members of the general public, visitors to



In addition to the precautions previously mentioned for all dosimeters, several special precautions should be noted:

1. Records must be maintained of exposure readings obtained at the time of reading for legal documentation.
2. Pocket dosimeters must be recharged (i.e., so the needle on the scale indicator reads zero) prior to each use. If the dosimeter cannot be zeroed, the reading on the dosimeter must be recorded prior to assigning it to an individual for use. Their actual exposure will be the final reading obtained less this initial reading.
3. Care must be taken not to drop or jar this type of dosimeter since it can cause the needle to move across the scale leading to erroneously high readings.
4. Pocket dosimeters used under conditions of high humidity may also produce erroneously high readings due to leakage of electric charge.
5. Pocket dosimeters should be used only to measure radiation dose from X and gamma radiation.

DOSIMETERS AND MPD'S

Regardless of the type of dosimeter you are assigned, each exists for one primary purpose, namely to measure radiation dose received in the course of performing your duties as a health care professional. In a previous chapter on biological effects of radiation, the concept of the maximum permissible dose (MPD) was introduced. This

patient's rooms, housekeeping staff, maintenance staff, venipuncturists, staff physicians, or laboratory personnel; these individuals are not assigned personnel dosimeters on any regular basis by the Radiation Safety Officer of the institution

2. Different parts of the body

this recognizes the fact that different parts of the body are more sensitive to the effects of radiation than others, for example, the blood forming organs are more sensitive to radiation exposure than the extremities such as the hands

3. Pregnant or potentially pregnant females

a developing fetus is especially sensitive to radiation exposure; as a result, special MPD's are established to assure minimal radiation dose to the fetus

The following list of MPD's are currently recognized upper limits established by the ICRP and enforced by State and Federal regulatory agencies.

CURRENTLY RECOGNIZED MPD'S

For Occupationally Exposed Individuals
(i.e., radiologists, x-ray techs, nuclear medicine technologists, radiation therapy technicians, nurses working with x-rays or radioactive materials, etc.)

Whole Body (lens of the eyes, gonads, and blood forming organs)	5 rem (or 5000 millirems) per year
Skin	15 rems (or 15,000 millirems) per year
Hands	75 rems (or 75,000 millirems) per year
Forearms	30 rems (or 30,000 millirems) per year
All other tissues, organs, and organ systems	15 rems (or 15,000 millirems) per year
Fertile woman (with respect to the fetus)	0.5 rem during the gestation period

Emergency Dose Limits - Life Saving

Individual (over 45 years of age, if possible)	100 rems (or 100,000 millirems)
Hands and Forearms	200 rems, additional (300 rems, total)

Emergency Dose Limits - Less Urgent

Individual	25 rems (or 25,000 millirems)
Hands and Forearms	100 rems (or 100,000 millirems, total)
Members of the General Public or Occasionally Exposed Individuals	
Whole Body	0.5 rem (or 500 millirems) per year

•From NCRP Report #39, Basic Radiation Protection Criteria

These MPD's are given in units of rams, the more commonly used unit of millirems, or the newer unit of dose equivalent - the Sievert. If your work requires that you perform your duties with or within the vicinity of radiation sources on a regular basis, your radiation protection officer will assign a personnel dosimeter to you (i.e., film badge, TLD, finger ring, etc). These dosimeters will be worn for a specified period of time (usually one month) and then will be exchanged for a new badge at the end of the period. Badges turned in will be processed and a report sent to your institution indicating your radiation dose incurred during the designated time period. This report is known as a radiation dosimetry report (sample report shown on next page). The dosimetry report is usually received within four to six weeks after the badges have been returned for processing. These reports may be sent to the Radiation Safety Officer (RSO) first for review, then forwarded to individual nursing wards or departments where it should be posted or made available to all workers for review.

The report usually consists of several columns (as shown) indicating various types of information which can be obtained. A typical report, such as that produced by Landauer, will show your name and social security number for identification purposes. A third column may utilize a code to indicate the type of personnel dosimeter, here "G-1" indicating a whole body badge and "U-3" indicating a fingerring.

Near the top of each report a date will indicate the period of time during which the exposure was incurred. For the dosimetry report shown, the exposures obtained occurred during the month of May, 1966. Each column of the report will be considered individually:

1. Exposure To Badge For Period Indicated Below

Doses shown in this column indicated readings obtained from the dosimeters which were worn during the time period indicated. It is important to realize that these numerical values are given in units of millirems (recall that 1 rem = 1000 millirems and that the whole body MPD is 5 rem or 5000 millirems per year, the annual MPD to the hands is 75 rems or 75000 millirems). Thus monthly readings on these reports should not exceed the values shown on the following page.

[illegible]

Area of Body	Type of Dosimeter	Monthly Reading Should Not Exceed:
Whole Body	film badge	$\frac{5000 \text{ mrems}}{12} = 416 \text{ mrems}$
Hands	fingerrings	$\frac{75,000 \text{ mrems}}{12} = 6250 \text{ mrems}$

An "M" in this column indicates "minimal radiation exposure", too low to accurately quantitate.

NOTE: Landsauer dosimetry reports separate radiation dose into "deep" and "shallow" categories in an effort to distinguish radiation dose received from penetrating ("deep" whole body dose) radiation (e.g., gamma and x-rays) and non-penetrating ("shallow" skin dose) radiation (e.g., beta and low energy gamma and x-rays). Film badge companies may vary in terms of how doses are distinguished. Therefore one should carefully review any legends, explanations, or remarks noted on the dosimetry report to assist in interpretation.

2. Cumulative Totals - Calendar Quarter (millirems)

In this column you will find your cumulative radiation dose equivalent for the three (3) month period indicated. Calendar quarters are divided as shown below:

first	January - March
second	April - June
third	July - September
fourth	October - December

Dose equivalents in this column are also given in units of millirems and therefore should not exceed:

$\frac{(5000 \text{ mrems}) \cdot (3 \text{ months})}{(12 \text{ months})} = 1250 \text{ mrems}$ (quarter)	for whole body badges
or	
$\frac{(75000 \text{ mrems}) \cdot (3 \text{ months})}{(12 \text{ months})} = 18,750 \text{ mrems}$ (quarter)	for fingerrings

3. Cumulative Totals - Year To Date (millirems)

Dose equivalents listed in this column indicate total radiation dose accumulated since January 1 of the current year. Units of measurement are again in millirems and therefore numerical values in this column should not exceed:

$n \frac{(5000 \text{ mrems})}{12}$ for whole body badges (12 months)
or

$n \frac{(75,000 \text{ mrems})}{12}$ for finger rings (12 months)

where n = the numerical value of the month for which the report is given (i.e., 1 for January, 2 for February, etc.)

4. Cumulative Totals - Permanent (millirems)

Dose equivalent listed here represent total radiation dose received since you were first assigned a radiation dosimeter (whole body badge and/or fingerring). Since this represents your total radiation dose as an occupationally exposed individual, it is most important that:

- you obtain a copy of your radiation exposure records and provide these to new employers (usually the institution's Radiation Safety Officer) upon termination of employment at any institution where you were assigned a radiation dosimeter. Obtain these records to provide to your new employer as soon as possible.
- if you work at two or more different institutions (e.g., working on weekends at a different hospital) where you work with or come into contact with sources of radiation, obtain a radiation dosimeter from each institution. Notify your Radiation Safety Officer at your primary institution and inform him of your working situation for specific instructions as to how your cumulative radiation exposure records should be maintained.
- monitor your own personnel dosimetry records each month to assure that your readings are below MPD's.

Personnel dosimetry reports are considered as legal documents and usually require your signature before exposure records can be released to new employers. These documents must be maintained for a specified number of years by the institution until permission is granted by the

regulating agency to do otherwise. Usually radiation dosimetry reports are first reviewed by your institution's Radiation Safety Officer (RSO), then forwarded to your department or individual nurse's station. It is your right to review your radiation exposure records as an occupationally exposed individual. These exposure reports, like that shown on page 65A, are normally posted in a prominent area for your review. If you are assigned personnel dosimeters on a regular basis, take care to review your exposure reports each month.

Always remember that radiation exposure can be reduced by:

1. Time - reduce your time spent near known radiation sources
2. Distance - increase your distance between yourself and known sources of radiation
3. Shielding - use appropriate shielding when available and practical

METHODS TO ASSURE ACCURACY OF YOUR RADIATION DOSIMETRY REPORTS

The radiation dose equivalents shown on your dosimetry reports should reflect, as accurately as possible, your radiation dose received during the period of time for which the report was issued. These numerical values will accurately represent occupational radiation dose received provided several simple precautions are taken.

For all types of personnel dosimeters (i.e., film badges, TLD's, fingerings, etc.) which might be worn:

1. Wear your personnel dosimeters when performing all duties which involve x-ray machines and radioactive sealed or unsealed sources.
2. Wear only personnel dosimeters which are assigned to you. Do not wear anyone else's or allow anyone else to wear yours.
3. Wear your whole body badge: clipped to your collar near the sternum. Do not wear dosimeters under a lead apron if lead aprons are used during a procedure. Fingerings are to be worn on the fingers and not attached to the collar. Fingerings also should be worn on the hand which would receive the greatest radiation exposure.

4. Great care should be taken not to lose your assigned personnel dosimeters. If lost or misplaced, report this immediately to your Radiation Safety Officer to obtain a replacement prior to working with any radiation sources.
5. If you work at more than one facility, wear only the personnel dosimeters provided by each institution while working at that location. Each medical facility at which you work should assign you personnel dosimeters which are to be worn only while working at that institution.
6. Do not wear personnel dosimeters during your own routine medical or dental x-ray examinations. Readings obtained on your dosimeter should reflect *occupational radiation dose* only.
7. Dosimeters should not be exposed to extreme heat (e.g., electric clothes dryers, stored in an automobile during the heat of summer, etc.)
8. Dosimeters should not be stored near sources of radiation when not being worn.

IMPORTANT CONCEPTS OF CHAPTER FIVE

1. Personnel dosimeters are devices worn on the body to measure radiation dose received during occupational exposure to radiation sources.

2. The most common types of personnel dosimeters used in medical facilities are:

- a. film badges
- b. thermoluminescent dosimeters (TLD's)
- c. pocket dosimeters

3. Film badges and TLD's are usually assigned to individuals whose work requires almost daily radiation exposure. Both types of dosimeters must be shipped for processing which usually requires four to six weeks.

4. Pocket dosimeters may be read immediately and may be reused. These are usually used in emergency situations where radiation exposure levels must be monitored closely.

5. Radiation dose received as a result of occupational exposure should not exceed established maximum permissible doses (MPD's)

6. Maximum permissible doses vary with:

- a. the part of the body exposed
- b. the time span over which the dose is delivered
- c. the age of the individual exposed
- d. whether individuals are occupationally or non-occupationally exposed

7. Important MPD's for occupationally exposed individuals include:

- | | |
|---|------------------|
| a. whole body, blood-forming organs, lens of the eyes, gonads | 5 rems per year |
| b. hands | 75 rems per year |

8. Other important MPD's include:

- | | |
|---|---|
| a. members of the general public (i.e., non-occupationally exposed individuals) | 0.5 rem per year |
| b. pregnant females | 0.5 rem with respect to the fetus during the gestation period |

9. Dosimeter reports should be reviewed on a periodic basis to assure that occupational exposure is kept *as low as reasonably achievable* (ALARA concept).

10. Occupational exposure can be reduced by applying any or all of the primary methods of radiation protection:

- a. TIME - minimize time spent near radiation sources
- b. DISTANCE - increase the distance between yourself and the source of radiation
- c. SHIELDING - use appropriate shielding when available

11. Take care of personnel dosimeters assigned to you in order that they accurately reflect the true occupational radiation exposure received during the specified time period.

Chapter 6

Specific Precautions - Nuclear Medicine Patients

The type of patients to be discussed in this and the next chapter are unique to patient care activities because their therapies utilize radioactive materials. A radioactive element, known as radionuclide, may emit particles (e.g., alpha or beta), pure energy (e.g., gamma or x-ray photons), or both. These emissions, whether they be particles or pure energy, are termed radiation.

Nuclear medicine makes use of the radiation emitted from specific radioactive elements chemically attached to a variety of chemical compounds to assist in the diagnosis and treatment of disease. The actual amounts of radioactive material used (known as the activity) is usually small for diagnostic doses but considerably higher for therapeutic doses.

Nuclear medicine utilizes a variety of radioactive elements in diagnostic studies, the most widely used being technetium-99m (Tc-99m). This radioactive form of technetium emits gamma radiation has a physical half life of six (6) hours (i.e., the amount of radioactivity remaining halves itself every six hours). Tc-99m can be attached or "tagged" to a variety of compounds which can then be intravenously injected into the patient. Once the material has been injected, the movement and subsequent localization of the labeled compound can be "traced" by an external radiation detector known as a gamma camera.

The primary therapy performed by nuclear medicine departments utilizes a radioactive form of iodine (I-131) in the treatment of thyroid carcinoma and hyperthyroidism. I-131 emits both beta and gamma radiation and deserves special precautions as a result of the affinity of thyroid tissue for iodine and the penetrating ability of the gamma radiation.

The radioactive materials used by nuclear medicine departments are primarily in liquid form which can be injected intravenously or taken orally. One must take extra precautions with liquid sources since there is always the chance of spillage or spread of the material, unknowingly, to countertops, hands, clothing, or floor areas. This is known as radioactive contamination. In addition to the possibility of contamination resulting from careless handling techniques, patient urine is also a source of contamination problems for approximately 24 hours post injection for many diagnostic nuclear medicine studies and up to one week post oral therapeutic administrations of radioiodine (I-131).

Precautions for each of these types of procedures will be addressed separately.

DIAGNOSTIC NUCLEAR MEDICINE PATIENTS

As previously mentioned, the most commonly used radioactive material in diagnostic nuclear medicine studies is Tc-99m, a gamma radiation emitter having a physical half-life of six (6) hours. In many of the studies performed, especially brain, bone, and renal studies, the radioactive compounds are removed from the body in the urine and occasionally in the stool.

In working with patients who have undergone standard diagnostic nuclear medicine studies, there are no special restrictions recommended with respect to the small amount of radiation emitted from these patients. Radiation levels will drop both as a result of urinary excretion and normal radioactive decay over the 24 hour period following the study. In the special case where intensive care nursing is required for prolonged periods of time at distances of 0.5 meter or less from the patient, appropriate shielding, such as lead aprons, may be required during the first 24 hours post injection.

In the event of spillage of patient excreta or vomitus, this should be promptly cleaned using normal hygienic techniques which includes the wearing of disposable gloves. Linens contaminated with urine during the first 24 hours can be placed in plastic bags and stored for 24 hours and then laundered. The patient can utilize normal bathroom facilities but if this is not possible, normal hygienic procedures, including the wearing of disposable gloves, should be adopted during the collection and disposal of excreta.

Any additional or special precautions may be advised by the Nuclear Medicine Department or the Radiation Safety Officer of your facility.

THERAPEUTIC NUCLEAR MEDICINE PATIENTS

I. Radioiodine (I-131) Therapy

Rationale:

When a radioactive element is administered or taken internally, the body does not distinguish it from the nonradioactive element and uses it in the same physiological manner as the nonradioactive form. The affinity of thyroid tissue for iodine makes radioiodine especially useful in the treatment of hyperthyroidism and thyroid carcinoma. Even small thyroid cancer metastases will tend to concentrate radioiodine very selectively. Though I-131 emits both beta and gamma radiation, it is the beta component which is used to deliver the major portion of the radiation dose to the malignant tissue.

The treatment of both hyperthyroidism and metastatic thyroid carcinoma with radioiodine is accomplished by the oral administration of the I-131. The primary difference between the two therapies is the amount of administered activity. Hyperthyroid patients are usually dosed with 5-10 millicuries of I-131 in the nuclear medicine department on an outpatient basis. Patients treated for metastatic thyroid carcinoma are usually dosed with 100-200 millicuries. These patients are required to remain hospitalized and in isolation until the levels of radioactivity within the patient's body drop to 30 millicuries or lower.

Room Selection, Preparation and Dose Administration:

Since approximately 80% of the administered dose of radioactivity will be removed from the patient's body, largely in the urine, during the first three (3) days following dose administration, special precautions must be taken in room selection and preparation. In addition to the patient's urine serving as a major source of radioactive contamination, other sources include perspiration, saliva, sputum and vomitus, especially during the first 24 to 48 hours after dosing.

Due to the high probability of contamination of the isolation room contents, rooms chosen for these therapies should be:

1. located at the end of a hallway, away from heavily used areas to avoid the possibility of the spread of contamination.
2. lead-lined, if possible, to reduce radiation exposure to patients in adjacent rooms from penetrating gamma radiation.
3. equipped with private bathroom facilities for patient use only.

Room preparation is usually performed the day that the radioiodine is to be administered. Room preparation includes covering of room floors with absorbent paper and covering of selected items (e.g., chair arms, TV remote controls, telephone receivers, etc.) which would likely become contaminated during the course of the therapy. Covering these items facilitates room decontamination when the patient is discharged from the hospital.

Prior to administration of the radioiodine, a nuclear medicine physician and staff technologist will acquire from the patient all proper consent forms. The therapy dose will be brought to the patient's room and administered to the patient by nuclear medicine staff. Only authorized personnel will be allowed in the room while the dose is administered to avoid the possibility of contamination.

After administration of the therapy, all personnel exiting the room will do so in the manner designated by the Radiation Safety Officer to avoid contamination of areas outside the patient's room. Gloves, shoe covers, surgical gowns, etc. will be removed and personnel will check feet, hands, etc. with a GM (i.e. Geiger counter) to detect any possible contamination prior to leaving the area. Materials or items contaminated during the administration of the therapeutic dose (e.g., absorbent pads, gloves, vials, etc.) will be removed by Radiation Safety Staff.

Precautions for Nurses in Care of ¹³¹I Therapy Patients:

Once the therapeutic dose of radioiodine has been administered, the patient will be confined to his room until released by the Radiation Safety Officer. The length of time that the patient will remain in isolation will vary with the individual but usually isolation is required for about three (3) days. The actual time period is governed by the amount of radioactivity remaining in the patient. As time passes, the radiation levels will decrease because of biological elimination (i.e., through urine excretion) and natural radioactive decay.

It is important to realize that after a patient has been dosed with a therapeutic amount of radioiodine for thyroid carcinoma, as much as 70 - 80% of the dose may be excreted in the urine. Also, a significant amount may be lost through perspiration and nasal secretions. Each of these bodily secretions will be sources of radioactive contamination. In order to minimize the risk of contamination outside the patient's room, nursing staff should strictly observe the following precautions:

1. Limit entry into the patient's room to only authorized personnel or those approved by the Radiation Safety Officer.
2. Anyone entering the patient's room during the course of the therapy must wear gloves, surgical gown, and two (2) pairs of shoe covers.
3. Nursing staff should always wear their assigned film badges when working with the therapy patient.
4. The patient should be instructed to care for himself as much as possible. The length of time spent in the room should be minimized but not to the point where adequate patient care and concern is jeopardized.
5. Meals are to be served on disposable food trays and with disposable utensils. All food items (including trays, utensils, etc.) will be deposited in a plastic bag in the patient's room and will be disposed by the Radiation Safety Officer. These items will be contaminated and are not to be deposited in normal waste containers.

6. Similarly, daily linen changes are to be stored in a separate plastic bag marked "Linen" and will also be collected by the Radiation Safety Officer. Linens are also likely to be contaminated and must NOT be collected by hospital laundry staff.

7. When exiting from the patient's room, one will generally notice a blue absorbent pad on the floor just outside the room. This should be considered a "clean" area and no possibly contaminated item should reach this area. While still just inside the patient's room, remove one shoe cover and place this foot on the pad. Then remove the first shoe cover from the second foot before placing the second foot on the pad. Deposit the pair of contaminated shoe covers, the surgical gown, and the gloves (removed from the inside out) in the plastic bag for these items just outside the room. Remove the second pair of shoe covers and deposit these also in the same bag. Move approximately 10-15 feet down the hall from the patient's room and check yourself, especially your hands and feet, for contamination with the Geiger counter provided. Wash your hands thoroughly with soap and water.

Instructions to Visitors and Patients:

131I therapy patients will be informed prior to administration of the dose that isolation is required. The patient will be released from isolation when the Radiation Safety Officer and the patient's physician determines that isolation is no longer required.

Ideally the patient should have no visitors during the course of isolation or at least not for the first 48 hours after dosing. If visitors are allowed during the isolation period, they must also abide by all regulations to avoid the spread of contamination (i.e., shoe covers, gowns, gloves, etc.). Time limits will be strictly enforced as prescribed by the Radiation Safety Officer. Visitors are also to be instructed to maintain a distance of six to eight feet between themselves and the patient. No food or drink is to be consumed by the visitor while in the patient's room.

Absolutely no persons under 18 years of age nor pregnant or potentially pregnant females are to be allowed in the patient's room. Any questions regarding visitors should be referred to the Radiation Safety Officer.

Emergency Procedures:

1. Vomiting/Nausea

Should the patient become nauseated during the first 24 hours after dosing, the Radiation Safety Officer should be notified. A container should be provided to the patient as soon as possible. Should vomiting

occur, the vomitus and sputum will be very radioactive. If this is in a container, it can be disposed via the toilet unless instructed otherwise by the Radiation Safety Officer. Notify the Radiation Safety Officer immediately. Abide by all precautions given previously.

If the patient should vomit on the floor, the vomitus should be covered with approximately 1/2 inch of absorbent material (e.g., bed sheets folded to form the desired thickness) as soon as possible. Work efficiently and quickly but avoid alarming the patient or other employees. Again, abide by all precautions given previously to avoid the spread of contamination. Upon exiting, keep the door to the patient's room closed and restrict entry to only those providing necessary patient care. **NOTIFY THE RADIATION SAFETY OFFICER IMMEDIATELY.**

2. Contamination (Actual or Suspected)

If accidental contamination results from patient excreta, vomitus, spillage, or any other source is suspected, **NOTIFY THE RADIATION SAFETY OFFICER IMMEDIATELY** from the area of contamination. While awaiting arrival of assistance, avoid moving to other areas for this will only spread the contamination.

The suspected contaminated area should be marked off or somehow designated. No unauthorized personnel should be allowed to walk through the area nor should anyone leave the area without being monitored with a Geiger counter to assure that they are free of contamination. Do not allow anyone who has come into contact with contamination to leave the area until they are cleared by the Radiation Safety personnel. This includes visitors and personnel who have completed their shift.

3. Patient Leaves Isolation Without Authorization

Notify hospital security and the Radiation Safety Officer immediately.

If there are any questions regarding contamination, problems with individual patients, or personnel exposure, the Radiation Safety Officer should be contacted. It should be emphasized at all times that the patient's care and well being can be assured while nursing personnel limit their own radiation exposure by practicing good radiation protection techniques.

II. Phosphorous (P-32) Therapy

Rationale:

Radioactive phosphorus-32 (^{32}P) in the chemical form of sodium phosphate is administered by means of intravenous injection. It is used as a palliative agent to alleviate severe pain caused by extensive osseous metastases.

Safety Instructions for Nursing Personnel:

^{32}P is a pure beta emitter and because of this poses a minimum radiation hazard. The radioactive material injected into the patient becomes deposited into the bone and is not excreted.

The patient's body tissue absorbs almost all radiation emitted and therefore this type of therapy patient poses no radiation hazard to nursing personnel, other patients, or visitors. There is also no chance of contamination with this type of patient.

NOTE: This is unlike the ^{32}P which is administered by Radiation Oncology. For their type of patient, there is also minimum radiation hazard to attending personnel but there is a slight chance of ^{32}P leakage from the site of the incision through which the material was introduced into the peritoneal cavity. Any leakage here can be a source of radioactive contamination.

Therefore, for the patient being treated with ^{32}P (sodium phosphate) for bone pain, no special precautions need to be taken by attending personnel. Any questions regarding this patient may be referred to the Radiation Safety Officer.

IMPORTANT CONCEPTS OF CHAPTER SIX

1. Nuclear Medicine departments primarily use liquid radioactive materials (unsealed sources) tagged to a variety of compounds which are intravenously injected into patients to perform a wide range of diagnostic studies.
2. Diagnostic nuclear medicine patients may be slightly radioactive, emitting low levels of gamma radiation, up to approximately 24 hour post injection of the radioactive material. Radiation levels are usually of such a level so as not to warrant any special precautions for attending staff or visitors unless intensive care nursing is required.
3. Many diagnostic nuclear medicine test result in the patient's urine being contaminated with the radioactive material used to perform the particular test. Attending nursing staff should wear disposable gloves when handling urine from these patients up to 24 hours after the diagnostic test (especially bone, renal, and brain scans) has been performed. Wash hands thoroughly at the conclusion of the procedure.
4. Larger doses of radioactive materials are administered to therapeutic nuclear medicine patients. These therapeutic nuclear medicine procedures include:
 - a. I-131 administration for hyperthyroidism:

usually administered on an "out-patient" basis; relatively minimal exposure and contamination problems associated with this patient; however, precautions should be advised for possible contaminated urine during the first 24-48 hours post-dosing
 - b. I-131 administration for thyroid carcinoma:

patient required to remain in isolation until radiation levels within the body drop below 30 mCi; special room preparation required due to radioactive contamination; everything patient touches should be considered to be contaminated with I-131; during the first 48-72 hours post-dosing, patients, urine, sputum, skin surface, and vomitus should be considered to be contaminated with radioactive I-131; special precautions regarding entering and exiting patient's room must be observed to minimize the possibility of radioactive contamination

Chapter 7

Specific Precautions - Radiation Therapy Patients

Radiation therapy departments utilize radiation as a method of control and cure for various types of cancer. The radiation may be administered in several different ways which include:

1. **Teletherapy** - the irradiation of cancerous lesions using a radioactive source, such as cobalt-60 (^{60}Co), external to the body.
2. **Linear Accelerators** - the irradiation of cancerous lesions using devices which can accelerate electrons to high energies; the electrons themselves can be used to irradiate the lesions or the electrons can be used to produce x-rays to treat deep seated tumors.
3. **Brachytherapy** - the irradiation of cancerous lesions using sealed radioactive sources by interstitial, intracavitary, or surface application.

For health care professionals working with radiation therapy patients, there is no hazard associated with patients receiving teletherapy or radiation therapy utilizing linear accelerators. These patients produce no more of a radiation hazard than a patient undergoing a conventional x-ray examination. This is not the case with brachytherapy.

Though in the past brachytherapy was conducted primarily with radium, today the most commonly used radioactive sources include cesium-137 (Cs-137), iridium-192 (Ir-192), gold-198 (Au-198), and iodine-125 (I-125). A summary of important properties of these radionuclides is shown on page 82.

- c. ^{32}P administration for alleviation of severe bone pain:

administered by intravenous injection; poses no radiation hazard to attending medical personnel since this is a pure beta emitter; becomes deposited into the bone and is not excreted; no contamination problems associated with this type of patient

5. Special precautions to be taken with I-131 therapy patients being treated for thyroid carcinoma:

- a. Rooms chosen for the... patients should be either special isolation or corner rooms away from heavily used hallways.

- b. The room chosen should have floors, visitor's chairs, night stands, telephone, remote control devices, etc. covered with plastic or absorbent paper prior to dose administration to minimize contamination of facilities.

- c. Upon the administration of the radioactive material to the patient, all items within the room should be considered to be contaminated with I-131 until properly surveyed with radiation detection equipment.

- d. Urine and blood samples should not be collected for at least 77 hours post administration of the radioactivity.

- e. All attending medical staff must wear double shoe covers, double gloves, and disposable gowns when entering the patients room. These should be removed, observing proper exiting techniques, upon leaving the patient's room.

- f. All linens, clothing, disposable food trays, shoe covers, gowns, gloves, and waste products generated during the course of the therapy are to be considered as radioactive waste and must be disposed of via your radiation safety personnel or Nuclear Medicine Department. These items are not to be disposed by usual methods by housekeeping staff.

- g. Upon release of the patient from isolation, the room must be thoroughly decontaminated by radiation safety personnel before use by another patient.

Important Physical Characteristics of Commonly Used Brachytherapy Sources

Radionuclide	Physical Half Life	Photon Energy (keV)	Half Value Layer* (mm of lead)
²²⁶ Ra	1600 yrs.	47-2450 (830 Average)	8.0
⁶⁰ Co	5.3 yr**	1170, 1330	11.0
¹³⁷ Cs	30 yrs	662	5.5
¹⁹² Ir	74.2 days	136-1060 (380 Average)	2.5
¹⁹⁸ Au	2.7 days	412	2.5
¹²⁵ I	60 days	28 Average	0.025

*That thickness of material, here the material being lead, required to decrease the radiation intensity from a radiation source by 50%. Each half value layer thickness will decrease the intensity by half.

With this method of therapy high doses of radiation can be delivered directly to a tumor site by placing the source in close proximity and allowing it to remain for a specified period of time. This is most often accomplished by placing the radiation sources into a body cavity and/or direct implantation of the radiation sources directly into the tumor involved tissue. Certain brachytherapy sources are used as temporary implants while others are implanted permanently.

Brachytherapy sources are doubly encapsulated within thin metal casings. Thus there is minimal, if any, chance of contamination with these types of radiation sources, thus the primary hazard associated with these sources is that of high radiation exposure only.

Important Note: No radiation source or suspected radiation source should ever be picked-up with the hands. Long handle tongs or forceps should be used to place the source in a shielded container as quickly as possible.

As indicated in the chart above, brachytherapy sources do emit penetrating photon radiation (i.e., gamma or x-rays) and thus the thin metal casings do not provide a substantial barrier to the radiation emitted. The metal casing acts only as a container for the radioactive contents and serves to minimize the possibility of any radioactive contamination.

The radiation sources used in brachytherapy procedures may vary in size and shape from radioactive "needles" (approximately 6 cm. long) to radioactive "tubes" (approximately 2 cm. long) to permanent implant radioactive "seeds" (approximately 2.5 mm long).

Though brachytherapy techniques may be used in the treatment of a variety of types of cancerous lesions and tumors, one of the most common applications is intracavitary therapy for treatment of cancers of the uterine cervix, uterine body, and vagina. The clinical aim is to localize the radiation to the directly involved areas and to the adjacent lymphatics using a device known as an "applicator" which is used to hold the brachytherapy sources in a fixed configuration. Several different types of applicators have been designed for the use (e.g., the LBW and Fletcher-Suit applicators) with each design generally consisting of a central tube, known as the tandem, and two (2) lateral containers known as ovoids or colpostats. Tubes containing a predetermined number, strength and arrangement of brachytherapy sources can then be inserted into the applicator tandem and ovoids for a prescribed period of time to produce the desired radiation effect.

Patient preparation usually occurs in the operating room and, while under general or spinal anesthesia, the cervix is dilated and an applicator is placed within the uterine canal and the vaginal vault. The applicator is kept in position by vaginal-packing material. The packing material is also used to displace the bladder and rectum away from the applicator. Regardless of the type of applicator used, attending nursing staff should be able to recognize these and be familiar with the approximately correct positions in which they are placed. Then, if you should notice any apparent slippage of the applicators, you must notify the radiation oncology physician immediately. Any movement of the applicators from their correct positions will change the radiation doses to the clinically significant areas. The radiation dosage rates in these areas are calculated and displayed through the use of computers and their associated software. This data is used clinically but provides valuable information for situations such as these or other incidents that may arise. The repositioning of the applicators will depend both upon this data and the planned, radiation treatment schedule to the clinically significant areas.

Applicators normally will not contain any radioactivity when the patient is returned to her room from the recovery ward. Patients are then scheduled to have the actual radiation sources placed into position after dose calculations have been completed. (This technique of inserting the radiation sources into tubes previously implanted in the tissue to be irradiated is known as "afterloading". This method eliminates unnecessary radiation exposure in the operating room, x-ray room, and areas through which the patient is transported). The Radiation Therapy Department then notifies the nurse's station and appropriate radiation safety personnel.

The Radiation Therapy Department will notify the nurse's station and Radiation Safety personnel of the exact time at which the actual radiation sources are to be inserted. The radiation therapy technician will position bedside shields in the patient's room just prior to insertion of the brachytherapy sources. A No Visitors sign should be posted on the door to the patient's room until radiation exposure rate measurements are made and time limits determined by Radiation Safety personnel. Radiation Safety personnel will evaluate the radiation hazard in the area through the use of a portable ionization chamber survey instrument. Readings obtained at various points within the room, in adjacent rooms, and in adjacent hallways will be used by safety personnel to determine time limits for nursing staff and visitors and to assure the safety of adjacent patients and members of the general public. Time limits for nursing staff and visitors will be posted on the door to the patient's room by Radiation Safety personnel upon completion of their calculations. This information will also be provided in the Radioactivity Precautions Notice entered directly into the patient's medical record maintained at the nurses' station.

Other types of applicators include a vaginal mold and the Syed plate. The vaginal mold is used to treat cancer in the vaginal vault or as a prophylaxis against recurrence after a hysterectomy for endometrial cancer. The Syed plate is a template guide for insertion of needles into the cervix and parametrium.

In summary, several important points should be emphasized regarding these applicators. Attending staff should be extremely careful to recognize:

1. Applicators that have moved or slipped.
2. Tubes that have apparently changed their position within an applicator or have been totally displaced in and out of the applicator.
3. Sources that have come out of the tubes of applicators.

EMERGENCY PROCEDURES

If any of the above items are observed, attending staff should respond rapidly and in a manner which does not alarm the patient. Proper action includes the following:

1. IF APPLICATOR HAS MOVED OR SLIPPED

Notify your Radiation Therapy Department or radiation therapy technician on call as soon as possible. Do not attempt to reposition the applicator yourself.

2. IF SURGICAL TAPE ON APPLICATOR BECOMES LOOSE OR PLASTIC SECURING ROD BECOMES DISLODGED

Contact radiation therapy personnel immediately.

3. IF TUBES HAVE CHANGED THEIR POSITION WITHIN AN APPLICATOR OR HAVE BEEN DISPLACED OUT OF THE APPLICATOR

If tube position within the applicator has changed, notify the Radiation Therapy Department as soon as possible. Do not attempt to reposition the tube yourself.

If the tube has been displaced out of the applicator, act quickly to reduce radiation exposure to the patient and to yourself:

- a. Use long handled tongs or forceps to remove the tube from the patient's bed. Deposit the tube quickly into the lead shielded container which should be located in the patient's room during the therapy.
- b. Place a No Visitors sign on the door to the patient's room until all radiation sources have been accounted for by radiation therapy technicians.
- c. Note the time that the tube was first noticed to be displaced from the applicator. Contact radiation therapy and radiation safety personnel immediately.
- d. Provide any necessary medical attention to the patient until appropriate personnel arrive.

4. IF RADIATION SOURCES BECOME DISLODGED AND ARE FOUND OUTSIDE THE APPLICATOR

- a. Use long handled tongs or forceps to quickly deposit the source within the lead shielded container within the patient's room.
- b. Place a No Visitors sign on the door to the patient's room until all radiation sources have been accounted for by radiation therapy technicians.
- c. Note the time that the source(s) was first discovered. Contact radiation therapy and radiation safety personnel immediately.
- d. Provide any necessary medical attention required by the patient until appropriate personnel arrive.
- e. Do not allow linens or trash to be removed from the patient's room until all radiation sources have been accounted for by radiation therapy personnel.

Recommendation: Most brachytherapy sources are so small that, if dislodged, they can be easily lost in bed linens, absorbent bed pads, etc. Therefore it should be strongly recommended that nursing and house-keeping staff be instructed not to remove linens or trash receptacles from these patient's rooms until they are taken to a secure area away from known radiation sources (including the patient) and surveyed with a radiation detector.

IODINE-125 IMPLANTS OF THE PROSTATE

You should familiarize yourself somewhat with the surgical procedure for this type of therapy. This would aid you in learning how the small seeds used in this type of radiation therapy can become dislodged from their positions within the prostate. During this form of treatment, the patient's urine is usually collected. If at any time during this treatment the Foley catheter is removed, the radiation therapy technician on call must be contacted. The radiation therapy technician will survey the area to determine if any of the radioactive seeds have become dislodged.

PHOSPHOROUS-32 AND GOLD-198 THERAPIES

One other method of administering a radioactive material to a patient is by instilling a liquid suspension of P-32 or Au-198 into a body cavity. This procedure is usually performed for ovarian carcinoma. Tubes are placed through the abdominal wall to serve as entrance channels for the radioactive liquid. The liquid is introduced through the tubes and flows throughout the abdominal cavity. The tubes are then removed and "purse-string" sutures are used to close the area of the incision.

Specific Precautions:

P-32 is radioactive material which emits beta radiation only. Thus due to the relative non-penetrating ability of beta radiation, these patients do not represent a radiation hazard to attending nursing staff or visitors. Au-198, however, emits both beta and gamma radiation. As a result specific precautions (e.g., shielding or time limits) may be required by your radiation safety personnel.

In addition to these precautions, there is the possibility that bed linens and bandages used to cover the area of the incision could become contaminated by seepage from the area of the wound. Thus:

1. If bandages must be changed, disposable gloves should be worn during the procedure to minimize the chance of skin contamination.

2. Soiled bandages or gauze should be handled with forceps and placed in a plastic bag for disposal as radioactive waste. Gloves worn during the procedure should also be placed in the same bag. These materials are not to be disposed of via normal disposal methods.

3. Wash hands thoroughly with soap and water and check hands with a Geiger counter, if one is available.

There are many applications of brachytherapy techniques in the treatment of a variety of tumors and cancerous lesions. All medical staff working with these patients should become familiar with:

1. The specific applications of brachytherapy utilized at your facility.
2. Specific characteristics of the brachytherapy sources used:
 - a. type of radioactive material used (i.e., I-125, Cs-137, Au-198, Ir-192, etc)
 - b. type of radiation emitted
 - c. type of shielding required for attending personnel
 - d. size, shape, and appearance of radiation sources used
3. Proper procedures to follow in the event of an emergency involving the patient (specific procedures may vary from one facility to another and thus attending staff should consult radiation therapy or radiation safety personnel for more detailed instructions).

IMPORTANT CONCEPTS OF CHAPTER SEVEN

1. Radiation therapy departments utilize various types of radiation sources in the treatment of tumors and cancerous lesions. These include:
 - a. teletherapy & linear accelerators
 - b. liquid radioactive material introduced into body cavities
 - c. brachytherapy
2. Teletherapy is the irradiation of tumors or lesions by radiation sources (e.g., cobalt-60) external to the body. Patients receiving radiation therapy from teletherapy (or linear accelerator) units present no radiation hazard to attending medical personnel.
3. Liquid radioactive materials injected into body cavities may or may not require special precautions depending upon the type of radiation emitted. With liquid, unsealed sources there is always the possibility of contamination.
4. Brachytherapy procedures utilize sealed radioactive sources which may be implanted directly into tumors or tissue either on a temporary or permanent basis. There is essentially no chance of radioactive contamination with these sources. However, radiation exposure levels may be quite high and thus warrant the establishment of time limits for staff and visitors.
5. No radiation source or suspected radiation source should ever be picked up with the hands. Long handled forceps or tongs should be used in handling such sources.
6. Medical staff attending any type of radiation therapy patient should familiarize themselves with the type of therapy conducted, the type of radioactive material and radiation emitted, special precautions to take, and specific emergency procedures. Special attention should be given to knowing the physical appearance of the radiation sources used.
7. Be familiar with your facility's specific emergency procedures in regards to radiation therapy patients.

8. Attending medical staff should always wear their radiation dosimeters (e.g., film badges, TLD's, or pocket dosimeters) when working with brachytherapy patients.
9. Always work with brachytherapy patients behind bedside shielding.
10. Observe time limits established for visitors and staff by radiation safety personnel.

Chapter 8

Specific Precautions - Procedures Involving X-Ray Equipment

Perhaps the most common and most widely used medical radiation source is the conventional x-ray machine. Unlike other radiation sources (i.e., radioactive materials) previously discussed, x-rays are emitted from these devices only when the unit is energized; that is, an electrical voltage in the kilovolt range must be applied across the electrodes within x-ray tubes before x-rays are produced. When this voltage is applied, a beam of electrons is accelerated across the x-ray tube and strike a tungsten target. Bremsstrahlung (braking) radiations, commonly known as x-rays, result. The x-ray beam actually consists of a spectrum of x-rays of different energies ranging from 25 kiloelectron-volts up to the maximum electron voltage applied (measured in units of kiloelectron volts or keV). X-rays at the very low energy end of this spectrum are completely absorbed within the tube. This is the reason there are essentially no x-rays of energies between zero and 25 keV.

As the applied voltage on the x-ray tube is increased, the maximum energy of the x-ray beam is also increased. Therefore as the kVp is increased, the penetrating ability of the resulting x-rays is also increased. One should remember that the amount of x-rays depend on a factor slightly greater than the square of the applied voltage; that is, by doubling the voltage, the x-ray intensity will be increased to a value more than four times the original intensity. When the electron current, known as the mA, within the x-ray tube is increased, the amount of x-rays are also proportionately increased.

A number of nurses find themselves faced with the task of using x-rays to make radiographs. These are made by placing cassettes containing photographic film behind patients given brief x-ray exposures. The resulting photographic images (of the internal physical structure of their bodies) can be used medically as diagnostic tools. In making x-ray radiographs, nurses should be able to use the proper technique in a manner known as proper practice. The practice is to make these images of good quality and at the same time keep the radiation exposure to themselves and patients as low as possible.

The primary factors affecting the quality of an x-ray image are called "technique factors". These are the voltage, current, and time settings of the x-ray machine. An increase in any of these will increase the exposure of the patient as well as to the photographic film. It is usually best to use technique factors recommended by the manufacturers of the x-ray film utilized.

When x-rays go through a material, some of them will completely pass through it without interacting in any way. Others will interact and are either partially or completely absorbed. Partial absorption results from the process known as

scattering. In the scattering process the initial x-ray changes direction and gives up part of its energy to the material. Therefore, these x-rays are of lower energy and are directed either toward or away from the photographic film. Scattered x-rays produce poorer quality images- not too dissimilar to what happens when raindrops strike a freshly penned letter. Scattered x-rays are not in any way beneficial to the x-ray examination and are more likely than before to be completely absorbed by the body, and this may occur in areas other than the clinical area of interest. The very low energy x-rays will usually be completely absorbed by the body regardless of the type of density of the body tissue through which they travel. This scatter radiation contributes to additional radiation exposure since it is of no benefit to the quality of the resulting radiograph.

An attenuating material is usually placed within x-ray machines to reduce the intensity of the lower energy components of the x-ray beam. They are in a sense filtered out. The greater the thickness of the attenuating material placed in their path the greater will be this filtration. Most diagnostic x-ray machines utilize at least 2.5 millimeters of aluminum for filtration. The filtered x-ray beam then has a balance of x-ray energies, the majority of which are beneficial in that they serve to help produce the diagnostic image of the internal physical structure of the patient. There is less exposure to those harmful x-rays which give no net benefit to the examination.

Poor quality radiographs may cause an error in the diagnosis or medical treatment later given to patients. X-ray images can be either underexposed or overexposed. When radiographs have to be repeated due to the lack of image contrast or sharpness, additional exposure has to be given until the proper technique is utilized.

Any individual operating an x-ray unit should be well trained by qualified personnel. There are many aspects to performing an x-ray study correctly and safely. Nurses often times do not get enough of the information they need to perform this type of work. They rely on what they have been told by physicians in charge or by x-ray machine service personnel. Much of what they learn is simply experience obtained while on the job.

If all that nurses do is to operate x-ray units, then their radiation exposure can be kept to a minimum. To do this, they must always stay behind the shielding provided by the walls of the x-ray control booth. When the control booths are properly designed and properly used, the personnel dosimeters worn will not be able to measure the low levels. Thus, the amount of radiation received will probably be below background levels. If, however, nurses become involved with the handling of patients being radiographed in such a way as to be by their side at the time of their exposure, then they may receive significant exposure themselves. They must then take the additional precaution of wearing a lead apron and lead gloves. They must try to stay as far from the primary x-ray beam as possible. It is better that no one person be utilized routinely to hold patients and best if restraining devices are used instead.

Time - reduce the time spent near the source of radiation, the x-ray tube or the patient being radiographed.

Distance - increase the distance between you and the source of radiation.

Shielding - use appropriate shielding whenever available, positioning it between the protected worker and the radiation source.

These methods of protection are valid for all types of radiation sources - x-rays or radiation emitted from radioactive materials.

Additional safety measures to reduce radiation exposure which should always be observed include:

1. Restrict the size of the primary beam to the clinical area of interest.

This reduces radiation exposure in several ways. First, the patient receives less direct exposure to radiation to other areas of the body. Secondly, the amount of scattered radiation is less, and consequently reducing secondary radiation. Thirdly, with less scatter, the radiograph is better, possibly reducing the chance of a repeat study.

2. Get the patient to remain as still as possible during the radiographic procedure.

This will reduce the possibility that a repeat study would later be necessary due to patient movement during exposure. If you expect there to be any movement at all, try to give the same exposure but in a briefer period of time. For example, you can double tube current and decrease the exposure by one-half. The effect is the same as for regular cameras; that is, the picture is better, even for moving objects. Restraining devices also reduce patient movement. Simply making the patient more comfortable often helps as well.

3. Shield the gonadal regions of the patient with at least 0.25 mm of lead.

This is the standard thickness normally available for lead aprons, and will stop nearly all of the x-rays.

4. Inform women as to the hazards of fetal exposure to radiation, and inquire as to the likelihood of their being pregnant.

This is particularly necessary when the radiograph involves the pelvic x-ray examination of a woman of childbearing age. In view of the possibility that such a woman might unknowingly be pregnant, it is recommended that such a procedure be limited to the first 8 to 10 days after the onset of menstruation (Ten Day Rule). The physician will make the decision as to the necessity of postponement of the exam.

5. Do not participate in radiographic procedures in the proximity of the x-ray tube or the patient being radiographed while you are either pregnant or think you are pregnant.

If radiation dosimeter reports show that you are receiving no radiation exposure during your work, it is probably safe enough to continue work as long as your usual routine is unchanged.

6. Use proper distance in positioning the x-ray tube from the patient.

As a general rule, the greater the distance, the sharper the image, but there are limitations such as room size and overhead distances. Chest radiographs are shot at a distance of 72 inches and most other radiographic procedures are performed at a distance of 40 inches from the patient.

7. Use the proper technique in performing the particular radiographic study.

Measure the thickness of the body being radiographed, use the technique factors determined from the technique chart, then position the patient properly in relation to the x-ray beam for the exposure. Remember that differences in patient size will greatly affect the radiographic quality. Higher kVp settings are required for thicker patients.

8. Always close the door to the x-ray room when performing a radiographic procedure.

Take appropriate action to assure that no one enters the room during any x-ray procedure.

9. Have the x-ray unit checked periodically by qualified personnel to ensure that it is working properly.

Some of the safety checks normally performed by health physicists are:

- a. Alignment of light and radiation fields
- b. Operation of positive beam limitation
- c. Check of filtration in the x-ray beam
- d. Reproducibility of exposures
- e. Accuracy of timer
- f. Exposure produced by the x-ray equipment at different technique factors at the treatment distances used
- g. Check of warning devices, warning posting and labeling
- h. Secondary radiation levels released by the equipment
- i. Check of shielding provided by lead aprons and lead walls
- j. Review of radiation dosimetry program

10. Personnel monitoring devices are required if weekly radiation doses to personnel equal or exceed 25 millirems.

It is best to always wear a radiation monitoring device if you are required to hold patients during radiographic procedures. These monitoring devices should be worn at collar level outside any protective shielding (e.g., lead apron) being worn. If you do not have a film badge and you are not needed to assist in the procedure, you should leave the room or move (Recall distance is one method of reducing your radiation exposure).

11. Always use lead shielding or protective barriers whenever available.

Lead aprons and gloves (if available) should always be worn with mobile radiographic procedures since there are no protective barriers with these units.

IMPORTANT CONCEPTS OF CHAPTER EIGHT

1. X-ray units produce their radiation only when energized.
2. The energy, or penetrating ability, of the x-rays produced depend upon the kVp setting chosen.
3. X-ray machines must be checked periodically for proper filtration to assure that lower energy x-rays are removed from the beam used for diagnostic x-ray procedures.
4. Lead aprons and lead lined gloves should always be worn when assisting with radiographic procedures to shield against lower energy scatter radiation.
5. Pregnant or potentially pregnant individuals should never assist with radiographic procedures without consulting the radiation safety officer.
6. Film badges should always be worn at collar level and outside the protective lead apron when assisting in any radiographic or fluoroscopic procedure.

Chapter 9

Radiation Precautions for Medical Facility Security and Police Personnel

Medical facility security and police personnel are perhaps most likely to become involved with medical radiation sources through one of the following activities:

1. routine security checks of building facilities
2. receipt of radioactive materials (e.g., sealed sources or radiopharmaceuticals) during non-working hours
3. facility emergencies (e.g., fire)

Each of these cases will be considered separately with recommendations for each. Security and police staff should always remember that when working with radiation sources, protection is afforded by the use of:

TIME - reduce your time spent near the source of radiation

DISTANCE - increase your distance between you and the source of radiation

SHIELDING - use appropriate shielding if practical and available

These general principles of protection are valid for all types of radiation sources found in a medical facility.

In preparation for any situation which might arise which would involve radiation sources, it is recommended that security and police personnel receive:

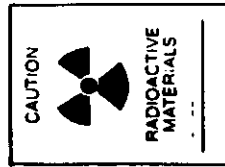
1. a listing of exact locations of radiation sources and laboratories in which radioactive materials are used within the facility; this listing should also include a brief description of the nature of the radiation hazard which exist in each location and any special precautions which should be taken with these sources
2. instruction in the proper use of a radiation detector, such as a Geiger counter
3. immediate notification of delivery of radiation sources or radiopharmaceuticals by common couriers (e.g., Federal Express, Purulator, Emery, Airborne Express, etc.) during non-working hours, especially if there is no secure, designated area at which such packages are to be delivered

4. instructions on how to contact the Radiation Safety Officer or radiation safety personnel both during and after normal working hours

Specific Precautions and Recommendations:

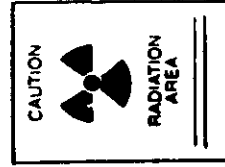
1. Routine Security Checks of Building Facilities

Security and police personnel should become familiar with the meanings of the various types of posting (i.e., labels or signs) required for areas in which radiation sources are housed. These labels are posted in obvious locations to give an indication as to the magnitude of the radiation hazard involved. The more common warning labels and their meanings are shown below.



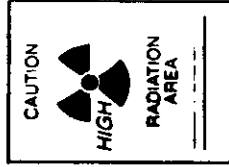
CAUTION-RADIOACTIVE MATERIALS

This sign is used to indicate rooms in which radioactive material is used and/or stored. Caution should be used in these areas for both exposure and possible contamination.



CAUTION-RADIATION AREA

This sign is used to indicate areas where an individual should be concerned more with radiation exposure. In these areas an individual's body could receive 5 mrem/hour or higher or 100 mrem in 5 consecutive days.



CAUTION-HIGH RADIATION AREA

These signs are used to indicate areas where sources producing high radiation exposure are used and/or stored. In these areas radiation levels are such that an individual's body could receive 100 mrem/hr or greater. These areas are to remain locked at all times except when in use.

All doors on areas displaying these signs should remain locked when not in use and during non-working hours. High radiation areas are to remain locked at all times when not in use. In addition, visible and audible alarms are required for High Radiation Areas.

If alarms in high radiation areas are activated during non-working hours, SECURE THE AREA BUT DO NOT ENTER. IMMEDIATELY NOTIFY THE RADIATION SAFETY OFFICER AND AWAIT HIS ARRIVAL.

In addition, the Radiation Safety Officer should be notified immediately of any of the following incidents involving rooms or areas posted with any type of radiation precautions signs:

- apparent vandalism
- leakage or spill of liquid
- rupture of water or gas lines
- explosion

In the event of any of these occurrences, secure and limit access to the area to emergency personnel and await arrival of radiation safety personnel.

Facility security staff should also take effective measures to assure that:

- boxes, bags, containers of liquid, or vials clearly marked with radiation precaution labels or tape are NOT left unattended in hallways; if such labelled materials are found, these should be placed in a secure area in the vicinity and the incident reported to the Radiation Safety Officer at the beginning of the next work day.

SPECIAL NOTE: Department of Transportation (DOT) Class Labels

Most shipping containers in which radiation sources are transported are required to display one of the DOT class labels shown below to indicate the radiation exposure rates at the surface of the package and at a distance of 1 meter (3 feet) from the package surface. These class labels (I, II, and III) are shown below.

DOT Class Label	At surface, exposure rate could be as high as	At 1 meter, exposure rates could be as high as
	0.5 mR/hr	No Detectable Radiation (NDR)
	50 mR/hr	1 mR/hr
	200 mR/hr	10 mR/hr

Thus, greater care should be taken with class II and class III packages. These packages especially should be stored in areas at least 15 feet from areas where individuals work.

3. Emergency Situations

The following actions should be taken by security or police personnel in the event of emergency situations involving areas where radiation sources are used or stored:

2. shipping boxes displaying Department of Transportation (DOT) radiation class labels (shown in next section) are not to be left unattended in hallways or on receiving docks (see next section for proper action to take); empty shipping boxes may be disposed with regular waste but only after all radiation precaution labels have been removed or defaced; if any materials displaying obvious radiation precautions labels are found in regular waste materials, the Radiation Safety Officer should be contacted for specific instructions.

2. Radioactive Materials Delivered After Normal Working Hours

If deliveries of radiation sources (e.g., radiopharmaceuticals or brachytherapy sources) occur after or before normal working hours, delivery personnel should be instructed (via written or posted instructions) that radioactive packages are to be left only in a designated secure area. If such arrangements cannot be made, then:

1. security personnel should be notified immediately upon delivery.
2. all radioactive packages should be placed in a secure location, preferably 15 feet or further away from areas occupied by individuals for extended periods of time.
3. notification of delivery should be given to the Radiation Safety Officer immediately at the beginning of the next work day.

a. Vandalism

1. Secure the area
2. Notify the Radiation Safety Officer
3. Restrict access to the area until radiation safety personnel arrive and assess the hazard

b. Spillage or Rupture of Water or Gas Lines

1. Take immediate steps to stop the leakage
2. Confine the area affected by using absorbent materials, if available
3. Contact the Radiation Safety Officer immediately
4. Secure the area
5. Restrict access to the area until the arrival of radiation safety personnel to assess the hazard

c. Fire or Explosion

1. Take immediate action to rescue personnel and extinguish fires. These actions take priority over potential radiation hazards. Fires may be fought at a distance to reduce radiation exposure.
2. Notify the Radiation Safety Officer immediately for specific instructions
3. Secure the area
4. Control access to the area until radiation safety personnel arrive to assess the hazard.

For situations which arise involving radiation sources for which policies have not been established, contact your Radiation Safety Officer.

Chapter 10

Specific Precautions for Housekeeping Personnel

The fact that housekeeping personnel usually enter most areas of the medical facility either before, during or after normal working hours mandates that these individuals receive specific instructions regarding medical radiation sources. With housekeeping staff potential problems arise for the medical facility not only from the radiation exposure or possible contamination of such an individual but also if radiation sources are accidentally disposed of via sewage, contracted disposal services or incineration as a result of improper training of staff members.

This chapter shall focus on several specific problems and precautions which should be taken by housekeeping staff in performing their routine duties. The following precautions can serve as general guidelines.

1. Never handle any vials, containers, bottles, bags, or instruments displaying radiation precaution stickers.
2. Never dispose of any waste bags, shipping boxes, or any type of container displaying a radiation precaution label. If any are found in normal waste materials, contact the Radiation Safety Officer. Do not dispose or incinerate.
3. Waste bags or containers displaying radiation precaution labels should not be left unattended in hallways. Similarly, shipping boxes displaying radiation precaution labels should not be left unattended in hallways or other non-secure areas. If such conditions are found, notify the Radiation Safety Officer or security personnel if before or after normal working hours.

In cleaning and caring for patient rooms:

4. Housekeeping staff should be notified of rooms used for I-131 therapies. No waste materials or linens should be collected from these rooms during the course of a therapy procedure. Rooms are not to be cleaned by housekeeping staff until the room is decontaminated and released by radiation safety personnel.
5. Rooms used for brachytherapy implant patients may or may not be open to housekeeping staff. Check for specific instructions with the nursing staff or the Radiation Safety Officer.
6. Bed linens and waste removed from a brachytherapy patients room should be inspected for possible dislodged brachytherapy sources. This can be done easily with a GM detector several feet away from the patient's room.

Note: Housekeeping staff should be aware of the shape and general appearance of brachytherapy sources so they may be easily recognized.

If a source is found in bed linens or waste, **DO NOT PICK THIS SOURCE UP WITH YOUR HANDS.**

Keeping your distance, quickly move the source to an area approximately 20 feet or farther from individuals working in the area.

CONTACT THE RADIATION SAFETY OFFICER IMMEDIATELY FOR SPECIFIC INSTRUCTIONS.

In performing housekeeping duties within the Nuclear Medicine Department:

1. **Never** handle anything labelled with a radiation precaution sticker.
2. **Never** reach behind lead shielding to do any cleaning.
3. **Never** empty any waste cans labelled with radioactive material signs or tape.
4. Floor areas may be cleaned unless otherwise instructed by nuclear medicine personnel or the Radiation Safety Officer.
5. Floors and toilets in patient bathrooms are often contaminated with radioactive material. Contact the Nuclear Medicine Department or Radiation Safety Officer for special instructions on cleaning these areas.
6. In case of any accidents: pills or contaminated areas, housekeeping supervisors should be notified by the Nuclear Medicine Department or the Radiation Safety Officer and special instructions will be issued to housekeeping personnel.
7. Trash cans not labelled with any precaution signs may be emptied as usual.
8. Linen containers not marked with any precaution signs may be laundered as usual.
9. Any spillage of material labelled with radiation precaution labels should be covered immediately with absorbent material (e.g., linens, towels, etc.). Contact the Radiation Safety Officer or Chief Technologist of Nuclear Medicine immediately. Follow his instructions carefully until he arrives in the department.

10. **Never** leave the Nuclear Medicine Department unlocked when unattended.

In performing housekeeping duties within the Radiation Oncology (Radiation Therapy) Department:

1. All areas may be cleaned as usual except rooms posted with Radioactive Materials, Radiation Area, or HIGH RADIATION AREA signs.
Obtain special instructions regarding housekeeping duties in these areas from the Radiation Therapy Department or Radiation Safety Officer.
2. If any radiation sources or suspected radiation sources are found during normal housekeeping activities, **DO NOT PICK UP THE SOURCE.**
Contact the Radiation Safety Officer or security personnel immediately.
In case of emergency in any area where radiation sources are used or stored or if you have any specific questions, notify the Radiation Safety Officer.

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APPENDIX A

MAXIMUM PERMISSIBLE DOSES (MPD's) FOR OCCUPATIONALLY EXPOSED INDIVIDUALS

Area of Body	MPD (Maximum Number of Rem Allowed)	MPD (Maximum Number of mSv Allowed)
Whole Body**	5 rem/year 1.25 rem/quarter 0.416 rem/month	50 mSv/year 12.5 mSv/quarter 4.16 mSv/month
Hands**	75 rem/year 18.75 rem/quarter 6.25 rem/month	750 mSv/year 187.5 mSv/quarter 62.5 mSv/month
Forearms**	30 rem/year 7.5 rem/quarter 2.5 rem/month	300 mSv/year 75 mSv/quarter 25 mSv/month
All Other Organs, Tissues & Organ Systems**	15 rem/year 3.75 rem/quarter 1.25 rem/month	150 mSv/year 37.5 mSv/quarter 12.5 mSv/month
Fetus in Utero (Resulting from occupational exposure Pregnant female)	0.5 rem during the entire gestation period	5 mSv during the entire gestation period of

*millisieverts

** somewhat higher MPD's are allowed in emergency situations. Consult NCRP Report #39

APPENDIX B

RATIONALE FOR WRITTEN NURSING PROCEDURES IN THE CARE OF PATIENTS RECEIVING THERAPEUTIC RADIATION

The purpose for written nursing procedures in the care of patients undergoing the therapeutic use of radioactive materials can be explained in many ways and is not limited to the following:

- To ensure the optimal and safe care of patients receiving therapeutic amounts of radioactive material.
- To ensure that the radiation exposure to any individual will not exceed safety guidelines and regulatory requirements, and will be kept to the lowest and most reasonably achievable level.
- To obtain the cooperation of patients, visitors, and personnel by instilling in them the necessity for precautionary measures.
- To prevent patients from feeling isolated and/or rejected by hospital personnel.
- To prevent unreasonable fear by personnel caring for the patient.
- To enable nursing personnel to perform proper action according to the use of these written precautions, the Radioactivity Precautions Notice, in the patient's medical record, posted warning signs, and the standard nursing procedures.
- To enable nursing personnel to accept the nurse's station, the corridors, and the rooms adjacent to radiation therapy rooms as safe areas.
- To minimize the potential spread of radioactive contamination.

APPENDIX C

RESPONSIBILITIES OF RADIATION SAFETY PERSONNEL IN REGARDS TO PATIENTS RECEIVING RADIATION THERAPY (BRACHYTHERAPY OR I-131 THERAPY)

- The Radiation Safety Officer is responsible for evaluation and approval of rooms to be used for radioactive patients.
- Ensuring proper room preparation, and arrangement of furniture and lead shielding within the patient's room for the optimal safety of the patients, personnel, and visitors.
- Ensuring proper room preparation, availability of proper radiation safety supplies, and initiation of control procedure for isolating the patient's room.
- Providing special and timely radiation safety instructions to all personnel charged with the care of patients undergoing radiation therapy.
- Posting of the Radioactivity Precautions Notice in the patient's medical record and warning signs and instructions on the patient's door.
- Notifying appropriate administrative and regulatory authorities in a timely manner in the event a radioactive source is lost or damaged.
- Conducting a prompt and thorough search for an radioactive source reported lost or reported missing as a result of a source inventory.
- Providing for the appropriate and timely disposal of therapeutic radioactive sources (i.e., seeds, wire, etc.) and maintaining records of the transfer and disposal of these sources.
- Performing radiation surveys in and about patient's rooms to evaluate the potential radiation hazards within and outside of restricted areas; this would include determining the time limits for nursing personnel and visitors.
- Responsibility in determining when the patient may be removed from isolation.
- Maintaining file copies of radiation surveys for radiotherapy patients.

APPENDIX D

SUMMARY OF RESPONSIBILITIES AND PRECAUTIONS TO BE TAKEN WITH NUCLEAR MEDICINE THERAPY PATIENTS (I-131 THERAPY PATIENTS)

Special Note: The material contained within this Appendix represents policies and procedures currently used at The University of Alabama at Birmingham. These policies and procedures may vary from one institution to another. Consult your Radiation Safety Officer for more specific information.

1. Room Requirements

Private rooms are required for patients receiving therapeutic quantities of radioactive materials. A corner room is preferable.

Arrangement of the furniture, lead shielding, radiation safety receptacles, and other radiation safety equipment must be maintained according to the instructions of the Radiation Safety personnel and as indicated on the Radioactivity Precautions Notice.

Private bath and toilet facilities must be provided for patients receiving quantities of radioactive materials by mouth (i.e., Iodine-131).

2. Assignment of Nursing Personnel

All nursing personnel assigned to care for patients who have received therapeutic quantities of radioactive materials shall be considered as individuals who are occupationally exposed to ionizing radiation. Steps must be taken to ensure that personnel radiation monitors are issued to them.

Personnel monitoring (i.e., film badges) is not required for nurses caring for patients being treated for hyperthyroidism with Iodine-131 or for treatment of bone malignancies with Phosphorus-32.

Monthly personnel radiation dosimeters must be worn by all nursing personnel who are attending to the care of thyroid cancer patients treated with Iodine-131. The dosimeters must not be worn while receiving medical or dental diagnostic x-rays or therapeutic x-rays.

Appropriate training shall include areas relevant to radiation protection. The amount of training will depend on the potential for radiation exposure, the complexity of the task, and the role and responsibility of the individual.

Nursing personnel are limited to 50 millirem per 24 hour period of whole body exposure to radiation during routine care of patients being treated with Iodine-131 for thyroid cancer. The "time limits for nursing personnel" are determined based on this limit.

Reports of radiation exposure must be posted in an area where assigned nursing personnel frequent.

The nurse-in-charge shall be responsible for information and instructions given to the next shift.

Spare dosimeters must be made available for assignment and use by new nursing personnel giving care to patients undergoing treatment for thyroid cancer.

Nursing personnel with open wounds must have them properly dressed and covered prior to working in rooms of patients receiving therapeutic amounts of Phosphorus-32 and Iodine-131.

Pregnant nurses must not be assigned to the routine care of these patients. In the event that it becomes known that there was a pregnancy during such care, the Radiation Safety Officer must be notified.

An employee or student under eighteen years of age shall not be permitted to take care of these patients.

In the event that a special duty nurse is required, the Radiation Safety Officer will be notified.

Care for patients receiving radiotherapy should be rotated among the staff as much as reasonably achievable.

In the event of an Iodine-131 spill (i.e., vomitus, urine spills, etc.), nursing personnel attending the patient must arrange for thyroid monitoring with the Radiation Safety Officer.

3. Responsibilities of the Nuclear Medicine Department

Only a physician, authorized by the Nuclear Medicine License may prescribe the type and the amount of radioactive material given to the patient.

Either a nuclear medicine physician or a intern physician with at least 30 hours of training in nuclear medicine therapy must be physically present while the patient is being dosed with radioactive material.

Preparation and administration of the radiotherapy dose to the patient.

Complete the Patient Report Form and Patient Consent Form and attach these to the patient's medical record. A copy of these will be maintained in the Nuclear Medicine Division.

Provide assistance to the Radiation Safety personnel, if required.

Provide consultation, when necessary, regarding handling of patient.

Notify the Radiation Safety Officer, the nurse-in-charge on the Nursing Unit, and Housekeeping of scheduled Iodine-131 therapy. Give the patient's name, type of therapy, the room number, and time schedule. The Clinical Laboratory should be reminded to take blood tests before the dosing of the patient.

Transport the radioactive dose from the Nuclear Medicine Division to the patient's room using direct routes and taking care to maintain a safe distance from others.

Nuclear Medicine Personnel attending patient should ensure that the door to the patient's room is closed during dosing with radioactive iodine.

Nuclear Medicine personnel attending patient should instruct the patient in the proper procedure in taking Iodine-131 doses orally so as to minimize exposure to the patient's lungs.

Nuclear Medicine personnel attending patient should wear suitable clothing (including shoe covers) to guard against Iodine-131 spills when entering patient's room and during dosing of the patient.

Nuclear Medicine personnel attending patient should carefully remove plastic gloves and shoe covers upon exiting the room taking care not to spread contamination.

Nuclear Medicine personnel attending patient should monitor hands, clothing, and shoes after exiting the patient's room at an appropriate distance from the patient's room.

Determine the amount of residual Iodine-131 in the patient prior to performing clinical nuclear medicine studies, for the patient, which utilize Iodine-131. The prior survey information provided by the Radiation Safety personnel may be used in these determinations.

4. Instructions for Nursing Personnel

Nurses must familiarize themselves with the content and instructions given on the Radioactivity Precautions Notice in the medical record of these patients. For instance, the bedside "time limit for nursing personnel" must be observed.

Urgent action to deal with accident situations arising from, explosion, or mechanical damage, or from the need to rescue or treat injured persons, should not be delayed because of the presence of the radioactivity in the therapy patient.

As any exposure may involve some degree of risk, any unnecessary exposure should be avoided and all doses kept as low as reasonably achievable (ALARA).

Good procedures are essential. All techniques must be well thought out and understood before work is undertaken. A balance should be struck between hurried manipulations, which may cause accidents, and prolonged operations, which may lead to excessive exposure.

The Radiation Safety Officer must be notified when any of the patients containing therapeutic quantities of radioactive material expires or is transferred to another hospital against medical advice.

Nursing personnel should learn to identify and check for appropriate "warning" signs on patients' doors, and ensure that posting is maintained as required by the Radiation Safety Officer.

Nursing personnel should record routine care given to patients on the patients' medical records, including patients' comments. Record any visits made by visitors.

Attendant nurses should be familiar with the time limit and minimum distance restrictions placed on the visitors of patients undergoing thyroid cancer treatment. Furthermore, visitors should be advised accordingly and the Radiation Safety Officer notified if these instructions are disregarded or otherwise violated.

All non-radioactive laboratory work for these patients (i.e., involving the taking of blood or urine samples) should be done prior to dosing them with radioactive material. Those which become necessary during the radioactive treatment should be delayed 48 hours following the time patients received the dose, if possible.

Unless required, nurses must not be in the patients' rooms during their dosing with radioactive material. At any other time, nursing personnel may enter their patients' rooms to perform their normal duties; however, they should not spend excessive time visiting with them nor performing nonvital personal services such as shaving or hairdressing.

Patients should be encouraged to care for themselves and to be as self-sufficient as possible, thus reducing the need for close contact with hospital personnel.

When required, the hazard from collection or elimination of excreta can often be reduced by asking the patients to take charge of the operation themselves.

Bedding and utensils must be placed in special receptacles within the patients' rooms. These will be returned to the normal hospital flow pattern after being released by the Radiation Safety Division.

Questions regarding the handling or disposal of contaminated clothing or instruments should be directed to the radiation Safety Officer or to other Radiation Safety health physics personnel.

The taking of blood samples for test should be delayed at least 48 hours. Use of gloves at this time is not required and is believed to be safe following careful prep. Hands should be washed thoroughly. Care must be taken to prevent urine or other patient excreta from being spilled on the floor. If a spill is suspected, the Radiation Safety Officer must be notified.

Gowns and suitable plastic or surgical gloves must be worn when handling the patients' bedpans, soiled bed linen, or clothes or any container of radioactive material (i.e., urine, vomitus, or excreta from incontinent patients) from the patient. They must be worn whenever and wherever contamination is likely. Once the gloves are removed and properly disposed, hands are washed thoroughly after giving care to therapy patients. If contamination is suspected, the hands must be monitored to make sure that no contamination remains using geiger counter provided by the Radiation Safety Division. The spread of contamination from these gloves to other surfaces should be avoided. Handling should be kept to a minimum.

Shoe covers must be donned before entering patients' rooms, worn while in the patients' rooms, and taken off properly while stepping off the papered thresholds to their rooms. Care should be taken to prevent contamination of the shoes and to properly discard shoe covers to receptacles provided at room entrances. For additional details regarding entry and exit to and from patients' rooms, refer to Sections 7 and 8.

Disposable dietary plates and utensils should be provided and used by the patient.

The door to any of these patients' rooms must be kept closed except during room entry or exit.

For any work carried out by nursing personnel during the first 48 hours of thyroid cancer treatment the number of persons in the room should be limited to those essential for the work. However, if only one person is involved, it is generally advisable that some other person be available to give assistance if required, but not necessarily be inside of the patient's room.

The warning signs and notices posted on the door to any patient's room by the Radiation Safety Officer should remain so until the patient's room has been decontaminated and patient isolation restrictions are released by the Radiation Safety Officer.

Monitoring equipment should be periodically checked to ensure satisfactory operation. Care should be taken so as not to contaminate radiation detectors.

Decontamination of body surfaces should be carried out by washing the affected part, using toilet soap or a mild detergent and swabbing with cotton swab or a brush. Washing should be continued for at least 5 minutes, with continuous running water, after which the area should be checked for remaining contamination. Washing may be repeated if necessary but should not be continued to the point of skin irritation. For persistent contamination, other procedures may be attempted but only under medical supervision.

Any contaminated tissue paper may be flushed down the toilet; other disposable and contaminated articles are to be saved in the bagged waste receptacles.

Decontamination of the eyes, nose, or mouth requires special care under medical attention. As an immediate action, the eyes should be irrigated with water or saline only, the mouth rinsed and the nose swabbed, efforts being made to minimize ingestion or inhalation during this procedure and to avoid introducing further activity from surrounding contaminated areas of skin. It is difficult to estimate the amount of residual contamination in these circumstances and advice of a specialist may be needed.

If any therapy patient is incontinent, the Radiation Safety Officer must be notified of this prior to treatment because special precautions are warranted (i.e., paper double-layering in some locations, requiring the wearing of non-absorbent shoe covers, very careful observation and monitoring upon room entry and exit).

The Radiation Safety Officer must be notified in the event any of these patients expire or emergency surgery is needed for a patient who has received therapeutic quantities of radioactive materials.

For additional information regarding patients or visitors, contact the Radiation Safety Officer for clarification.

5. Patient Instructions

Patients with bathroom privileges are instructed to flush the toilet at least three times after using it. Patients must sit on toilet when using the toilet.

Patients may have visitors 48 hours after the time they received their therapy dose. The visitors must stay at least 6 feet from these patients.

Patients must restrict travel about their room to the papered portions of the floor and to refrain from sitting in or touching any chairs to be used by visitors when such visits are allowed. Patients may not leave their rooms until so notified by Radiation Safety personnel.

As allowed by the Radiation Safety Officer, patients leaving their rooms must wear shoe covers. These are donned at the threshold exit from the room. After the patient's room and clothing has been monitored and/or decontaminated by Radiation Safety personnel, shoe covers will no longer be necessary.

6. Visitor Instructions

Visitors are instructed to refrain from eating, drinking, or smoking while in the patient's room.

Visitors are instructed to wash their hands and/or arms thoroughly if contamination is suspected. Their hands should be washed first.

Visiting time is limited to the maximum time given in the notice to visitors posted on the door to the patient's room.

Children (under 18 years of age) and pregnant women should not be allowed to enter the patient's room. Any exceptions to this rule must be approved by the Radiation Safety Officer.

7. Procedures for Decontamination of Radioactive Spills

Any spills or releases from a radioactive patient (i.e., vomitus, urine, sputum, etc.) is to be considered as being radioactive and will necessitate decontamination. These spills will generally occur in the patient's room. Until a plan has been worked out for decontamination after major spills, only minimum emergency action should be taken. Proceed as follows:

- a. Stop all operations, which, if continued, would add to the contamination, and shut off room ventilation. (call hospital maintenance, if necessary).
- b. Remove affected clothing and leave it in the contaminated area.
- c. Evacuate all non-essential staff, ensuring that no persons proceed far into clean areas until they have been monitored and found free from significant contamination. However, treatment of serious injury shall take precedence over decontamination of an individual.
- d. Control entry to the area by posting warning notices or other means.
- e. Notify the Radiation Safety Officer and the nurse-in-charge.
- f. While awaiting response from the Radiation Safety Officer, mark off the entire region of potential contamination.
- g. If there is appreciable liquid on a non-absorbent surface, then any linen immediately available should be dropped on top of it and left there.
- h. Essential personnel remaining in the room should remain at least six feet from affected area.
- i. Before the contaminated area can be used again by nursing personnel, a complete radiation survey must be made by Radiation Safety personnel.

8. Room Entry and Exit Procedures for I-131 Therapy

How To Enter Room:

- a. Put on two (2) pairs of shoe covers
- b. Put on one (1) disposable isolation gown
- c. Put on two (2) pairs of disposable gloves
- d. Put on one (1) surgical mask

How To Exit Room:

- a. Remove one outer shoe cover and place foot on exterior pad just outside door
- b. Remove the other outer shoe cover of other foot and place on exterior pad just outside door
- c. Remove isolation gown
- d. Remove outer pair of gloves
- e. Remove surgical mask
- f. Remove one shoe cover and place foot on bare floor
- g. Remove final shoe cover and place foot on bare floor
- h. Remove final pair of gloves
- i. Return to nurse's station and check yourself for contamination with Geiger counter

(Place all materials in bag for disposal by Radiation Safety)

9. Operating Procedures for G-M Detectors (Geiger Counters)

Operation of Geiger Counter:

- a. Turn switch to battery check position, "Batt"; the needle should be in area marked "Batt OK"
- b. Turn switch to the most sensitive scale position "X 0.1"
- c. Turn response knob all the way to the right (clockwise)
- d. Check yourself for contamination with probe about 1/4 inch away from surface. If the needle goes past "2" on upper portion of scale, wash contaminated surface and recheck
- e. Turn switch to "OFF" position

APPENDIX E

SUMMARY OF RESPONSIBILITIES AND PRECAUTIONS TO BE TAKEN WITH RADIATION THERAPY PATIENTS (BRACHYTHERAPY PATIENTS)

Special Note: The material contained within this Appendix represents policies and procedures currently used at the University of Alabama at Birmingham. These policies and procedures may vary from one institution to another. Consult your Radiation Safety Officer for more specific information.

1. Room Requirements

Private rooms are required for patients receiving therapeutic quantities of radioactive materials. A corner room is preferable. Only rooms approved by the Radiation Safety Officer may be used for patients undergoing therapy treatment with radioactive materials of the following types and in amounts* greater than specified below:

Radium-226	30 millicuries
Cesium-137	90 millicuries
Iridium-192	100 millicuries
Cobalt-60	20 millicuries

Arrangement of the furniture, lead shielding, radiation safety receptacles, and other radiation safety equipment must be maintained according to the instructions of the radiation safety personnel and as indicated on the Radioactivity Precautions Notice.

Private rooms must be provided for patients receiving therapeutic treatment from sealed sources.

A list of rooms approved by the Radiation Safety Officer for this type of therapy should be provided to Hospital Admitting with instructions for assigning brachytherapy patients to these rooms.

*These quantities may vary from one facility to another. Consult your Radiation Safety Officer.

2. Assignment of Nursing Personnel

All nursing personnel assigned to care for patients who have received therapeutic quantities of radioactive materials shall be considered as individuals who are occupationally exposed to ionizing radiation. Steps must be taken to ensure that personnel radiation monitors are issued to them.

Monthly personnel radiation dosimeters must be worn by all nursing personnel who are attending to the care of radiotherapy patients. The dosimeters must not be worn while receiving medical or dental diagnostic x-rays or therapeutic x-rays.

Appropriate training shall include areas relevant to radiation protection. The amount of training will depend on the potential for radiation exposure, the complexity of the task, and the role and responsibility of the individual.

Nursing personnel are limited to 50 millirems* per 24 hour period of whole body dose to radiation during routine care of these patients. The "time limits for nursing personnel" are determined based on this limit.

Reports of radiation exposure must be posted in an area where assigned nursing personnel frequent.

The nurse in charge shall be responsible for information and instructions given to the next shift.

In the event of a cardiac arrest or similar emergency situation which would necessitate working in close proximity to the patient, the registered nurse in-charge will determine the need for removal of sources from patient. This nurse will be authorized to remove the sources in the event that radiation therapy personnel or a physician on the floor is not immediately available. The criteria to be used by the registered nurse-in-charge will be a need for extended patient care under these circumstances. In such an event, the radiation therapy technician on-call will be immediately notified following source removal. At this time the technician will respond, carefully observe the situation, and perform a source count and radiation survey. The Radiation Safety Officer will also be notified at once. Registered nurse-in-charge should note the time the sources are removed from the patient.

Spare dosimeters must be made available for assignment and use by new nursing personnel giving care to patients undergoing treatment.

*Dose limit used at the University of Alabama at Birmingham.

Pregnant nurses must not be assigned to the routine care of these patients. In the event that it becomes known that there was a pregnancy during such care, the Radiation Safety Officer must be notified.

An employee or student under eighteen years of age shall not be permitted to take care of these patients.

In the event that a special duty nurse is required, the Radiation Safety Officer will be notified.

Care for patients receiving radiotherapy should be rotated among the staff as much as reasonably achievable.

If the packing or dressing appears disturbed, the radiation therapy technician on call shall be notified immediately. In this situation, nothing should be removed from the room until it has been checked for the presence of possible dislodged sealed sources.

The Radiation Safety Officer must be notified immediately if there is any suspicion that a radiation source has been lost or if the source container or applicator has been opened.

3. Responsibilities of the Radiation Therapy Department

Only a physician authorized by the Radiation Therapy License may prescribe the type and the amount of radioactive material given to the patient.

Preparation and administration of the radiotherapy dose to the patient.

Complete the Patient Prescription Form and Patient Consent Form and attach these to the patient's medical record. A copy of these will be maintained in the Radiation Therapy Department.

Provide assistance to radiation safety personnel, if required.

Provide consultation, when necessary, regarding handling of patient.

Notify the Radiation Safety Officer and the nurse-in-charge of the Nursing Unit of scheduled radiotherapy. Give the patient's name, type of therapy, the room number, and time schedule. Timely notification of changes in treatment schedules should also be given.

Transport the radioactive therapy source from the Radiation Therapy department to the patient's room using direct routes and taking care to maintain a safe distance from others. The transport container should provide adequate shielding. Tools used to handle the radioactive sources will be left either near the sources or in a designated area where readily available.

Radiation Therapy personnel attending patient will ensure that the door to the patient's room is closed during insertion of sealed sources.

Notifying the Radiation Safety Officer in the event a radioactive source is lost or damaged.

Surveying the patient and the patient's room with an appropriate radiation survey meter to ensure that all sources have been accounted for following their removal from the patient. For patients being treated with Iodine-125 seed implant of the prostate, a radiation therapy technician will be present to survey for dislodged seeds at the time the patient's Foley catheter is discontinued. In conjunction with this procedure, it is necessary to collect all voided urine for 24 hours after the catheter is removed and to survey the catheter bag for the presence of dislodged seeds.

Removing radiation warning signs and labels from patient's room after radioactive therapy sources have been removed from the patient.

4. Instructions for Nursing Personnel

Nurses must familiarize themselves with the content and instructions given on the Radioactivity Precautions Notice in the medical record of these patients. For instance, the bedside "time limit for nursing personnel" must be observed.

Urgent actions to deal with accident situations arising from fire, explosion, or mechanical damage, or from the need to rescue or treat injured persons, should not be delayed because of the presence of the radioactivity in the therapy patient.

The lead shields, when placed beside a patient's bed, must be utilized whenever possible for attendant care within two feet of the patient.

As any exposure may involve some degree of risk, any unnecessary exposure should be avoided and all doses kept as low as reasonably achievable (ALARA).

Good procedures are essential. All techniques must be well thought out and understood before work is undertaken. A balance should be struck between hurried manipulations, which may cause accidents, and prolonged operations, which may lead to excessive exposure.

The Radiation Safety Officer and the Radiation Therapy Department must be notified when any of the patients containing therapeutic quantities of radioactive material expires, requires emergency surgery, is unmanageable, fails to observe isolation requirements during treatment, or leaves the hospital against medical advice.

Nursing personnel should record routine care given to patients on the patients' medical records, including patients' comments. Record any visits made by visitors.

Bed baths performed by nursing personnel should be extremely limited while the sealed sources are in place within patients. Attendant nurses should be familiar with the time limit and minimum distance restrictions placed on the visitors of patients undergoing treatment. Furthermore, visitors should be advised accordingly and the Radiation Safety Officer notified if these instructions are disregarded or otherwise violated.

All nonradioactive laboratory work for these patients (i.e., involving the taking of blood or urine samples) should be done prior to insertion of sealed sources. When such work is necessary during treatment specimens should be collected as rapidly as possible (i.e., within 5 minutes) and radiation shields utilized as much as possible. Unless required, nurses should not be in the patients' rooms during insertion of sealed sources. At any other time, nursing personnel may enter their patients' rooms to perform any and all normal duties; however, they should not spend excessive time visiting with patients nor perform such nonvital personal services as shaving or hairdressing.

Any dressings or bandages used to cover an area of insertion with colloidal gold (Au-198) or chromic phosphate (P-32) shall be changed only by the attending physician. The dressings are to be kept in a receptacle within the patient's room awaiting disposal. It may be disposed only by the radiation therapy technician or radiation safety personnel.

For sealed sources, no contamination hazard exists, however, care should be exercised to avoid loss of radioactive sources. For example, the source may become dislodged from its location in the patient. No special precautions for sealed sources are needed for vomitus, spunk, urine, feces, or for eating utensils since no radioactive contamination is expected to be present.

Linen, clothing, and bed pans should be examined visually on a regular basis to make sure that no radioactive tube or needle has fallen out of the patient.

If a metal object which might be a sealed source is seen, it must not be touched. A moist towel should be placed over it and the radiation therapy technician on call and the Radiation Safety Officer called at once. Forceps or hemostat or some

other long handled instrument should be used if it is necessary to pick it up. It should then be put into the shielded transport cart. This cart should be placed in the patient's room before picking up the source.

Patients should be encouraged to care for themselves and to be as self-sufficient as possible, thus reducing the need for close contact with hospital personnel.

The door to any of these patients' rooms must be kept closed except during room entry or exit.

For patients being treated with Iodine-125 seed implant of the prostate, call the Radiation Therapy Department and request a technologist at the time the Foley catheter is discontinued. After removal of the catheter, collect all voided urine for 24 hours, then call for it to be surveyed before being discarded.

The warning signs and notices posted on the door to any patient's room by radiation safety personnel should remain so until patient isolation restrictions are released by the Radiation Therapy Department.

5. Patient Instructions

Patients must stay in bed and not sit up.

Patients must remain in their rooms during radiotherapy treatment.

Patients must try not to snore or otherwise dislodge therapy sources.

6. Visitor Instructions

Visitors are instructed to refrain from smoking while in the patients room.

Children (under 18 years of age) and pregnant women should not be allowed to enter the patient's room. Exceptions to this rule must be approved by the Radiation Safety Officer.

APPENDIX F

PROCEDURES FOR CLEAN-UP OF BACTEC® SPILLS

There are several steps to take when performing the cleanup of a Bactec culture bottle spill, all of which will only take approximately 5 - 10 minutes.

If a vial is dropped onto a nonabsorbing surface such as a countertop or floor, the first thing to remember is not to spread the contamination. Let us suppose that the leakage occurred on a floor next to where you are standing.

1. Restrict traffic through the area.
2. If you suspect that the material is on or under your shoes, minimize your movement to avoid spread of contamination. If possible, have someone else bring supplies to your locations; otherwise, gather the items yourself. If contamination is suspected on your shoes, immediately remove the suspected shoes and place feet onto unaffected area of floor. Place two shoe covers over each possibly affected foot. These shoe covers are to remain on your feet until the "on-call" radiation safety technician can be notified. If material is splattered onto your skin, then proceed to wash the area with soap and water, thus decreasing the chance of absorption into body. If hosiery is involved, remove the hose or sock and place same into a plastic sack.
3. With gloved hands, pick up any large pieces of glass and the metal seal. Place this into a small plastic sack (or if none are available, place glass and seal onto the absorbent side of a chuck).
4. With disposable plastic gloves still on your hands, use a pad of paper towels or a rag to mop up the liquid and to pick up the small pieces of glass.
5. If a puncture in your skin occurs, proceed to the Emergency Department to have the cut cleaned and bandaged. Fill out accident report form. Upon notification of the puncture wound, the uptake, if any, will be monitored by urine assays performed by the Radiation Safety Officer.

*BACTEC culture vials, often found on nursing units and medical laboratories, contain 1-2 μ Ci of radioactive carbon-14. Though these constitute an extremely low radiation hazard, the half-life of ^{14} C is ~5730 years.

**These should be available on each nursing unit:

1. cleaning agents
2. absorbent pads
3. gloves
4. shoe covers
5. plastic sacks.

APPENDIX G

ASSIGNMENT OF PERSONNEL RADIATION DOSIMETERS

Nurses involved in care of patients undergoing therapeutic treatment with more than 20 millicuries of radioactivity of Iodine-131, Cesium-137, Radium-226, Iridium-191, or Cobalt-60 must wear a radiation monitor. These monitors must be worn properly and exchanged for new monitors on the first day of each new monitoring period. Until further evaluation, each monitoring period will be one month. The assignment of these monitors is very important. The designated registered nurse in charge should keep a sufficient number of spare monitors available for assignment to nurses only occasionally involved with the care of radioactive therapy patients. Spare monitors are identified by the appearance of "SPR" after the number on its face.

Any nurse recurrently involved with radioactive therapy patients from month to month must have a permanently assigned monitor. No other nurse may wear this monitor. The nurse's last name will appear on the face of the monitor along with the alphabetic series code, which identifies the nursing unit to which the nurse is assigned. Written requests should be sent to the dosimetry technician or Radiation Safety Officer concerning changes in the number of spares and changes affecting the personnel monitoring status of a nurse who is permanently monitored. The guidelines given below must be strictly followed in order to maintain proper radiation monitoring control in each nursing unit.

1. Assign monitors in numerical sequence and alphabetical order initially.
2. Obtain the name, social security number, and birth date of each nurse monitored. When spares are assigned, print the last name on the face of the badge. Once used, it can no longer be used by any other nurse. A monitor may only be used in the monitoring interval for which it was intended.
3. Any unnecessary holders into which the film monitors are inserted should be returned to the Radiation Safety Officer. An unnecessary holder is one for which neither a permanent or spare film monitor is available or scheduled for use. Institutions are usually penalized for each unreturned personnel monitoring holder.

6. When all glass fragments have been removed and the free liquid absorbed, use more towels or rags and a cleaning and germicidal solution (such as 1:4 dilution of "Wescodyne" or agent of similar germicidal efficiency) to clean the affected area.

ALWAYS clean the perimeter of the spill area first and work into the middle of the spill. This procedure will reduce spread of contamination outward from the spill area. Between each cleaning, change into a fresh pair of disposable gloves. After having cleaned the area several times using clean towels or rags each time, dry the area also using clean towels or rags.

7. Lastly, place all towels or rags, used gloves, and the broken glass into a plastic sack or roll all material into an absorbent pad (with plastic backing), and mark this sack or rolled absorbent pad so that anyone will be able to recognize that radioactive material is inside. This will be kept in any out-of-the-way place, such as a utility room until such time it is retrieved by radiation safety personnel. Remember that Carbon-14 presents no problem externally. The beta emission is of low energy, with a maximum range in air of approximately 25 cm (.38 mm in skin - thus barely penetrating the dermal layer).

8. Spills or Bactec vial breakages which occur during normal working hours should be reported to the Radiation Safety Officer. If the spill occurs at night or on a weekend, the radiation safety technician on call should be notified. If your shift ends before the radiation safety technician arrives, you must remain on your floor until released by the radiation safety technician.

9. After notification of a Bactec spill, the technician on call will respond to monitor and/or decontaminate the area (and personnel if necessary). At this time, shoes or other personal items will be monitored, gross contamination removed (if necessary), such that these items may be returned to the hospital staff member soon after the initial monitoring.

4. Arrange a collection box or envelope in the most accessible place for nurses to leave the monitors if they cannot be collected personally. Ideally, you should have some security over the monitors during the collection process.

5. Contact the dosimetry technician or the Radiation Safety Officer concerning any questions you might have regarding personnel monitoring in your unit. Any lost or washed monitors must be reported as soon as possible to either of the above individuals.

APPENDIX H

PUBLICATIONS OF INTEREST TO MEDICAL FACILITY RADIATION PROTECTION PROGRAMS

- | | |
|---------------------|--|
| 1. NCRP Report #33: | Medical X-ray and Gamma-Ray Protection For
Energies Up to 10 MeV - Equipment Design and Use |
| 2. NCRP Report #37: | Precautions in the Management of Patients
Who Have Received Therapeutic Amounts of
Radionuclides |
| 3. NCRP Report #39: | Basic Radiation Protection Criteria |
| 4. NCRP Report #40: | Protection Against Radiation From
Brachytherapy Sources |
| 5. NCRP Report #48: | Radiation Protection for Medical and Allied
Health Personnel |
| 6. NCRP Report #65: | Management of Persons Accidentally Contaminated
with Radionuclides |

Information on prices and how to order can be obtained directly from:

NCRP Publications
7910 Woodmont Avenue
Suite 800
Bethesda, MD 20814

7. Prehospital Management of Radiation Accidents
Robert C. Ricks, Ph.D.

8. Hospital Emergency Department Management of Radiation Accidents
Robert C. Ricks, Ph.D.

The above two publications may be obtained directly from:

REACTS

Oak Ridge Associated Universities
P.O. Box 117
Oak Ridge, TN 37830
(615) 576-3131

at a cost of \$10.00 each. A videotape presentation on each of the above topics is also available from REAC/TS at a cost of \$75.00 for each tape.*

*Prices valid as of May 1986.

