PRACTICAL RADIATION SAFETY MANUAL

Manual on HIGH ENERGY TELETHERAPY

Incorporating:
Applications Guide
Procedures Guide
Basics Guide

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INTERNATIONAL ATOMIC ENERGY AGENCY

MANUAL ON HIGH ENERGY TELETHERAPY
IAEA, VIENNA, 1996
IAEA-PRSM-4 (Rev.1)

Printed by the IAEA in Austria
March 1996

FOREWORD

The use of radiation sources of various types and activities is widespread in industry, medicine, research and teaching in virtually all Member States of the IAEA and is increasing. Although a number of accidents have caught the attention of the public in recent years, the widespread use of radiation sources has generally been accompanied by a good safety record. However, the control of radiation sources is not always adequate. Loss of control of radiation sources has given rise to unplanned exposures to workers, patients and members of the public, sometimes with fatal results.

In 1990 the IAEA published a Safety Series book (Safety Series No. 102) providing guidance on the safe use and regulation of radiation sources in industry, medicine, research and teaching. However, it was felt necessary to have practical radiation safety manuals for different fields of application aimed primarily at persons handling radiation sources on a daily routine basis, which could at the same time be used by the competent authorities, supporting their efforts in the radiation protection training of workers or medical assistance personnel or helping on-site management to set up local radiation protection rules.

A new publication series has therefore been established. Each document is complete in itself and includes three parts:

— **Applications Guide** — which is specific to each application of radiation sources and describes the purpose of the practice, the type of equipment used to carry out the practice and the precautions to be taken.

— **Procedures Guide** — which includes step by step instructions on how to carry out the practice. In this part, each step is illustrated with drawings to stimulate interest and facilitate understanding.

— **Basics Guide** — which explains the fundamentals of radiation, the system of units, the interaction of radiation with matter, radiation detection, etc., and is common to all documents.

The initial drafts were prepared with the assistance of S. Orr (UK) and T. Gaines (USA), acting as consultants, and the help of the participants of an Advisory Group meeting which took place in Vienna in May 1989: J.C.E. Button (Australia), A. Mendonça (Brazil), A. Olombel (France), F. Kossel (Germany), Fatimah, M. Amin (Malaysia), R. Siwicki (Poland), J. Karlberg (Sweden), A. Jennings (Chairman; UK), R. Wheelton (UK), J. Glenn (USA) and A. Schmitt-Hannig and P. Zúñiga-Bello (IAEA).

These drafts were revised by R. Wheelton from the National Radiation Protection Board in the UK and B. Thomadsen from Wisconsin University in the USA. In a second Advisory Group meeting held in Vienna in September 1990, the revised drafts were reviewed by P. Beaver (UK), S. Coornaert (France), P. Ferruz (Chile), J. Glenn (USA), B. Holliday (Chairman; UK), J. Karlberg (Sweden), A. Mendonça (Brazil), M.A. Mohamad-Yusuf (Malaysia), J.C. Rosenwald (France), R. Wheelton (UK), A. Schmitt-Hannig (Germany), and P. Ortíz and P. Zúñiga-Bello (IAEA). Finalization of all six manuals was carried out by A. Schmitt-Hannig, Federal Office for Radiation Protection (Germany) and P. Zúñiga-Bello (IAEA).

CONTENTS

APPLICATIONS GUIDE: HIGH ENERGY TELETHERAPY

Principles of Teletherapy

Some types of radiation can kill cancer cells and help cure cancers. One of the most common ways of using radiation employs a source of photons in a machine that allows a beam of photons to be directed towards the patient. The use of such a machine is called *teletherapy*. A teletherapy machine can usually treat about 40 patients a day, each patient taking about 15 minutes.

This Guide will be limited to deep seated tumours which require high energy photons. Superficial therapy, such as skin treatment, is not considered here. In high energy teletherapy the photon beam must pass through normal, healthy tissue on its way to the tumour, and continues beyond the tumour, irradiating the normal tissue on the other side. Unfortunately, the intensity of the photon beam, which increases in the first few millimetres below the skin, decreases as it goes deeper into the patient (see Fig. 1). A change in beam energy will change the beam penetration; this means that with higher energies deeper tissues in the body can be reached. However, if a high enough dose is given to cure the cancer using a single treatment delivered by a photon beam with a single orientation in the patient, the tissue just under the skin would receive too high a dose and would suffer radiation damage. Most teletherapy minimizes this damage to normal tissue in two ways:

Fractionating the dose to the tumour. Instead of delivering the treatment dose in one, single treatment, the patient receives many small treatments. Normal tissue recovers better between fractions than cancers do. Typically, a curative course of therapy might consist of 35 treatments of 2 Gy each, for a dose to the tumour of 70 Gy. The exact total dose and the dose delivered at each fraction depend on the type of cancer under treatment, the location in the body, the patient's condition, and the time between fractions. A trained physician must determine the total dose and dose per fraction for any particular patient and has to make sure that the treatment dose is accurately delivered.

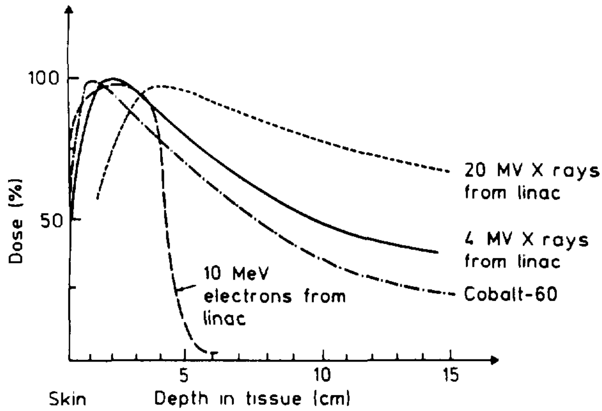

FIG. 1. Variation of dose as a function of depth for cobalt-60 and linacs operated at different energies for photons or electrons. In all cases the dose increases in the first few millimetres below the skin and then decreases, rapidly for the electrons, slowly for the photons. The higher photon energies give lower doses at the skin and higher penetration. The dose has been arbitrarily called 100% at the depth of the maximum.

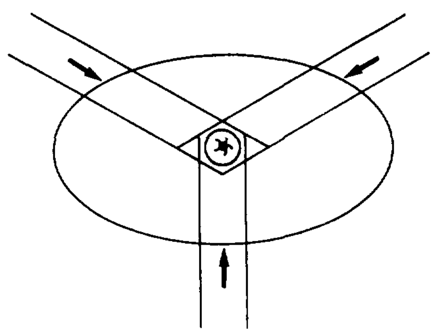

FIG. 2. Several photon beams focusing on a tumour. The dose can be made higher and more uniform in the tumour volume by adding in this volume the doses from several individual beams, leaving the healthy tissues either irradiated by only one beam or completely outside of all primary areas.

Using more than one beam. By using several photon beams, all focusing on the tumour but entering the patient at different locations on the body (see Fig. 2), the dose builds up in the tumour, but spreads out over the normal tissue. In this way, high doses can be delivered to the tumour while the doses to the normal tissue are kept to tolerable levels. In general (unless the tumour lies near the skin), at least two beams must be used. When going to high, curative doses, more beams must be used. To make it easier to use multiple fields, many treatment machines rotate around an axis, called an isocentre. By placing the tumour at the isocentre, it becomes easy to aim all photon beams at the tumour, and simply rotate the machine from one entry position to the next. The choice of the treatment technique should be made jointly by the radiotherapist in charge of the treatment and by a trained medical physicist.

Types of Teletherapy Machines

Teletherapy machines use one of two sources for their photon beams:

Cobalt-60[1]. Large sources of this radioactive material provide photons (called gamma rays) with energies of 1.17 MeV and 1.33 MeV. Because the source is radioactive, it emits photons all the time. When the machine is 'OFF', the source is shielded behind thick shielding material blocking the gamma rays.

Linear accelerators. These machines use microwaves to accelerate electrons along long tubes to get them moving very fast. At the end of the tube, the high speed electrons slam into a target of metal with a very high atomic number. As the electrons collide with the nuclei of the target atoms, they slow down and lose some of their energy. The energy that they lose becomes X rays. The X rays have energies that range from the energy of the electrons which produced them down to approximately 1 MeV. For example, a linear accelerator (or linac for short) which accelerates electrons to 10 MeV produces X rays from 1 MeV up to 10 MeV.

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[1] Some radiotherapy departments still use caesium-137 irradiation units. These are no longer recommended because of the low penetration of the beam.

Linear accelerators can produce much higher energy photons than cobalt-60 units. As shown in Fig. 1, the higher energy results in lower doses to the patient's skin and normal tissue in front of a tumour. However, linear accelerators require very constant electrical power, more maintenance, and a more specially trained service staff.

Since cobalt-60 units use a high activity source to provide photons, the dose rate always decreases with time as a result of radioactive decay. This decrease amounts to approximately 1% per month. After 5.27 years, which represent one half-life, treatments take twice as long as initially. This poses problems when treating patients, because longer treatment times give patients more time to move during treatments, and increase the possibility that the tumour may move out of the beam, or some sensitive normal structure may move into the beam and be damaged. Patients in a great deal of pain have particularly great difficulties holding still for long treatments. Thus, at least every 5 years a new cobalt-60 source must be purchased. However, it should be taken into account that cobalt units require much less maintenance than linacs.

In addition to X ray beams, some linacs can use the accelerated electrons directly, instead of running them into a target. Electron beams do not penetrate very deeply into the patient, but, rather, deliver their dose in a range from the skin down to some depth (seldom more than 5 cm) and then stop very quickly (see Fig. 1). Such beams provide appropriate dose distributions when the target organ lies near the skin with sensitive structure below, such as lymph nodes in the neck with the spinal cord behind.

Control of Radiation Doses

Over a short period of time (for instance, a day), a cobalt-60 source produces photons at approximately a constant rate. Because of the constant dose rate, the dose is proportional to the time the source irradiates the patient. The machine calibration consists of determining the dose rate from the unit. It has to be carried out by a well qualified expert in radiation physics and verified. Then the dose given to a patient can be controlled by simply setting the proper exposure time (the duration that the source stays in the unshielded position). Once calibrated, the dose rate at any future time follows the law of radioactive decay, and may be calculated. Periodic measurements of the dose rate can detect problems in the cobalt units, or in the measurement equipment if the measured dose rate differs from that calculated. After each source replacement or major modification the complete calibration has to be repeated.

Because linear accelerators produce their photon beams in unevenly sized pulses and with a varying number of pulses per unit time, the amount of radiation that a linac delivers to a patient in one minute may be quite different from the amount delivered the next minute. To prevent this variation in dose rate from affecting the dose to the patient, instead of controlling the exposure using a timer, linacs use radiation detectors (ionization chambers) in the beam, located in the source housing, to measure the amount of radiation produced by the machine. Electronic circuits connected to the detectors trip a counter each time they measure a certain amount of radiation.

The trip level can be set so that one count corresponds to a specific dose to a patient for a given field size, distance from the source and depth in the patient (for example, one count, or monitor unit, commonly equals 0.01 Gy at peak depth for a 10 cm × 10 cm field at the normal source to skin distance). To treat a patient to a desired dose, the operator sets a calculated number of monitor units on the linac's control according to the data obtained from the calibration performed by the qualified expert.

Malfunctions

Any teletherapy unit may fail to stop irradiating a patient at the end of a treatment. Instructions for such a situation appear in the Procedures Guide, and should be posted by the control panel of the treatment unit. Personnel should practise handling such emergencies to become familiar with the steps. Quick actions reduce the potential harm to the patient. The general rules to follow are:

(1) Try to turn the machine off with the 'EMERGENCY OFF' button.
(2) If that does not work, quickly remove the patient from under the beam.
(3) While removing the patient, STAY OUT OF THE BEAM YOURSELF.

If the rescuer stays out of the photon beam, removing the patient in the event of an emergency does not usually give a high radiation exposure. In the beam, however, a person is exposed to high levels of radiation within a short period of time.

Other emergency procedures such as rotating the gantry or closing the collimator from outside can also be considered as appropriate before anyone enters the room to remove the patient, depending on local conditions. Only after the patient has been removed from under the beam and you have left the room (closing the door) should thought be given to manual movement of a cobalt-60 source to the 'OFF' position by qualified personnel or the manufacturer. There is no hurry to turn the source off if no one is in the room. The unit should not be used again until the cause of the malfunction has been found and corrected by qualified service personnel.

Cobalt-60 machines are much more likely to fail to go to the 'OFF' position than a linac is to keep producing radiation after the preset dose has been reached, but failure to stop can happen with either type of unit. Personnel must be prepared to react to such a situation before the patient receives too much radiation. The operator should always be alert when treating a patient, and watch the time or monitor units as treatment progresses.

Every cobalt-60 unit should have a radiation monitor with a warning light (and/or audible sound) inside the room, but placed so it can be seen as soon as the door is opened. Such a monitor flashes the light when the source is 'ON'. By looking at the warning light, anyone entering the room can see if the source has properly returned to its shielded position or not. Linacs which give an audible signal when producing radiation do not require such a monitor.

All teletherapy machines produce large amounts of very penetrating radiation during operation. To protect the operator and other persons who may be around the treatment room, the walls of the room must be heavily shielded. After installation of a treatment unit, radiation level measurements in adjacent areas, with the beam on and the field defining diaphragms (also called collimators or jaws) open to their fullest extent, must be taken to ensure the safety of persons in these areas.

With properly shielded treatment rooms, the operators of the treatment machines should receive very little radiation exposure while performing their jobs. Interlocks on the door to the room should prevent running of the unit with the door open. Not only would operating the unit with the door open let some radiation escape, but it could also allow unauthorized persons to accidentally enter the room during treatment. The doorway should be marked with appropriate warning signs.

Cobalt-60 units also have the possibility of leakage of some of the radioactive material. Although this seldom happens, the machine should be leak tested, at least once every two years. To leak test the source, ensure that the source is in the 'OFF' position and put on a pair of gloves. Wet a piece of gauze, paper towel or rag with some alcohol, and wipe the collimator blades as close to the source as possible. A pair of forceps often helps to reach well up near the source opening. Count the gauze using the most sensitive detector available (such as a Geiger counter) to check for radioactivity on the sample. If the counter measurement of the sample shows a significant reading above background, the source may be leaking and the manufacturer should be contacted.

Quality Assurance and Safety Checks

At regular intervals, a series of operational tests should be performed to check that the treatment unit and its peripheral devices operate correctly. Items to be checked include:

- Positioning devices, such as lasers or positioning lights
- Source-to-skin distance measurement devices
- Readouts or indicators of machine settings, such as gantry angle and field size
- Light localizer alignment
- Door interlocks and warning systems.

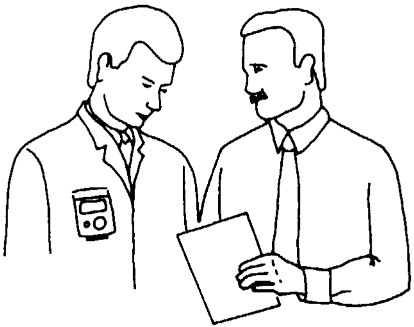
In the case of linacs it is good practice to measure daily the dose rate in the beam in a fixed geometry and also to check periodically the beam uniformity.

The supervisor, preferably with the assistance of a radiation expert, establishes the exact procedures for each of the tests. Approximately twice a year, a radiation expert should perform a complete calibration of the dose rate and beam characteristics for the unit.

Record Keeping

Clear records form the foundation for successful radiation therapy. Records of all of the calibrations and the daily quality assurance tests should be kept in logbooks. Immediately after each beam treatment on a patient, the relevant information must be entered onto the patient's chart.

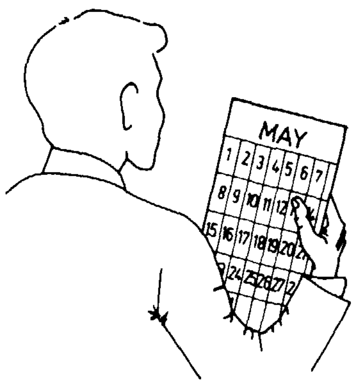
PROCEDURES GUIDE:
HIGH ENERGY TELETHERAPY



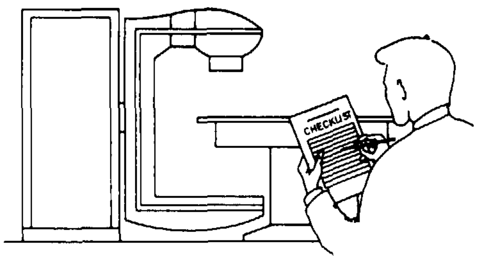
PROCEDURES GUIDE: HIGH ENERGY TELETHERAPY

Follow authorized procedures when carrying out teletherapy. Only trained personnel who have had medical examinations and wear a dosimeter should carry out teletherapy. In normal circumstances, such personnel should not have received a dose greater than 50 mSv to the whole body in the current calendar year.

Before proceeding with the work, read and ask questions about these safety guides. Discuss the contributions all the personnel involved will make to this important work.



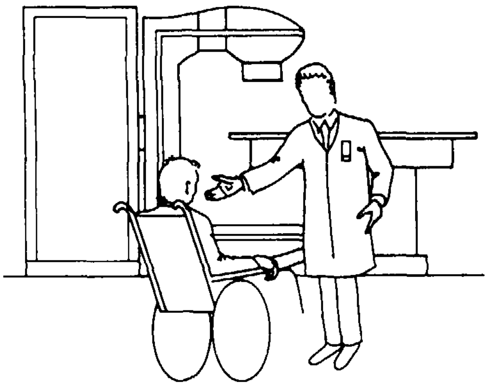
Make sure all periodic tests are performed on schedule. Mark a calendar ahead with the dates to carry out the beam calibration and quality assurance for a cobalt-60 source, due every 6 months.



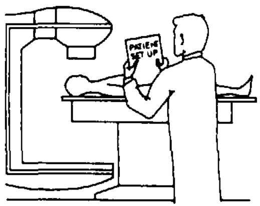
Before beginning treatments each day, run through a checklist to make sure that the treatment machine works properly. The tests should check:

(1) For linacs, the *dose rate* using an ionization chamber in a fixed geometry or a commercial beam checker, exposed for a predetermined time. The reading should always fall within $\pm 3\%$ of the posted value of the check.
(2) That the *timer* on a cobalt-60 unit or dose monitor on a linac stops the machine after the indicated setting.
(3) That the *door interlock* prevents use of the unit with the door open, and stops the exposure when the door opens during a treatment.
(4) The *emergency 'off' switch.*
(5) *Indicator lights*, such as beam-on lights and warning lights.
(6) Patient *alignment devices*, such as lasers or alignment lights.
(7) *Treatment unit readouts*, such as gantry angle, field size, couch angle.

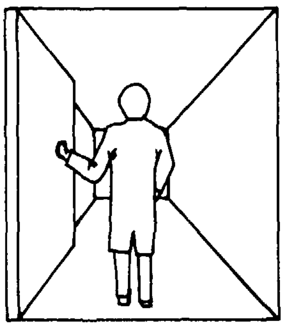
If ANY test falls outside of the limits set for that test, notify the supervisor immediately, and do not treat patients until further notice.



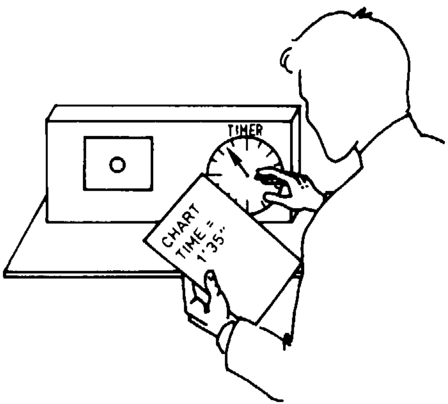
Be sure that the patient understands what will happen during the treatment, and explain the procedure step by step.



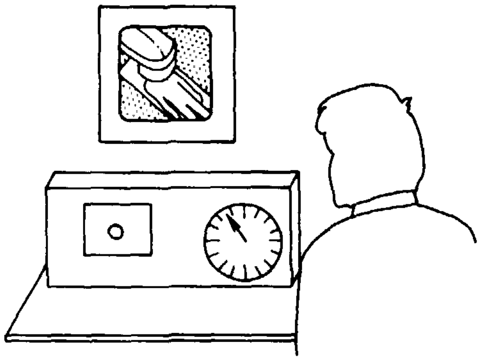
Check the patient's identity and the treatment prescription before taking the patient into the treatment room. Check the treatment set-up before leaving the room. Check the proper settings on the distance to the skin, field size, gantry angle, couch angle and height, and use of wedge or blocks.



Check that no one remains in the treatment room except the patient, and close the door or barrier.



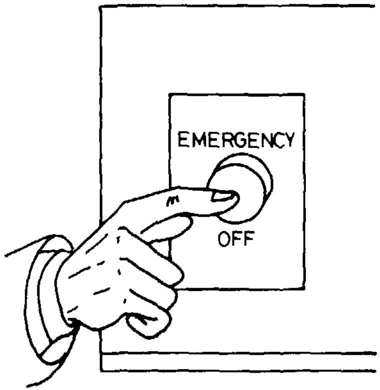
Check the time or monitor units set on the control panel before initiating the treatment.



Pay attention to the treatment while in progress. Do not allow yourself to be distracted. Watch for patient movement through the viewing window or on the television monitor and make sure that the machine operates normally throughout the treatment. If the patient moves significantly or if the unit appears to malfunction, stop the treatment immediately and inform your supervisor.

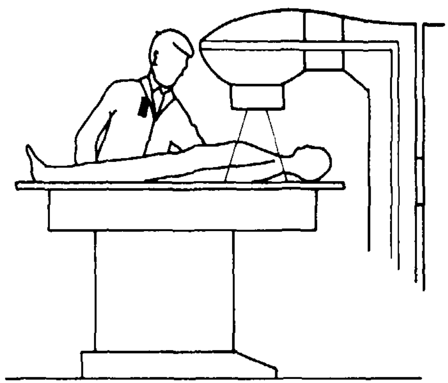
Examples of such malfunctions are:

- — Failure of the unit to turn 'OFF' at the end of treatment, or when interlocks should stop the treatment (such as when the door opens).
- — The source being 'ON' when it should not be.
- — Failure of the unit to come 'ON' when treatment should begin.
- — Inaccuracies in the timer or dose monitor settings.



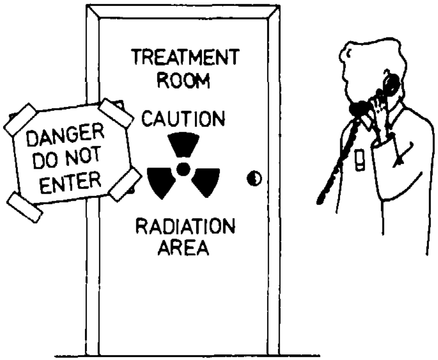
Emergency

Should the treatment unit fail to turn off after delivering the prescribed treatment, try to turn the machine off with the 'EMERGENCY OFF' button.



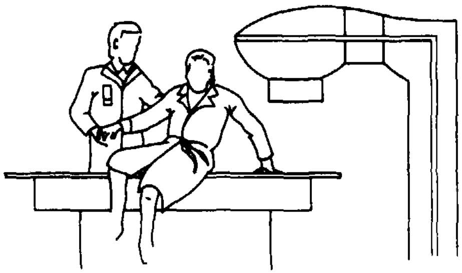
Emergency

If that does not work, quickly remove the patient from under the beam according to the local procedures. (While removing the patient, stand away as far as possible and ALWAYS OUT OF THE BEAM YOURSELF.)

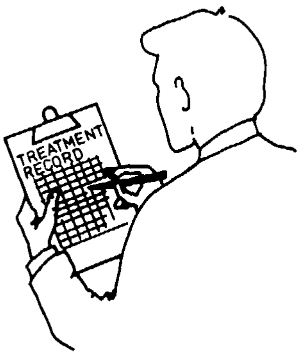


Emergency

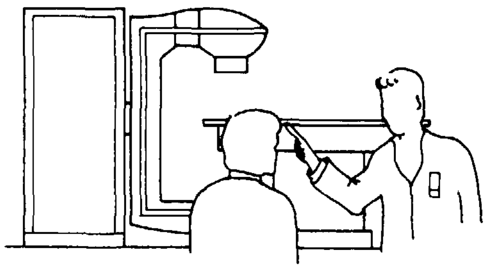
After removing the patient from under the beam, leaving the room and closing the door, talk with qualified maintenance personnel about turning the source off and repairing the unit.



After treating with all of the beams prescribed for the treatment session, remove the patient from the room.

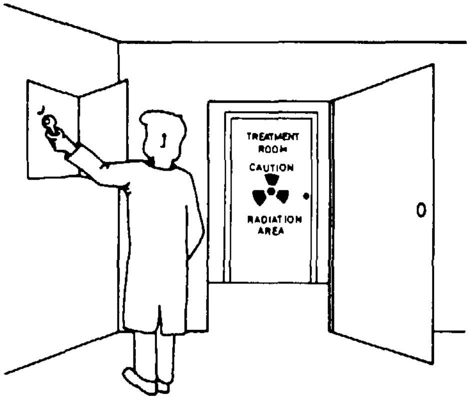


Enter the details of the treatment in the patient's treatment record, including the date, fields treated, the time or monitor units for each beam, the doses delivered during the session, and the running total dose for each of the target areas.



Report to your supervisor any indications of possible faults or treatment mistakes:

- — Incorrectly set treatment times or monitor unit setting, distances, field sizes, beam orientation (such as gantry angle or couch angle), blocking, use of wedges, or treatment mode or energy.
- — Anything else which seems to you *might* make a difference in the patient's treatment.



At the end of the day, make sure that the machine is turned off, the room is locked, and the keys to the machine and the room put away in a location not near the treatment room.

BASICS GUIDE FOR USERS OF IONIZING RADIATION

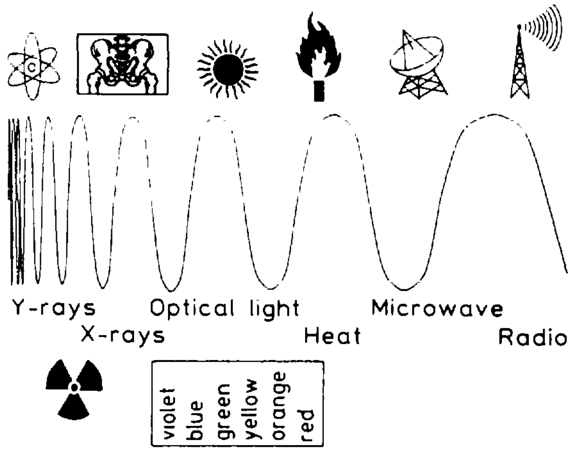
BASICS GUIDE FOR USERS OF IONIZING RADIATION

Production of Radiation

Radioactive substances are predictable and continuous emitters of energy. The energy emitted can be in the form of alpha (α) particles, beta (β) particles and gamma (γ) rays. Interaction of these radiations with matter can, in certain circumstances, give rise to the emission of X rays and neutron particles.

Gamma and X rays consist of physical entities called photons that behave like particles, suffering collisions with other particles when interacting with matter. However, large numbers of photons behave, as a whole, like radio or light waves. The shorter their wavelength the higher the energy of the individual photons.

The very high energy of gamma rays and their ability to penetrate matter results from their much shorter wavelengths.



Spectrum of radiations similar to gamma rays.

X rays are produced by an X ray machine only when it is electrically supplied with thousands of volts. Although they are similar to gamma rays, X rays normally have longer wavelengths and so they carry less energy and are less penetrating. (However, X rays produced by linear accelerators can surpass the energies of gamma radiation in their ability to penetrate materials.) The output of X radiation generated by a machine is usually hundreds or even thousands of times greater than the output of gamma radiation emitted by a typical industrial radioactive source. However, typical teletherapy sources are usually thousands of times greater in output than industrial radiography sources.

The gamma rays from iridium-192 (^{192}Ir) are of lower energies than those of cobalt-60 (^{60}Co). These are useful differences which allow selection from a wide range of man-made radionuclides of the one that emits those radiations best suited to a particular application.

Beta particles are electrons and can also have a range of energies. For example, beta particles from a radionuclide such as hydrogen-3 (^{3}H) travel more slowly and so have almost one hundredth of the energy of the beta particles from a different radionuclide such as phosphorus-32 (^{32}P).

Neutron particle radiation can be created in several ways. The most common is by mixing a radioactive substance such as americium-241 (^{241}Am) with beryllium. When it is struck by alpha particles emitted by the americium-241, beryllium reacts in a special way. It emits high energy, fast neutrons. Americium-241 also emits gamma rays and so from the composite americium-241/beryllium source are produced. Another way to create neutrons is using a radiation generator machine combining high voltages and special targets. Special substances in the machine combined with high voltages can generate great numbers of neutrons of extremely high energy.

Alpha particles in general travel more slowly than beta particles, but as they are heavier particles they are usually emitted with higher energy. They are used in applications which require intense ionization over short distances such as static eliminators and smoke detectors.

Radiation Energy Units

A unit called the electron-volt (eV) is used to describe the energy of these different types of radiation. An electron-volt is the energy aquired by an electron accelerated through a voltage of one volt. Thus, one thousand volts would create a spectrum (range) of energies up to 1000 eV. Ten thousand volts would create X rays of up to 10 000 eV. A convenient way of expressing such large numbers is to use prefixes, for example:

1000 eV can be written as 1 kiloelectron-volt (1 keV);
10 000 eV can be written as 10 kiloelectron-volts (10 keV);
1 000 000 eV can be written as 1 megaelectron-volts (1 MeV);
5 000 000 eV can be written as 5 megaelectron-volts (5 MeV).

Radiation Travelling Through Matter

As radiation travels through matter it collides and interacts with the component atoms and molecules. In a single collision or interaction the radiation will generally lose only a small part of its energy to the atom or molecule. However, the atom or molecule will be altered and becomes an ion. Ionizing radiation leaves a trail of these ionized atoms and molecules, which may then behave in a changed way.

After successive collisions an alpha particle loses all of its energy and stops moving, having created a short, dense trail of ions. This will occur within a few centimetres in air, the thickness of a piece of paper, clothing or the outside layer of skin on a person's body. Consequently, radionuclides that emit alpha particles are not an external hazard. This means that the alpha particles cannot cause harm if the alpha emitter is outside the body. However, alpha emitters which have been ingested or inhaled are a serious internal hazard.

Depending upon their energy, beta particles can travel up to a few metres in air and up to a few centimetres in substances such as tissue and plastic. Eventually, as the beta particle loses energy, it slows down considerably and is absorbed by the medium. Beta emitters present an internal hazard and those that emit high energy beta particles are also an external hazard.

Radionuclide	Type of radiation	Range of energies (MeV)
Americium-241	alpha gamma	5.5 to 5.3 0.03 to 0.37
Hydrogen-3	beta	0.018 maximum
Phosphorus-32	beta	1.7 maximum
Iodine-131	beta gamma	0.61 maximum 0.08 to 0.7; 0.36
Technetium-99m	gamma	0.14
Caesium-137	beta	0.51 maximum
(Barium-137m)	gamma	0.66
Iridium-192	beta gamma	0.67 maximum 0.2 to 1.4
Cobalt-60	beta gamma	0.314 maximum 1.17 and 1.33
Americium-241/ beryllium	neutron gamma	4 to 5 0.06
Strontium-90/ (Yttrium-90)	beta beta	2.27 2.26
Promethium-147	beta	0.23
Thalium-204	beta	0.77
Gold-198	beta gamma	0.96 0.41
Iodine-125	X ray gamma	0.028 0.035
Radium-226	alpha beta gamma	4.59 to 6.0 0.67 to 3.26 0.2 to 2.4

Heavier atoms such as those of lead do absorb a greater part of the beta's energy in each interaction but as a result the atoms produce X rays called bremsstrahlung. The shield then becomes an X ray emitter requiring further shielding. Lightweight (low density) materials are therefore the most effective shields of beta radiation, albeit requiring larger thicknesses of material.

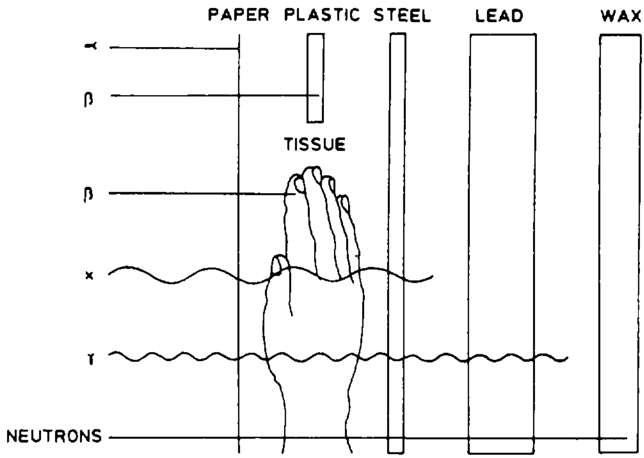
Radionuclide	Maximum beta particle energy (MeV)	Maximum range			
		Air (mm)	Plastic (mm)	Softwood (mm)	Aluminium (mm)
Promethium-147	0.23	400	0.6	0.7	0.26
Thalium-204	0.77	2400	3.3	4.0	1.5
Phosphorus-32	1.71	7100			
Strontium-90/ Yttrium-90	2.26	8500	11.7	14.0	5.2

Gamma rays and X rays are more penetrating. However, as they cause ionization they may be removed from the beam or lose their energy. They thus become progressively less able to penetrate matter and are reduced in number, that is attenuated, until they cease to be a serious external hazard.

One way of expressing the quality or penetrating power of gamma and X rays also provides a useful means of estimating the appropriate thickness of shields. The half value thickness (HVT) or the half value layer (HVL) is that thickness of material which when placed in the path of the radiation will attenuate it to one half its original value. A tenth value thickness (TVT) similarly reduces the radiation to one tenth of its original value.

Radiation producer	HVT and TVT values (cm) in various materials					
	Lead		Iron		Concrete	
	HVT	TVT	HVT	TVT	HVT	TVT
Technetium-99m	0.02					
Iodine-131	0.72	2.4			4.7	15.7
Caesium-137	0.65	2.2	1.6	5.4	4.9	16.3
Iridium-192	0.55	1.9	1.3	4.3	4.3	14.0
Cobalt-60	1.1	4.0	2.0	6.7	6.3	20.3
100 kV_p X rays	0.026	0.087			1.65	5.42
200 kV_p X rays	0.043	0.142			2.59	8.55

Material which contains heavy atoms and molecules such as steel and lead provide the most effective (thinnest) shields for gamma radiation and X rays.



The penetrating properties of ionizing radiations.

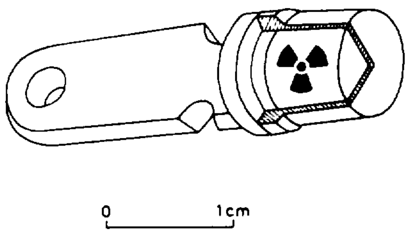
Neutrons behave in complex ways when travelling through matter. Fast neutrons will scatter (bounce) off much larger atoms and molecules without losing much energy. However, in a collision between a neutron and a small atom or molecule, the latter will absorb a proportion of the neutron's energy. The smallest atom, the hydrogen atom, is able to cause the greatest reduction in energy.

Hydrogenous materials such as water, oil, wax and polythene therefore make the best neutron shields. A complication is that when a neutron has lost nearly all its energy it can be 'captured', that is absorbed whole by an atom. This often results in the newly formed atom becoming a radionuclide, which in many instances would be capable of emitting a gamma ray of extremely high energy. Special neutron absorbing hydrogenous shields contain a small amount of boron which helps to absorb the neutrons.

Damage to human tissue caused by ionizing radiation is a function of the energy deposited in the tissue. This is dependent on the type and energies of the radiations being used. Hence the precautions needed to work with different radionuclides also depend on the type and energy of the radiation.

Containment of Radioactive Substances

Radioactive substances can be produced in any physical form: a gas, a liquid or a solid. Many medical and most industrial applications use sources in which the radioactive substance has been sealed into a metal capsule or enclosed between layers of non-radioactive materials. Often these sources are in 'Special Form' which means that they are designed and manufactured to withstand the most severe tests, including specified impact forces, crushing forces, immersion in liquid and heat stress, without leaking radioactive substance.

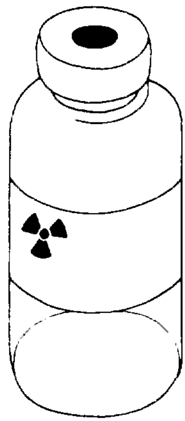


A sealed source, showing the encapsulated radioactive substance.

All sealed sources are leak tested after manufacture and the test (also called a wipe test) must be repeated periodically throughout the working life of the source. More frequent testing is required for sealed sources which are used in harsh environments or in applications that are likely to cause them damage. Most sealed sources can remain leak-free and provide good, reliable service for many years but eventually must be safely disposed of and replaced because the activities have decayed below usable levels.

Sealed sources present only an external hazard. Provided that the source does not leak there is no risk of the radioactive substance being ingested, inhaled or otherwise being taken into a person's body.

Unsealed radioactive substances such as liquids, powders and gases are likely to be contained, for example within a bottle or cylinder, upon delivery, but may be released and manipulated when used. Some unsealed sources remain contained but the containment is deliberately weak to provide a window for the radiation to emerge. Unsealed radioactive substances present both external and internal hazards.



A bottle of radioactive liquid.
The rubber cap sealing the bottle may be removed or pierced to extract liquid.

The Activity of Sources

The activity of a source is measured in becquerels (Bq) and indicates the number of radionuclide atoms disintegrating per second (dps or s^{-1}).

1 Becquerel is equivalent to 1 atom disintegrating per second

Industrial and medical applications usually require sealed sources with activities of thousands or millions of becquerels. A convenient method of expressing such large numbers is to use prefixes, for example:

1 000 becquerels is written 1 kilobecquerel (1 kBq);
1 000 000 becquerels is written 1 megabecquerel (1 MBq);
1 000 000 000 becquerels is written 1 gigabecquerel (1 GBq);
1 000 000 000 000 becquerels is written 1 terabecquerel (1 TBq).

The activity of a source is dependent on the half-life of the particular radionuclide. Each radionuclide has its own characteristic half-life, which is the time it will take for the activity of the source to decrease to one half of its original value. Radionuclides with short half-lives are generally selected for medical purposes involving incorporation into the body via oral, injection or inhalation, whereas those with relatively longer half-lives are often of benefit for medical, therapeutic (external or as temporary inserts) and industrial applications.

Radionuclide	Half-life[a]	Application
Technetium-99m	6.02 h	Medical diagnostic imaging
Iodine-131	8.1 d	Medical diagnostic/ therapy (incorporated)
Phosphorus-32	14.3 d	Medical therapy (incorporated)
Cobalt-60	5.25 a	Medical therapy (external) Industrial gauging/radiography
Caesium-137	28 a	Medical therapy (temporary inserts) Industrial gauging/radiography
Strontium-90	28 a	Industrial gauging
Iridium-192	74 d	Industrial radiography, or medical therapy
Radium-226	1620 a	Medical therapy (temporary inserts)
Iodine-125	60 d	Medical diagnostic/therapy
Americium-241	458 a	Industrial gauging
Hydrogen-3	12.3 a	Industrial gauging
Ytterbium-169	32 d	Industrial radiography
Promethium-147	2.7 a	Industrial gauging
Thalium-204	3.8 a	Industrial gauging
Gold-198	2.7 d	Medical therapy
Thulium-170	127 d	Industrial radiography

[a] The abbreviation 'a' stands for 'year'.

When radioactive substances are dispersed throughout other materials or dispersed over other surfaces in the form of contamination, the units of measurement which are most commonly used are:

(a)	for dispersion throughout liquids	$Bq \cdot mL^{-1}$
(b)	for dispersion throughout solids	$Bq \cdot g^{-1}$
(c)	for dispersion throughout gases (most particularly air)	$Bq \cdot m^{-3}$
(d)	for dispersion over surfaces	$Bq \cdot cm^{-2}$

An older unit of activity which is still used, the curie (Ci), was originally defined in terms of the activity of 1 gram of radium-226. In modern terms:

1 Curie is equivalent to 37 000 000 000 dps, that is 37 GBq:

1 nCi	1 μCi	1 mCi	1 Ci	10 Ci
37 Bq	37 kBq	37 MBq	37 GBq	37 TBq

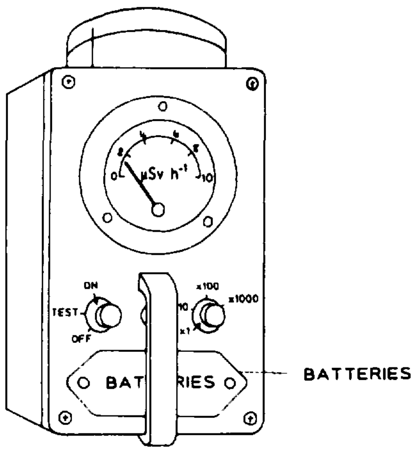
Measurement of Radiation

Ionizing radiation cannot be seen, felt or sensed by the body in any other way and, as has already been noted, damage to human tissue is dependent on the energy absorbed by the tissue as a result of ionization. The term used to describe energy absorption in an appropriate part or parts of the human body is 'dose'.

The modern unit of dose is the gray (Gy). However, in practical radiation protection, in order to take account of certain biological effects, the unit most often used is the sievert (Sv). For X ray, gamma and beta radiation, one sievert corresponds to one gray. The most important item of equipment for the user is a radiation monitoring device. There are instruments and other devices that depend on the response of film or solid state detectors (for example, the film badge or thermoluminescent dosimeters).

Two types of instruments are available: dose rate meters (also called survey meters) and dosimeters.

Modern dose rate meters are generally calibrated to read in microsieverts per hour ($\mu Sv \cdot h^{-1}$). However, many instruments still use the older unit of millirem per hour ($mrem \cdot h^{-1}$). 10 $\mu Sv \cdot h^{-1}$ is equivalent to 1 $mrem \cdot h^{-1}$.



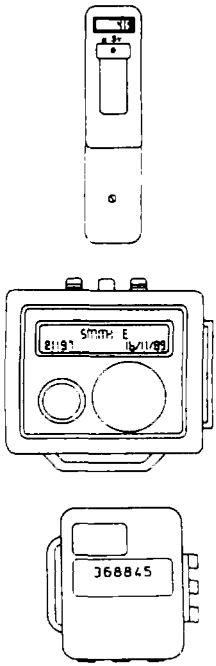
A typical dose rate meter.

Neutron radiation can only be detected using special dose rate meters.

Most dose rate meters are battery powered and some have a switch position that enables the user to check the battery condition, i.e. that it has sufficient life remaining to power the instrument. It is important that users are advised not to leave the switch in the battery check position for long periods and to switch off when not in use. Otherwise the batteries will be used unnecessarily.

A check that an instrument is working can be made by holding it close to a small shielded source but some instruments have a small inbuilt test source. Workers should be instructed on the use of test sources since regular checks will not only increase their own experience but give them confidence and provide early indication of any faults. It is important that users recognize the great danger of relying on measurements made using a faulty instrument.

A dosimeter measures the total dose accumulated by the detector over a period of time. For example, a dosimeter would record 20 μSv if it was exposed to 10 $\mu Sv \cdot h^{-1}$ for two hours. Some dosimeters can give an immediate reading of the dose. Others, like the film badge and the thermoluminescent dosimeter (TLD), can only provide a reading after being processed by a laboratory.



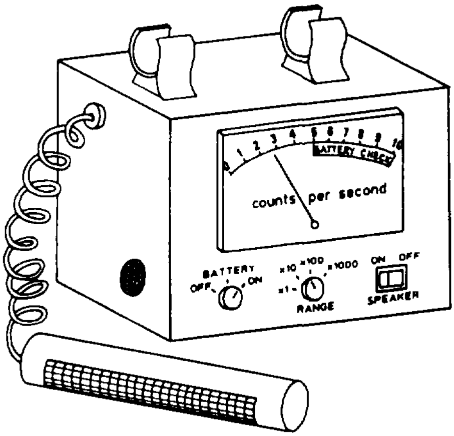
(a) Electronic dosimeter

(b) Thermoluminescent dosimeter

(c) Film badge dosimeter

Personnel dosimeters.

A third type of instrument will be needed by users of unsealed sources: a surface contamination meter. This is often simply a more sensitive detector which should be used to monitor for spillages. When the detector is placed close to a contaminated surface the meter normally only provides a reading in counts per second (cps or s^{-1}) or sometimes in counts per minute (cpm or min^{-1}). It needs to be calibrated for the radionuclide in use so that the reading can be interpreted to measure the amount of radioactive substance per unit area ($Bq \cdot cm^{-2}$). There are many surface contamination meters of widely differing sensitivities. The more sensitive instruments will indicate a very high count rate in the presence of, for example 1000 $Bq \cdot cm^{-2}$ of iodine-131, but different detectors measuring the same surface contamination will provide a lower reading or possibly no response at all. When choosing a detector it is best to use one that has a good detection efficiency for the radionuclide in use and gives an audible indication. The internal hazard created by small spillages can then be identified and a safe working area maintained.



A typical surface contamination meter.

Radiation and Distance

Ionizing radiation in air travels in straight lines. In such circumstances the radiation simply diverges from a radioactive source and the dose rate decreases as the inverse square of the distance from the source.

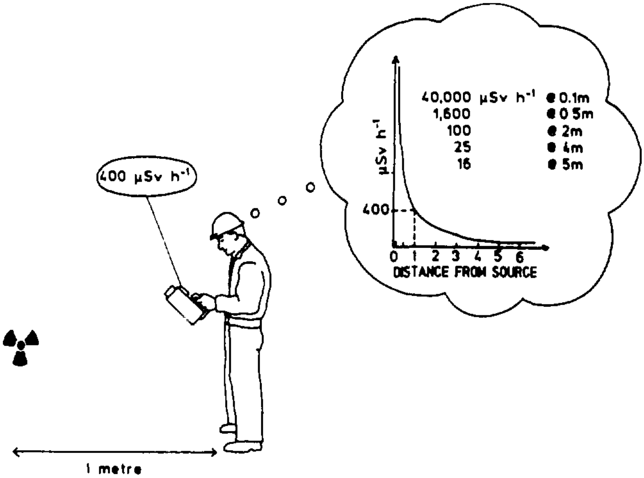
For example:

If the measured dose rate at 1 m is 400 $\mu Sv \cdot h^{-1}$;
the expected dose rate at 2 m is 100 $\mu Sv \cdot h^{-1}$;
the expected dose rate at 10 m is 4 $\mu Sv \cdot h^{-1}$;
the expected dose rate at 20 m is 1 $\mu Sv \cdot h^{-1}$; etc.

Distance has a major effect in reducing the dose rate.

Solid shields in the radiation path will cause the radiation to be attenuated and also cause it to be scattered in various directions. The actual dose rate at a point some distance from a source will not be due only to the primary radiation arriving from the source without interaction. Secondary radiation which has been scattered will also contribute to the dose rate.

However, it is simple to calculate the dose rate at a distance from a source. The primary radiation energies will be constant and known if the radionuclide is specified.



After measuring the dose rate, estimates can be made of the dose rates at different distances from the source.

The dose rate is obtained using the equation:

$$\text{Dose rate} = \frac{\text{Gamma factor} \times \text{Source activity}}{(\text{Distance})^2}$$

Gamma factor is the absorbed dose rate in $mSv \cdot h^{-1}$ at 1 m from 1 GBq of the radionuclide;
Activity of the source is in gigabecquerels;
Distance is in metres from the source to the point of interest.

Gamma emitting radionuclide	Gamma factor Γ
Ytterbium-169	0.0007
Technetium-99m	0.022
Thulium-170	0.034
Caesium-137	0.081
Iridium-192	0.13
Cobalt-60	0.351

However, the dose rate from the source is best determined using a reliable dose rate meter.

Notation for the examples of calculations.

Examples of Calculations

(1) What will be the dose rate at 5 m from 400 GBq of iridium-192?

$$\text{Dose rate} = \frac{\Gamma \times A}{d^2} = \frac{0.13 \times 400}{5^2} \text{ mSv}\cdot\text{h}^{-1}$$

$$= 2.08 \text{ mSv}\cdot\text{h}^{-1}$$

(2) A dose rate of 1 $mGy \cdot h^{-1}$ is measured at 15 cm from a caesium-137 source. What is the source's activity?

$$\text{Dose rate} = 1 \text{ mSv}\cdot\text{h}^{-1}$$

$$= \frac{0.081 \times \text{activity}}{0.0225} \text{ mSv}\cdot\text{h}^{-1}$$

$$\text{Activity} = \frac{1 \times 0.0225}{0.081} \text{ GBq} = 0.278 \text{ GBq}$$

(3) A dose rate of 780 $\mu Gy \cdot h^{-1}$ is measured from 320 GBq cobalt-60. How far away is the source?

$$\text{Dose rate} = 0.78 \text{ mSv}\cdot\text{h}^{-1}$$

$$= \frac{0.351 \times 320}{d^2} \text{ mSv}\cdot\text{h}^{-1}$$

$$\text{Distance} = \sqrt{\frac{0.351 \times 320}{0.78}} \text{ m} = 12 \text{ m}$$

(4) A 1.3 TBq iridium-192 source is to be used. What distance will reduce the dose rate to 7.5 $\mu Gy \cdot h^{-1}$?

$$\text{Dose rate} = 0.0075 \ mGy \cdot h^{-1}$$

$$= \frac{0.13 \times 1.3 \times 1000}{d^2}$$

$$\text{Distance} = \sqrt{\frac{0.13 \times 1.3 \times 1000}{0.0075}} \ m = 150 \ m$$

(5) A dose rate of 3 $mSv \cdot h^{-1}$ is measured at 4 m from a gamma emitting source. At what distance will the dose rate be reduced to 7.5 $\mu Sv \cdot h^{-1}$?

$$\text{Dose rate} = \frac{\text{Gamma factor} \times \text{Activity}}{(\text{Distance})^2}$$

Gamma factor × Activity is the source output and is constant. Therefore, Dose rate × $(\text{Distance})^2$ is constant.

Hence, $0.0075 \times d^2 = 3 \times 4^2$

$$d = \sqrt{\frac{3 \times 4^2}{0.0075}} \ m$$

$$d = 80 \ m$$

Radiation and Time

Radiation dose is proportional to the time spent in the radiation field. Work in a radiation area should be carried out quickly and efficiently. It is important that workers should not be distracted by other tasks or by conversation. However, working too rapidly might cause mistakes to happen. This leads to the job taking longer, thus resulting in greater exposure.

Radiation Effects

Industrial and medical uses of radiation do not present substantial radiation risks to workers and should not lead to exposure of such workers to radiation in excess of any level which would be regarded as unacceptable.

Possible radiation effects which have been considered by the international bodies (e.g. the International Commission on Radiological Protection, International Atomic Energy Agency) are:

(a) Short term effects such as skin burns and eye cataracts;
(b) Long term effects such as an increased disposition to leukaemia and solid cancers.

Current recommendations for dose limitations are contained in IAEA Safety Series No. 115. In summary, these are:

(a) No application of radiation should be undertaken unless justified;
(b) All doses should be kept as low as achievable, economic and social factors being taken into account; and
(c) In any case, all doses should be kept below dose limits.

For reference, the principal dose limits specified in IAEA Safety Series No. 115 are:

Adult workers	20 mSv per year (averaged over five years)
Members of the public	1 mSv per year.

96-01017

Printed by the IAEA in Austria
March 1996
IAEA-PRSM-4 (Rev.1)