Manual on
THERAPEUTIC USES
OF IODINE-131

Incorporating:
Applications Guide
Procedures Guide
Basics Guide
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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. Ortiz 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).
Principles of Radioactive Iodine-131 Therapy

As the distance from a source of radiation increases, the intensity of the radiation from the source decreases as the increase square of this distance. This principle can be used to advantage by placing radioactive sources near cancer cells so they receive high doses of radiation, while normal, healthy cells further away receive lower, less damaging doses. This form of treatment is called brachytherapy. The ultimate approach is to place the radioactive material inside the cancer cells themselves. In such a case, the dose to the cell containing the radioactive material becomes extremely high. If the normal cells do not absorb the radioactive material, their dose remains quite low. Because iodine is taken into thyroid cells, radioactive iodine, usually the isotope I-131, can be used in just such a manner to treat some types of thyroid cancers, or for treatment of thyroid hormone overproduction (hyperthyroidism).

For treatment with I-131, a patient is given the material either orally (solution or capsules) or intravenously. For treatment of hyperthyroidism, patients usually take about 1 GBq of I-131. Patients undergoing treatment for cancer therapy often take from 3 to 6 GBq of I-131. It is not recommended to let the patient return home immediately. Instead, he or she should be kept at the hospital for a period of between some hours and several days. The maximum activity at which a patient is allowed to return home depends on national practice and on the individual situation of the patient. It usually ranges between 0.2 and 1 GBq.

The physical characteristics of I-131 are shown below. Iodine-131 emits both beta and gamma radiation. The dose to the cells containing the iodine is mostly due to the emitted beta particles and the dose at a distance is mostly due to the gamma rays.
**CHARACTERISTICS OF IODINE-131**

<table>
<thead>
<tr>
<th>Half-life</th>
<th>Type of radiation</th>
<th>Energy (MeV)</th>
<th>Gamma factor (mSv at 1 m per GBq × h)</th>
<th>Half-value layer in lead (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 d</td>
<td>beta 0.61 (max)</td>
<td>0.364</td>
<td>0.058</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The activity of a sample of I-131 decays over time with a half-life of 8 days. Thus, a vial containing 2 GBq of I-131 today will contain 1 GBq in 8 days, 0.5 GBq in 16 days, and so on. In the body the amount of radioactive iodine decreases much faster, because, in addition to radioactive decay, the body also excretes iodine. In a normal person, the amount of I-131 in the body decreases by half about every three days. The time required for the activity in the body to fall by half is called the effective half-time. The effective half-time can become much longer than 3 days (but never longer than 8 days) in patients with certain diseases which cause the retention of iodine.

**Radiation Protection in Iodine-131 Therapy**

Radiation protection associated with I-131 treatments must address the hazards of radiation exposure and radioactive contamination. Lost or unaccounted for radioactive material has also to be considered.

*Radiation exposure*

The three main considerations are time, distance and shielding.

*Time:* When preparing the radioactive material for a patient, be sure to plan what to do and have all equipment and containers ready before taking the material out of the shielded container. Staff coming in contact with a patient containing radioactive iodine should not stay near the patient longer than the time which is needed to nurse the patient properly.
Distance: Never handle the radioactive material, either the capsules or the vial containing the material as a liquid, with the fingers; rather, use instruments such as forceps. At all times, stay as far from the sources as possible and still perform necessary functions quickly. Nurses should perform functions with as much distance between them and the patient as possible, without sacrificing patient care.

Shielding: Iodine-131 should be kept behind shielding (lead bricks in the storage room, or a shielded transportation container when in transit), except during assay and when being given to the patient. Once the iodine is in the patient, shielding barriers should be used to provide some protection for the staff and visitors. Usually, a centimetre or two of lead is required to reduce the dose rates to acceptable levels. Fluoroscopy aprons provide no protection against the radiation from I-131.

For the safety of the patients and the public, the dose rate outside the room should be kept to acceptable levels, such as 6 $\mu$Sv/h in areas to which the public has access. To comply with these requirements it may be necessary to shield the treatment rooms or to leave adjacent rooms empty (except for other iodine therapy patients).

Radioactive contamination

When working with I-131, radioactive contamination always presents a potential hazard. The danger from such contamination comes from the possibility that persons working with either the material itself or a patient containing some iodine may take some of the radioactive iodine into their body, giving high doses of radiation to their thyroids. Iodine can be absorbed into the body by the mouth, directly through the skin, or by inhaling vaporized iodine in the air. The first line of defence against radioactive contamination is to ALWAYS WEAR DISPOSABLE PLASTIC WHEN WORKING WITH I-131 OR INSTRUMENTS USED TO HANDLE I-131.
Important sources of radioactive contamination include:

*Airborne iodine vapours.* Iodine gives off vapours. Solutions containing I-131 pose the greatest danger. Containers of I-131 should always be stored and handled under a fume hood. With respect to this risk, capsules should be used instead of liquids.

*Patients’ body fluids.* Approximately 80% of the iodine given to a patient comes out in the urine during the first 24 hours. That means that the patient’s urine contains large amounts of I-131. In all cases this urine must be collected and treated as radioactive waste, according to the local rules. It is good practice for thyroid cancer treatment to store the urine of the first 24 hours after treatment in closed containers in a locked and shielded room for approximately two months to allow for decay, and then release it to the sewer system. However, the best solution is to treat the patient in a special room where the toilet is connected to a separate storage container. When nursing the patient the staff should always wear disposable plastic gloves and aprons to protect clothing. Upon release of the patient, the linen and cloths must be checked for contamination, and if contaminated, must be cleaned separately. Any item which cannot be cleaned must be stored in the radioactive source storage room, where, over time, through radioactive decay, the contamination will eventually disappear.

*Contact with the source material.* Radioactive iodine frequently contaminates the outside of containers. The contamination can be spread by people touching the container itself, or the instruments used to handle the container. Assume that all handling tools used with I-131 could be contaminated. Store them on disposable paper pads (to prevent contamination of the tabletop) near the hood. Never touch these instruments without wearing gloves, and never use them for other purposes.

*Spilling the material.* To restrict the risk of contamination from a vial accidentally spilled it should always stay on a disposable, plastic backed absorbent pad on a tray with lips around the edge to contain this contamination. In Table II, model rules for the safe use of radiopharmaceuticals are given.
Prevention of loss or unaccounted disappearance of radioactive material

A careful accounting system for radioactive material from its arrival through its use or disposal provides the best prevention against loss. The system should include a record book which contains at least the following information: isotope, date, lot or batch number and the vial's serial number, date of assay, total assay activity and volume. The same information must also appear on labels for the vials.

After being used, the vials themselves can be stored in a locked storage room awaiting decay of the radioactivity before being disposed of as normal waste.

Evaluation of Exposure to Personnel

Monitoring personnel working with I-131 must include evaluation of their exposure to the radiation from the iodine, and whether they took any iodine into their body. Their personal dosimeter indicates the exposure level. To make sure that there is no significant amount of iodine taken into their body, they could have a thyroid count, just as the patients do.

Preparation for an Iodine-131 Treatment Programme

Before an I-131 treatment programme is started, it should be ensured that:

(1) All staff involved in planning the programme are properly trained and know the rules as given in Table II.

(2) The facility has a radioactive storage and preparation room with a shielded area under a hood for storage of the material. The room should have walls and floors with surfaces that are easy to clean. The storage room should not be a passageway, nor a shared room such that persons not involved with the I-131 treatments spend time in the room. The storage facility should provide secure closure to prevent unauthorized access to the sources, and also maintain acceptable radiation levels, such as 20 μSv/h, to
persons around the facility. A thick leaded glass window protects the eyes of persons working with the sources.

(3) The treatment room could be either a room adjacent to the storage and preparation room or the patient room itself, which should have walls and floors with surfaces that are easy to clean.

(4) The facility has an adequate supply of long handled instruments for use in handling the sources, trays with lips and absorbent pads.

(5) All persons involved in the programme have and wear personal dosimeters and there are two Geiger counters available: one for use in the storage room, and one outside the storage room for use if a source spills and contaminates the other detector.

(6) An accounting system has been established to keep track of the source material.

(7) A proper system has been established for radioactive waste disposal, especially for urine disposal.

Iodine-131 provides effective treatment for some thyroid patients, but can be dangerous if approached casually, or without thorough preparation.

**Model Rules for Safe Use of Radiopharmaceuticals**

You may use the following model rules or, if you prefer, develop your own similar rules for safe use of radiopharmaceuticals.

**MODEL RULES**

(1) Wear laboratory coats or other protective clothing at all times in areas where radioactive materials are used.

(2) Wear disposable gloves at all times while handling radioactive materials.

(3) Either after each procedure or before leaving the area, monitor your hands for contamination in a low background area with a crystal probe or camera.

(4) Use a syringe shield for routine preparation of multidose vials and administration of radiopharmaceuticals to patients, except in those circumstances in
which their use is contraindicated (e.g. recessed veins, infants). In these exceptional cases, consider the use of other protective methods such as remote delivery of the dose (e.g. through the use of a butterfly valve).

(5) Do not eat, drink, smoke or apply cosmetics in any area where radioactive material is stored or used.

(6) Do not store food, drink or personal effects in areas where radioactive material is stored or used.

(7) Wear personnel monitoring devices at all times while in areas where radioactive materials are used or stored. These devices should be worn as prescribed by the Radiation Safety Officer. When not being worn to monitor occupational exposures, personnel monitoring devices should be stored in the workplace in a designated low background area.

(8) Wear a finger exposure monitor during the elution of the generator, during the preparation, assay and injection of radiopharmaceuticals and when holding patients during procedures.

(9) Dispose of radioactive waste only in designated, labelled and properly shielded receptacles.

(10) Never pipette by mouth.

(11) Wipe-test all byproduct material storage, preparation and administration areas weekly for contamination. If necessary, decontaminate or secure the areas for decay.

(12) With a radiation detection survey meter, survey the generator storage, kit preparation and injection areas daily for contamination. If necessary, decontaminate or secure the area for decay as appropriate.

(13) Confine radioactive solutions in shielded containers that are clearly labelled. Radiopharmaceutical multidose diagnostic vials and therapy vials should be labelled with the isotope, the name of the compound and the date and time of receipt or preparation. A logbook should be used to record the preceding information and total prepared activity, specific activity as Bq/cm$^3$ at a specified time, total volume prepared, total volume remaining, the measured activity of each patient dosage, and any other appropriate information. Syringes and unit dosages should be labelled with the radiopharmaceutical name or abbreviation, type of study, or the patient's name.
(14) Assay each patient dosage in the dose calibrator before administering it. Do not use a dosage if it is more than 10% off from the prescribed dosage, except for prescribed dosages of less than 10 μCi. When measuring the dosage, you need not consider the radioactivity that adheres to the syringe wall or remains in the needle. Check the patient’s name and identification number and the prescribed radionuclide, chemical form and dosage before administering.

(15) Always keep flood sources, syringes, waste and other radioactive material in shielded containers.

(16) Because even sources with small amounts of radioactivity exhibit a high rate on contact, you should use a cart or wheelchair to move flood source waste and other radioactive material.

Radiation Safety Check List for Discharged Patients Containing Radionuclides

Name of patient: _______________ Age: __________
Address: ________________________ Tel. No.: ________

Name of person interviewed: ________________________
Description of dwelling: ____________________________
In multifamily buildings, possible proximity of neighbours.
Household: Names, relationships, ages: ______________

Regular visitors to dwelling: ________________________

Persons regularly visited by patient outside dwelling: _______

Matters discussed:
- Handling of extruded source
- Importance of separate beds
- Importance of distance
- Importance of special care in regard to young persons
- Procedure in case of hospitalization or death

Film badges issued: _____________________________
Identification card, or wristband issued: ______________

Date: ____________

Physician or Radiation Protection Supervisor

This should be a part of the patient’s record
Instructions for
Family of Released Patient

Name of patient: ____________________________
Name of hospital: _______ Address: _______ Tel. No.: ______
For further information contact: ________________ Tel. No.: ______
Please show this form to every physician consulted concerning
the patient until ____________________________

_________________________________________ was treated on: ____________, 19__

(Name of patient)

with _____ GBq of _____________ in the form of _____________

NO SPECIAL RADIATION SAFETY PRECAUTIONS ARE
NECESSARY AFTER ____________________________

(date)

UNTIL THAT DATE:
Persons under 45 years of age should not remain closer than the
following distances from the patient, for the time period indicated:

a) _____________________ to _____________________
   (date)                       (date)
   Permissible distance ___ metres or more, for ___ hours per week.
   (At other times, remain farther than 2 metres.)

b) _____________________ to _____________________
   (date)                       (date)
   Permissible distance ___ metres or more, for ___ hours per week.
   (At other times, remain farther than 2 metres.)

Note: During the above times brief periods of closer contact (for
example while shaking hands, or kissing the patient) are
permissible.

SPECIAL PRECAUTIONS:

a) Spouse or other person caring for patient:
   ____________________________
   ____________________________
   ____________________________

b) Children or pregnant women: _________
   ____________________________
   ____________________________
   ____________________________

   c) Sleeping arrangements: ________________
       ____________________________

IF THE PATIENT IS TO BE HOSPITALIZED, OR IF DEATH
SHOULD OCCUR, NOTIFY THE FOLLOWING INDIVIDUAL(S)
IMMEDIATELY:

__________________________________________

A copy of this form should be kept with the patient's record.
PROCEDURES GUIDE: THERAPEUTIC USES OF IODINE-131

Follow authorized procedures when carrying out iodine therapy.

Only trained personnel who have had medical examinations and wear a dosimeter should carry out iodine therapy. In normal circumstances, such personnel should not have received greater than the dose limit (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 that the integrity of the shielding is correct and that the hood's exhaust is working properly.
After each preparation the surface should be monitored to detect possible contamination. Make sure that the rates in the source storage room are checked periodically (for example every six months) and that they are below acceptable levels, such as 20 μSv/h.
When ordering I-131, be sure the delivery service knows where in the hospital to deliver the material. Make sure that the package is expected and that no one will open it upon arrival.
Upon receiving a package of I-131, put on a pair of disposable plastic gloves. Check the box. If the box looks damaged in any way, contact your supervisor.
Wear your personal dosimeter when working in the source storage room. Before entering the room, make sure that a Geiger counter is available in the source storage room and that it is working properly: check the batteries of the counter, and test the counter with a check source, if available; take note of the reading before entering the room. Be aware of the sound of the Geiger counter as you work in the room. If the counter sounds more active than usual without explanation (such as removing a vial of I-131), leave the room and contact your supervisor or radiation expert.
Always wear gloves when handling I-131.
When working with radioactive iodine, keep the sources behind shielding blocks whenever possible and handle the vials with forceps or similar long handled instruments.
Prepare the sources so that the correct activity is given according to the following rules:

1. Keep the vials under the hood and on trays with lips, lined with plastic backed absorbent pads.
2. Keep vials in their lead shielded containers at all times.
3. Always use a lead syringe holder.
4. Cover the container with lead after use.
5. Do not smoke, eat or drink.
Check the activity using an activity meter, such as a well type ionization chamber, which has been properly calibrated.
Enter the information about the use of the iodine for the patient in the logbook.
If the administration of I-131 to the patient takes place far from the preparation room, use a transport container with absorbent pads.

Make sure that a ‘Caution: Radioactive Materials’ sign is on the transport container, marked with ‘I-131’, the activity and the date. Take the prepared sources to where they will be used, travelling by the most direct route that avoids the more heavily occupied areas.
Administer the iodine to the patient according to one of the following procedures:

Procedure 1: Administration by taking iodine capsules.

- Remove the lead container from the transport box and put it on the table close to the patient.
- Have the patient remove the vial from the lead container and take the capsules himself.
- Make sure that all precautions are taken in case of patient vomiting (see emergency procedures).
Procedure 2: Administration by taking iodine in liquid form.

- Remove the lead container from the transport box and put it on the table close to the patient.
- Have the patient sip the liquid using a straw or pipette.
- Rinse the vial at least two times and have the patient drink the liquid.
- Make sure that all precautions are taken in case of patient vomiting (see emergency procedures).
Procedure 3: Intravenous administration

- Take out from the vial the required amount of activity using a shielded syringe.
- Put it in an infusion bottle where the iodine is diluted.
- Link the bottle to the patient using an intravenous catheter.
- Keep the patient in bed until the bottle is empty.
- Remove the bottle and the catheter and dispose of them as radioactive waste.
If appropriate, move in shields to provide some protection for the nursing staff. Remember that shielding must be quite thick to protect from I-131 radiation. Fluoroscopy aprons provide no protection against the radiation from I-131.
Make sure that a copy of radiation isolation nursing instructions (a sample can be found in the Applications Guide) and a ‘Caution: Radioactive Materials’ sign is on the door to the patient’s room and in the patient’s chart. Write the allowed times (see the Applications Guide) in the instructions.
Make sure that the nursing staff is aware of the following rules:

(1) Pregnant staff may not enter the room.
(2) Minimize the time spent near the patient, while still performing necessary nursing care.
(3) Keep as far from the patient as possible while performing nursing duties and stand behind the shield when possible.
(4) Wear disposable plastic gloves whenever touching anything in the room, and leave the gloves in the garbage container in the room when leaving.
(5) Wear a gown over clothing if handling a urine bag or bed pan.
(6) Only adult visitors are allowed in the room. They should be properly instructed about precautions to be taken against radiation exposure through contamination.
(7) Urine must be collected or flushed down the toilet according to the local rules. Excreta can be flushed down the toilet without any problem. Make sure the nursing staff knows who to contact in case of a problem.
(8) Bed linen and cloths must be checked for contamination at the end of the treatment.
Return the transport box, lead container and vial to the material storage room. Store the vial for decay with other waste contaminated with iodine.
The patient should be kept at least two hours and, if possible, one day in the hospital. In the case of cancer treatment, the patient should generally be held several days. In all cases, the dose rate at 1 m from the patient should be down to acceptable levels, such as 5 μSv/h. Appropriate instructions should be given to patients containing radioactive materials.
Check the room with a Geiger counter to detect any significant contamination. Give special attention to linen and clothes, door handles, telephones, etc. Anything that shows 'counts' more than three times the background is considered contaminated, and must be cleaned as described below or disposed of as radioactive waste.
Some situations may occur which require special actions, such as the following:

EMERGENCY 1: IF A SHIPMENT OF I-131 FAILS TO ARRIVE ON SCHEDULE, OR WITHIN A REASONABLE TIME THEREAFTER

Check first all possibilities in the hospital, then call the company and inform them of the failure so they can trace the shipment and find out where the radioactive material is.
EMERGENCY 2: IF A SMALL AMOUNT OF LIQUID IODINE SPILLS

Quickly blot the spill with an absorbent pad to keep it from spreading.
Take a plastic bag which should be always available, to hold articles contaminated during the cleaning, and some damp paper towels. Remove the pad from the spill, and wipe with a towel from the edge of the contaminated area toward the centre.
Dry the area and wipe it with a paper towel moistened with alcohol. Test the towel for radioactivity with a Geiger counter. Any count in excess of three times the background count rate indicates contamination. If contamination is still found upon counting, repeat the cleaning with paper towels. A mild solvent cleaning fluid may be used, but very abrasive cleansers should be avoided. After cleaning, repeat the wipe test. Continue the cycle of cleaning and wipe testing until the wipe sample indicates less than three times background. Notify your supervisor of the situation.
EMERGENCY 3: IF LARGE AMOUNTS OF LIQUID IODINE SPILLS (vial itself, urine, vomit)

KEEP CALM! Cover the spill with absorbent pads to contain the liquid.
Close door and windows and notify everyone in the room that radioactive liquid has been spilled.
Everyone in the room go the the door and kick off their shoes with their feet, stepping out of the room as their feet leave their shoes. DO NOT WALK FURTHER! Remove your gloves and shoes if they have been in contact with the spill and leave them together with anything which could be contaminated by the spill. Close the door.
Call for assistance. If no one can hear, one person only should walk no further than is necessary to find someone to call a radiation expert and get a Geiger counter. (The one left in the room may be contaminated.)
Using the Geiger counter, measure the radiation count rates all over the bodies of those persons who were in the room, with particular attention to the hands and feet.
Remove immediately any contaminated clothing and place it in a large plastic bag or other container and dispose as radioactive waste.
Wash any contaminated skin with a mild soap and plenty of water; do not use a hard brush, or abrasive soap. After washing, take measurements again with the Geiger counter. The washing and measuring should be repeated until no counts above background can be measured or until the count rate does not change after three cycles of washing. Skin moisturising lotion should be applied between washings, if available.
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 (\(^{192}\text{Ir}\)) are of lower energies than those of cobalt-60 (\(^{60}\text{Co}\)). 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 (\(^{3}\text{H}\)) travel more slowly and so have almost one hundredth of the energy of the beta particles from a different radionuclide such as phosphorus-32 (\(^{32}\text{P}\)).

Neutron particle radiation can be created in several ways. The most common is by mixing a radioactive substance such as americium-241 (\(^{241}\text{Am}\)) 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 acquired 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, radio-nuclides 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.
<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Type of radiation</th>
<th>Range of energies (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Americium-241</td>
<td>alpha</td>
<td>5.5 to 5.3</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>0.03 to 0.37</td>
</tr>
<tr>
<td>Hydrogen-3</td>
<td>beta</td>
<td>0.018 maximum</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>beta</td>
<td>1.7 maximum</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>beta</td>
<td>0.61 maximum</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>0.08 to 0.7; 0.36</td>
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<td>Technetium-99m</td>
<td>gamma</td>
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<td>(Barium-137m)</td>
<td>gamma</td>
<td>0.66</td>
</tr>
<tr>
<td>Iridium-192</td>
<td>beta</td>
<td>0.67 maximum</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>0.2 to 1.4</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>beta</td>
<td>0.314 maximum</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>1.17 and 1.33</td>
</tr>
<tr>
<td>Americium-241/beryllium</td>
<td>neutron</td>
<td>4 to 5</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>0.06</td>
</tr>
<tr>
<td>Strontium-90/ (Yttrium-90)</td>
<td>beta</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>beta</td>
<td>2.26</td>
</tr>
<tr>
<td>Promethium-147</td>
<td>beta</td>
<td>0.23</td>
</tr>
<tr>
<td>Thallium-204</td>
<td>beta</td>
<td>0.77</td>
</tr>
<tr>
<td>Gold-198</td>
<td>beta</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>0.41</td>
</tr>
<tr>
<td>Iodine-125</td>
<td>X ray</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>0.035</td>
</tr>
<tr>
<td>Radium-226</td>
<td>alpha</td>
<td>4.59 to 6.0</td>
</tr>
<tr>
<td></td>
<td>beta</td>
<td>0.67 to 3.26</td>
</tr>
<tr>
<td></td>
<td>gamma</td>
<td>0.2 to 2.4</td>
</tr>
</tbody>
</table>

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.
<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Maximum beta particle energy (MeV)</th>
<th>Maximum range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air (mm)</td>
<td>Plastic (mm)</td>
</tr>
<tr>
<td>Promethium-147</td>
<td>0.23</td>
<td>400</td>
</tr>
<tr>
<td>Thallium-204</td>
<td>0.77</td>
<td>2400</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>1.71</td>
<td>7100</td>
</tr>
<tr>
<td>Strontium-90/Yttrium-90</td>
<td>2.26</td>
<td>8500</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Radiation producer</th>
<th>HVT and TVT values (cm) in various materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lead</td>
</tr>
<tr>
<td></td>
<td>HVT</td>
</tr>
<tr>
<td>Technetium-99m</td>
<td>0.02</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>0.72</td>
</tr>
<tr>
<td>Caesium-137</td>
<td>0.65</td>
</tr>
<tr>
<td>Iridium-192</td>
<td>0.55</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>1.1</td>
</tr>
<tr>
<td>100 kV X rays</td>
<td>0.026</td>
</tr>
<tr>
<td>200 kV X rays</td>
<td>0.043</td>
</tr>
</tbody>
</table>

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

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.

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

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

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:

\[ 1 \text{ nCi} = 1 \mu \text{Ci} = 1 \text{ mCi} = 1 \text{ Ci} = 10 \text{ Ci} \]

\[ 37 \text{ Bq} = 37 \text{ kBq} = 37 \text{ MBq} = 37 \text{ GBq} = 37 \text{ TBq} \]

**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 (\( \mu \text{Sv} \cdot \text{h}^{-1} \)). However, many instruments still use the older unit of millirem per hour (mrem \cdot \text{h}^{-1}). 10 \( \mu \text{Sv} \cdot \text{h}^{-1} \) is equivalent to 1 mrem \cdot \text{h}^{-1}.

57
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 \( \mu \text{Sv} \) if it was exposed to 10 \( \mu \text{Sv} \cdot \text{h}^{-1} \) 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 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·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·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.
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 μSv·h⁻¹;
the expected dose rate at 2 m is 100 μSv·h⁻¹;
the expected dose rate at 10 m is 4 μSv·h⁻¹;
the expected dose rate at 20 m is 1 μSv·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·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.

<table>
<thead>
<tr>
<th>Gamma emitting radionuclide</th>
<th>Gamma factor ( \Gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ytterbium-169</td>
<td>0.0007</td>
</tr>
<tr>
<td>Technetium-99m</td>
<td>0.022</td>
</tr>
<tr>
<td>Thulium-170</td>
<td>0.034</td>
</tr>
<tr>
<td>Caesium-137</td>
<td>0.081</td>
</tr>
<tr>
<td>Iridium-192</td>
<td>0.13</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>0.351</td>
</tr>
</tbody>
</table>

However, the dose rate from the source is best determined using a reliable dose rate meter.
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 \text{h}^{-1} is measured at 15 cm from a caesium-137 source. What is the source's activity?

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

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

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

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

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

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

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 μGy·h⁻¹?

Dose rate = 0.0075 mGy·h⁻¹

\[ \frac{0.13 \times 1.3 \times 1000}{d^2} \]

Distance = \[ \sqrt{\frac{0.13 \times 1.3 \times 1000}{0.0075}} \] m = 150 m

(5) A dose rate of 3 mSv·h⁻¹ is measured at 4 m from a gamma emitting source. At what distance will the dose rate be reduced to 7.5 μSv·h⁻¹?

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

Gamma factor \times Activity is the source output and is constant. Therefore, Dose rate \times (Distance)^2 is constant.

Hence, \[ 0.0075 \times d^2 = 3 \times 4^2 \]

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

\[ d = 80 \text{ m} \]

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.