CHAPTER 3

RADIATION DOSE

INTRODUCTION

This chapter begins with a review of the ionisation process, very briefly describes the effects of this process on the body's molecules, and then goes on to explain the units we use for describing the amount of radiation absorbed by the body.

After that, we'll describe the various levels of radiation we receive routinely, both from natural sources and from man-made sources of radiation.

REVIEW OF IONISATION

Radiation is the emission of particles or electromagnetic waves from a source. Radiation from radioactive materials has the ability to split atoms and molecules into charged fragments or ions. This process is called ionisation, and the radiation responsible for it is called ionising radiation.

In a neutral atom, the positive charge of the nucleus is equal and opposite to the total negative charge of the orbital electrons. If such an atom loses an electron, a pair of charged fragments called an ion pair is formed. The atom will now have a net positive charge and is called a positive ion; the electron with its negative charge is the negative ion.

EFFECT OF IONISING RADIATION ON TISSUE

Since about 60% of human body weight is water, let us look at what radiation does to water molecules.

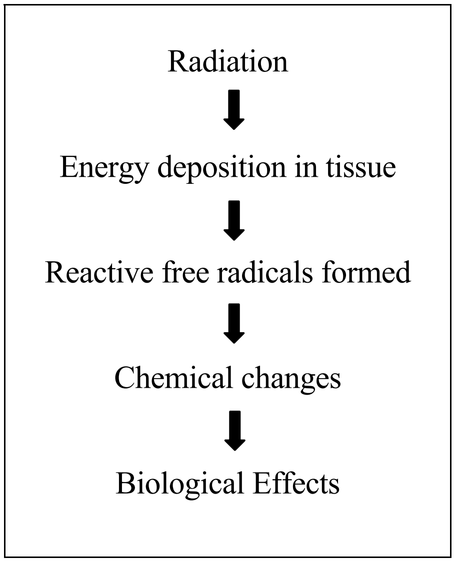
The symbol for water is H_2O. This means that two hydrogen atoms and one oxygen atom are bonded together to exist as one water molecule. When an H_2O molecule is struck by radiation, the molecule picks up the energy lost by the radiation in the collision. If the energy gain is sufficient to overcome the bonding force holding the molecule together, the molecule will break up as shown below:

$$H_2O \longrightarrow H^+ + OH^-$$

These two ions produced from an H_2O molecule are known as "free radicals". They are very reactive and can cause harmful chemical changes in the organic molecules in the cells of the tissue.

The organic molecule in tissue that is most important in the potential risk from ionising radiation is **deoxyribonucleic acid** or **DNA**. The DNA molecule carries the blueprints for life: in humans, there are more than 10,000 instructions for life processes encoded along its length.

Most of the chemical changes in the structure of the DNA, whether these occur spontaneously or because of exposure to radiation or other agents, are actively repaired by living cells. The instructions for this repair are themselves encoded in the DNA. A small fraction of the DNA damage is not correctly repaired and so results in permanent changes in the DNA structure. Some of these changes may express themselves as a harmful biological effect, such as an inherited genetic defect or as a cancer.



Alpha particles deposit their energy in a very small distance, so they will produce many sites of damage very close together. This means that repair errors are more likely there than for the damage caused by gamma radiation, where the sites of damage are more widely scattered.

At radiation doses that are low enough to permit survival of the irradiated cell, the fraction of permanent changes with harmful biological effects is less than 0.01% of the total chemical changes produced in the DNA by the radiation.

PENETRATION OF BODY TISSUES

An important characteristic of the various ionising radiations is how deeply they can penetrate the body tissues. X-rays, gamma rays, and neutrons of sufficient energy can reach all tissues of the body from an external source.

A thin sheet of paper, on the other hand, stops alpha particles. They are also stopped by the superficial dead layer of skin that is only 70 μm thick. Therefore, radionuclides that emit only alpha particles are harmless unless you take them into the body. This you might do by inhalation (breathing in) or ingestion (eating and drinking).

The depth to which beta particles can penetrate the body depends on their energy. High-energy beta particles (several MeV) may penetrate a cm or so of tissue, although most are absorbed in the first few mm. Remember, in Chapter 2 you learnt that most beta particles have energies well below the maximum beta energy E_{max} that is characteristic of the radionuclide emitting them. As a result, beta emitters outside the body are hazardous only to surface tissues such as the skin or the lenses of the eye. When you take beta emitters into the body, they will irradiate internal tissues and then become a much more serious hazard.

ABSORBED RADIATION DOSE

Just as for drugs, the effect of radiation depends on the amount you have received. Therefore, amounts of radiation received are referred to as **doses**, and the measurement of such doses is known as **dosimetry**.

To digress for a moment, consider the diverse effects of a teaspoon of castor oil given to a 25 g mouse and a 70 kg man. What is important in a shituation like this is not so much the total dose to the whole system as the dose per kg. (That's why a doctor will prescribe smaller doses of medicine for children than for adults. At least, let's hope so.)

A similar approach is used in radiation protection measurements, where the unit of **ABSORBED DOSE** is specified in terms of the amount of energy deposited by radiation in 1 kg of material. This unit is the **gray**, abbreviated **Gy**. (It was named in honour of Louis Gray, who was a very big name in the early days of radiation dosimetry).

An absorbed radiation dose of 1 GRAY corresponds to the deposition of 1 joule of energy in 1 kg of material.

The gray is a measure of energy absorbed by 1 kg of any material, be it air, water, tissue or whatever. A person who has absorbed a whole body dose of 1 Gy has absorbed one joule of energy in each kg of body tissue. As we shall see later, the gray is a fairly hefty dose, so for normal practical purposes we use the **milligray** (abbreviated **mGy**) and the **microgray** (abbreviated **μGy**).

Absorbed dose is given the symbol D; D is measured in grays.

The gray is a physical unit. It describes the physical effect of the incident radiation (i.e., the amount of energy deposited per kg), but it tells us nothing about the biological consequences of such energy deposition in tissue.

Studies have shown that alpha and neutron radiation cause greater biological damage for a given energy deposition per kg of tissue than gamma radiation does. In other words, equal doses of, say, alpha and gamma radiation produce unequal biological effects. As already mentioned on page 72, this is because the body can more easily repair damage from radiation that is spread over a large area than that which is concentrated in a small area. Because more biological damage is caused for the same physical dose (i.e., the same energy deposited per unit mass of tissue), one gray of alpha or neutron radiation is more harmful than one gray of gamma radiation.

QUALITY FACTORS

Quality factors are used to compare the biological effects from different types of radiation. For example, fast neutron radiation is considered to be 20 times as damaging as X-rays or gamma radiation. You can also think of fast neutron radiation as being of "higher quality", since you need less absorbed dose to produce equivalent biological effects. This quality is expressed in terms of the **Quality Factor (Q).**

The QUALITY FACTOR of a radiation type is defined as the ratio of the biological damage produced by the absorption of 1 Gy of that radiation to the biological damage produced by 1 Gy of X or gamma radiation.

The Q of a certain type of radiation is related to the density of the ion tracks it leaves behind it in tissue; the closer together the ion pairs, the higher the Q.

The Quality Factors for the various types of radiation are listed on the right. They are valid for relatively long-term exposures; they don't apply to very large life-threatening doses received in a short period of time like minutes or hours.

TABLE 3.1. QUALITY FACTORS

Radiation	*Energy*	*Q*
gamma	all	1
beta	all	1
neutrons	slow	5
neutrons	fast	20
alpha	all	20

EQUIVALENT DOSE

The absorbed radiation dose, when multiplied by the Q of the radiation delivering the dose, will give us a measure of the biological effect of the dose. This is known as the **EQUIVALENT DOSE**. Equivalent dose is given the symbol H. The unit of H is the **sievert** (**Sv**). It was named after the Swedish scientist Rolf Sievert, who did a lot of the early work on dosimetry in radiation therapy, rather than Hans Sievert, a different Swede who was once a big name in the Decathlon.

An equivalent dose of one SIEVERT represents that quantity of radiation dose that is equivalent, in terms of specified biological damage, to one gray of X or gamma rays.

In practice, we use the **millisievert** (**mSv**) and **microsievert** (**μSv**). Equivalent dose, quality factor and absorbed dose are related by the expression

H (Sv) = D (Gy) x Q.

The sievert is the unit that we use all the time, because it is the only one that is meaningful in terms of biological harm. **In calculating the equivalent dose from several types of radiation (we call this "mixed radiation"), all measurements are converted to Sv, mSv or μSv and added.**

Most of the radiation instruments we use to measure doses or dose rates reads in mSv or µSv. We have some instruments reading in mGy or µGy, but they measure only gamma radiation. So, no problem, since the sievert and the gray are identical for gamma.

There are more terms in use for radiation dose than there are days in the month — often we'll just call it "dose". If the "dose" is quoted in sieverts, you'll understand that we're talking about equivalent dose, and that's what we're almost always going to do. Now that you have a feel for what radiation dose is, let's look at the various types of radiation to which we are all exposed.

NATURAL BACKGROUND RADIATION

Every day since our forefathers first crawled out of the swamp, the human race has been exposed to ionising radiation from natural sources. This radiation is called the **natural background radiation**. It is of interest to us because everyone is exposed to it, and because it gives us something to which we can relate the levels of man-made radiation from modern technology.

Natural radiation comes from

1) Cosmic rays which reach earth from outer space,
2) Radioactive substances in the earth's crust,
3) Trace amounts of radioactivity in the body.

Cosmic Rays

Cosmic rays are extremely high-energy particles (largely protons) originating from our sun and other stars. They collide with atoms in the earth's outer atmosphere to produce showers of lower-energy particles. Most of these lower-energy particles are absorbed by the kilometres of air between the earth's outer atmosphere and its surface. This means that the higher the elevation above sea level, the greater is the dose rate received from cosmic rays.

Populations living in cities such as Bogota, Lhasa, or Quito, which are all at an altitude of 3 km or more, receive about 1 mSv a year from cosmic radiation, but there are no major cities in Canada at these altitudes.

You can see how the dose rate increases with altitude, because we once checked it out on a Montreal – Fredericton flight. The results are shown in Fig. 3.1. The ground level dose rate was about 0.10 µSv/h; but at the maximum flight altitude (8.8 km or 29,000 ft), it was about 2.0 µSv/h. The total excess dose for the Montreal to Freddy flight is only 0.7 µSv.

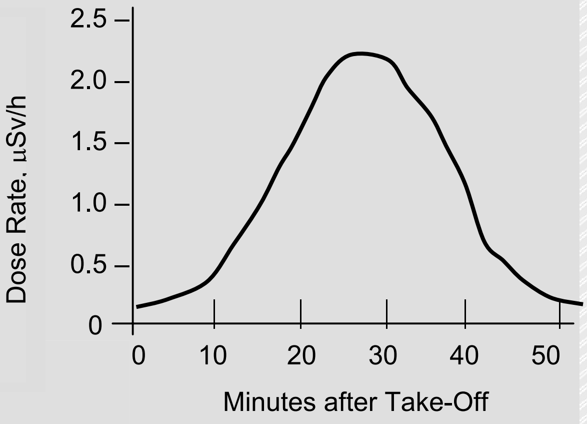


Fig. 3.1. Dose Rate vs. Time

Although supersonic planes like the Concorde can make a transatlantic flight in 3.5 hours, the exposure rate at their altitude of 18 km is increased enough to result in the same cosmic ray exposure per crossing as for conventional jets trundling along at about 8 km. Yet solar flares associated with sunspot activity can increase exposure rates at high altitudes to tens of mGy/h. Although such exposure rates are not likely to happen more than once a year. Concordes are fitted with radiation monitors that alarm at high exposure levels (500 μGy/h) to allow the pilot to reduce altitude and make use of atmospheric shielding to reduce dose rates.

Carbon-14, a radioactive isotope of carbon ($T_{1/2}$ = 5730 y), is produced from atmospheric nitrogen by cosmic ray interactions. As a result, all living biological substances contain the same amount of C-14 per gram of carbon, that is 0.3 Bq of C-14 activity per gram of carbon. Once the substance dies, the C-14 concentration is no longer maintained, and decreases at a rate governed by the half-life of 5730 years. This is the basis of the so-called **carbon dating** method, which can be used to assess the age of bones or fossils. By measuring the amount of C-14 in a sample, and comparing it with the original activity, it is easy to calculate the time since the plant or animal died.

The C-14 in our bodies gives us an annual dose of about 10 μSv. Enjoy.

Radioactivity in the Earth's Crust

When the earth was formed, a relatively large number of its isotopes must have been radioactive. In the four billion years or so since then, all the shorter-lived isotopes have decayed. The radionuclides that now remain are those that are long-lived (with half-lives of 100 million years or more), and those that are formed from the decay of these long-lived radionuclides. So it's a good thing that the half-life of U-235 is long enough for some of it to be around still, or none of us would have jobs in the nuclear power business.

Three very important naturally occurring radionuclides are U-238, U-235 and thorium-232. As they decay, not only do they emit radiation, but they also produce other radionuclides with shorter half-lives. These decay in turn, and so on. The U-238, U-235 and Th-232 parent nuclides lead to three separate decay series of radionuclides — you will remember that we used the U-238 series as an example on p. 37 to explain decay schemes. These three families of radioactive heavy elements are all found in the earth's crust and account for much of the radioactivity to which man is exposed. Large deposits of ore containing uranium or thorium have been found in many parts of the world — in fact, in Canada we are lucky in having more than our fair share of uranium.

These naturally occurring radionuclides in the ground lead to two different types of radiation exposure: internal exposure from radon and its daughters, and external gamma exposure.

Radon Daughters

Radon-222 is produced in the uranium decay series, i.e., the one that starts with U-238. Radon is a gas and diffuses out of the ground to mix with air. As the radon decays, its daughters can attach themselves to particulates in the air, and these particulates can be trapped in the lungs of people breathing the air. The result is lung dose from alpha and beta radiation emitted by the radon daughter products.

It is fairly easy to reduce the high concentrations of radon daughters that may occur in the air in some existing homes, and to minimise these concentrations when building new homes.

A survey in 1979 of several Canadian cities indicated that the average annual lung dose ranged from about 2000 to 8000 μSv depending on the city. The risk from these exposures to only the lungs is the same as that which would result from 240 to 960 μSv delivered over the whole body. If we assume an average whole-body dose of 600 μSv from radon daughter exposures, we probably won't go too far wrong for most people in Canada.

Experience with measurements in other countries suggests that higher doses can be expected as the study is expanded — in other words, the harder you look, the more you find. For example, a British survey in 1983 indicated an average whole-body equivalent dose of about 800 μSv in that country, but more recent surveys have found that some houses have levels much higher than this. Indeed, 20,000 houses in Britain are estimated to cause radon exposures of more than 20 mSv/year to their occupants. In the late 1980s, the Brits reported on one house where the radon level represented a lung dose that was equivalent to a dose of 5000 mSv to the whole body. This is not a typo.

It is now generally agreed by radiation experts that radon represents the largest of all natural radiation exposures to the general public.

Even at Point Lepreau, we find radon in significant concentrations in areas where there is little ventilation such as tunnels and sumps. If you walk through the CCW tunnel, you will often become contaminated with radon daughters. The dose you would receive from radon and its daughters in walking through tunnels or in entering sumps is quite small and can be ignored unless you work there all the time.

The Health Physics Department has a Radon Meter that you can borrow to check your home for radon. A procedure is supplied with the meter, and anyone who has passed this course should be able to figure out what to do. So wait till then, OK?

External Gamma

The radionuclides in the ground also emit gamma radiation, and the radiation intensity at the surface depends on the type of ground or rock below it. For example, the average annual dose at a height of 1 m above limestone is about 200 μGy, while for granite areas it is around 1000 μGy. These figures vary widely, however.

In our environmental monitoring program, we look at external radiation background near Point Lepreau. A sample of the results is shown in Fig. 3.2. You can see that there hasn't been a dramatic increase since we started the place up in 1983.

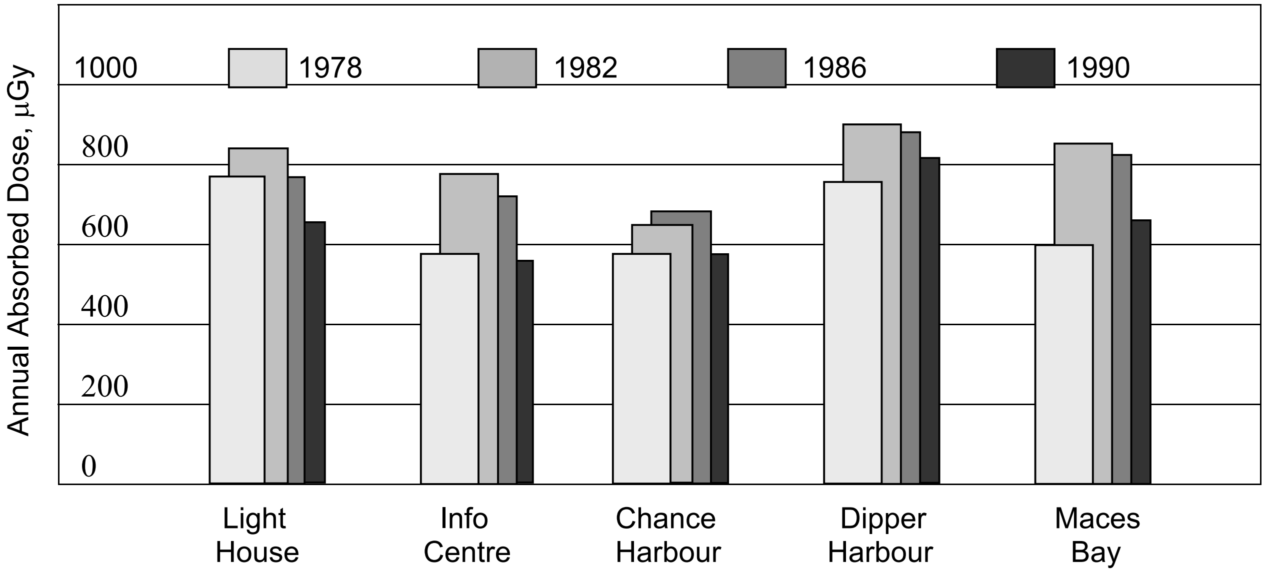


Fig. 3.2. Annual Variation in Background Radiation Near Point Lepreau (inc. Cosmic Rays)

Such variations over a few km are not surprising. In fact, repeated measurements made at the same location will vary over the year. Fig. 3.3 shows how the dose rate (averaged over a period of 24 hours in my backyard in Fredericton) changed over a year. Any ideas why?

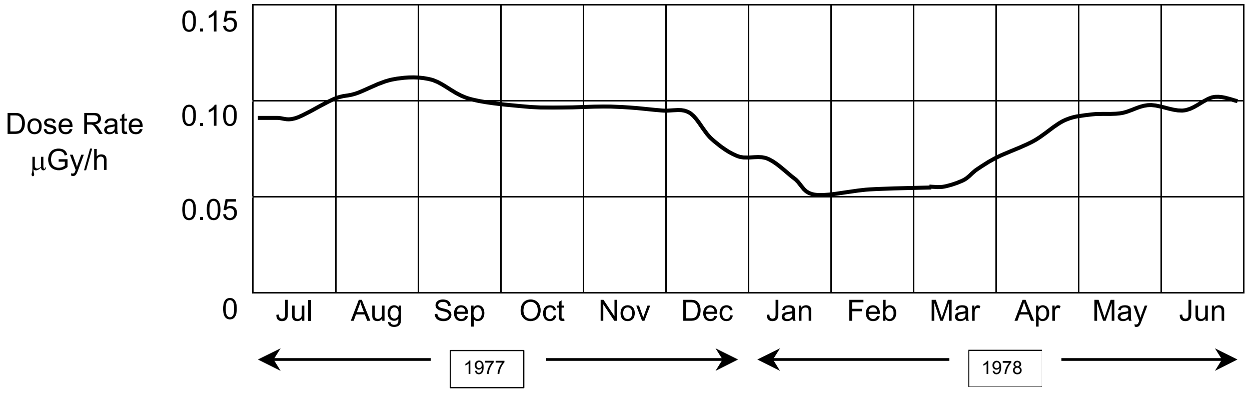


Fig. 3.3. Seasonal Variations in Natural Background Radiation

Natural Radioactivity in Your Body

Traces of radioactive materials are normally present in your body. They come from radioactivity present in tiny concentrations in our food supplies. The only radionuclide that contributes significantly to human exposure from ingestion is the K-40 isotope of potassium. A 70-kg man contains about 140 g of potassium; most of that is located in muscle. About 0.01% of the potassium is K-40, and this isotope delivers about 200 μSv a year. There is another 10 μSv from C-14.

Apart from K-40, traces of radioactive thorium, radium and lead can be detected in most people when very sensitive and extremely sophisticated techniques are used. The equivalent doses involved are very low indeed and vary a lot from one person to another.

Average Dose from Natural Radiation

The average dose received by Canadians from natural radiation sources amounts to about 2000 μSv per year. This varies with altitude, latitude, the type of underlying rock in a given area, and the structural material of the buildings we live in. The radiation dose comes partly from cosmic rays, partly from radioactivity in the ground, and partly from naturally occurring radionuclides in the body.

MAN-MADE SOURCES OF RADIATION

These include medical uses of radiation, fall-out from weapons testing, and radiation sources leading to occupational exposure. We'll briefly discuss the highlights.

Medical Uses of Radiation

After natural sources, the largest source of radiation dose to Canadians is the diagnostic use of X-rays in medicine, and the medical use of radioactive materials.

Diagnostic X-Rays

Diagnostic X-ray exams account for about 90% of the radiation dose the population receives from medical sources. Chest X-rays are the most common (25% of all X-ray exams), followed by X-rays of the shoulder, pelvis and limbs (another 25%) and dental X-rays (10%). Recent measurements show that the average dose from a diagnostic chest X-ray or a mammogram in Canada is about 70 μSv, and about 20 μSv from a dental X-ray.

Much larger doses are given in examinations of the digestive and urinary tracts. They involve multiple exposures and the administration of contrast agents to outline soft tissues. Doses received by patients in these exams may be as high as 1 mSv.

In computer-aided tomography (CAT) an X-ray source rotates around the patient, and the X-rays that pass through the patient's body are measured by a row of detectors. Many measurements are made, and the results are fed to a computer that reconstructs an image of a cross-section of the patient. A CAT scan therefore gives an image of adjacent slices of the patient's body. Doses can be quite high; as much as 40 mSv per scan.

Nuclear Medicine

In diagnostic nuclear medicine, the patient receives a drug containing a gamma-emitting radionuclide. The drug chosen is one that is taken up by a particular organ or tissue whose functioning is to be assessed. A gamma camera is then used to follow the distribution of the drug in the patient. Sometimes the radioactive drug can be used in the treatment itself: an example is the treatment of thyroid disease with I-131. Nuclear medicine procedures are much rarer than X-ray exams, and contribute about 5 μSv a year to the medical dose of the average Canadian.

The dose from diagnostic procedures (X-rays and nuclear medicine) done in Canada is about 0.6 mSv a year when averaged over the whole population.

Radiotherapy

Radiotherapy is the treatment of cancer by killing tumour cells using beams of high-energy gamma rays from cobalt-60 or from accelerators. The aim of the treatment is to deliver a very high dose to the tumour, but as little dose as possible to the surrounding healthy tissue. A large source, providing a narrow beam of gamma radiation, is rotated around the patient. The hospital physicist carefully works out the pattern and properties of the beam to maximise destruction of the tumour and minimise irradiation of healthy tissue. The treatment is drastic and accompanied by unpleasant side effects. Doses to the tumour are typically around 100 to 200 Sv per treatment. Very heavy stuff.

Fall-Out

Fall-out from nuclear weapons already exploded generally has been decreasing since large scale testing was stopped by the U.S. and by Russia in 1963. Equivalent doses from this source dropped from about 130 μSv/year in 1963 to about 10 μSv/year in recent years.

Occupational Exposures

In Canada, there are about 3000 radioisotope licences for industrial and scientific uses of radiation. They include industrial radiography, measurements using level gauges and thickness gauges, well-logging, detection and analysis of elements in biological materials, medical sterilisation, food irradiation, smoke detectors and emergency lighting. The doses from all these are trivial except for industrial radiography.

Since we have quite a bit of radiography done at PLGS by outside contractors, it is worth explaining what goes on. A typical "crank-out camera" is shown in Fig. 3.4. It consists of a shielded container that houses a gamma source. The source can be moved along the guide tube using a crank and a long cable. When the crank is turned, the source is moved to a predetermined position, such as inside a pipe below a weld. A strip of film placed around the weld will provide a radiograph of the weld and reveal any defects. The radiographer operating the equipment can stand well back from the source, and so should receive very little dose during the operation.

The type and strength of the gamma source depends on the thickness and material of the object. High-energy gamma radiation is used for massive, dense objects, and low-energy gamma rays are used for light, thin objects.

When radiography is done at PLGS, we use a barrier tape to stop people from entering any area where the dose rate will be greater than 10 μSv/h. We also make PA announcements immediately before the radiography starts.

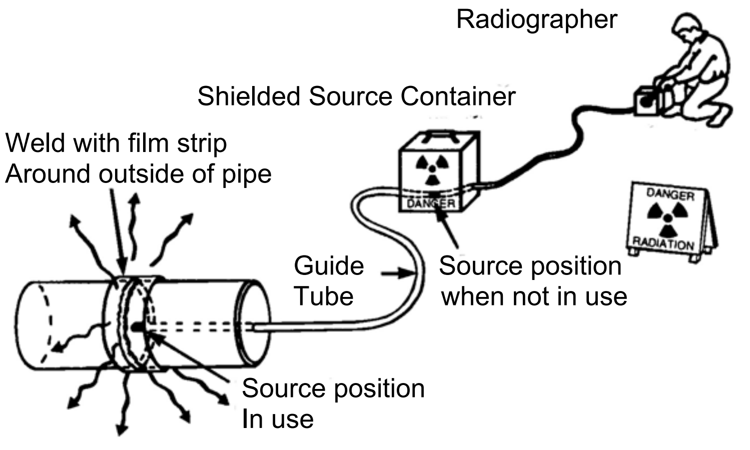


Fig. 3.4. Crank Operated Radiography Unit

Throughout the world there have been some very bad accidents involving radiographic sources. Usually the cause was that the operator was confused about the position of the source, or that the source had become detached from the cable. Either event is easily recognised by taking measurements of the radiation field.

Radiographers are not the only ones exposed to ionising radiation, as you well know. In fact, about one in 100 Canadian workers is classified as **Nuclear Energy Workers** (NEW), i.e., those who work with radiation routinely. They include radiographers, nuclear station workers, uranium miners, hospital employees who operate X-ray and radiotherapy machines.

NEWs are required to wear dose-measuring devices called **dosimeters** to measure the dose they receive at work. Such dosimeters are provided and read out by a licensed dosimetry service. (The Canadian nuclear power plants and Chalk River Labs have their own service). All results are reported to the National Dose Registry managed by Health Canada.

The data in Table 3.2 was provided from their records for 1998. We will discuss the dose records system and dose results for PLGS in Chapter 10. In the meantime, all you need to know is that the average dose for people working with radiation at PLGS has been about 2 mSv/year.

TABLE 3.2. AVERAGE ANNUAL DOSES

Occupation	*Dose (mGy)*
Dentist	0.44
Doctor	0.67
Nurse	0.42
Veterinarian	0.46
Isotope Technician	1.70
Industrial Radiographer	6.15
Nuclear Fuel Processor	2.92
Reactor Operator	2.18
Reactor Mechanical Maintainer	3.57
Uranium Miner	9.63

Miscellaneous Other Sources

These include colour TVs, watches, ceramics and false teeth containing uranium, flying in aircraft, smoke detectors and numerous other small miscellaneous sources. They add only about 3 μSv a year to the population average. (The dental boys put uranium into your false snappers so that they glow in the UV lighting used in some of the more ghastly discos. Without the uranium, your face would have a black hole in it.)

RANGE OF RADIATION EXPOSURES FROM ALL SOURCES

The range of radiation exposures that people may experience is enormous, and it extends over several decades. One way to describe such a wide range easily is by using a log scale as shown in Fig. 3.5 on the next page. Here equal space is given to each decade (i.e., from 1 to 10 is given the same space as 10 to 100, or 100 to 1000). This enables us to locate information in more or less the right spot on a standard page rather than having to use a piece of paper stretching from here to Richibucto. Take a look at Fig. 3.5. Some of the information might surprise you.

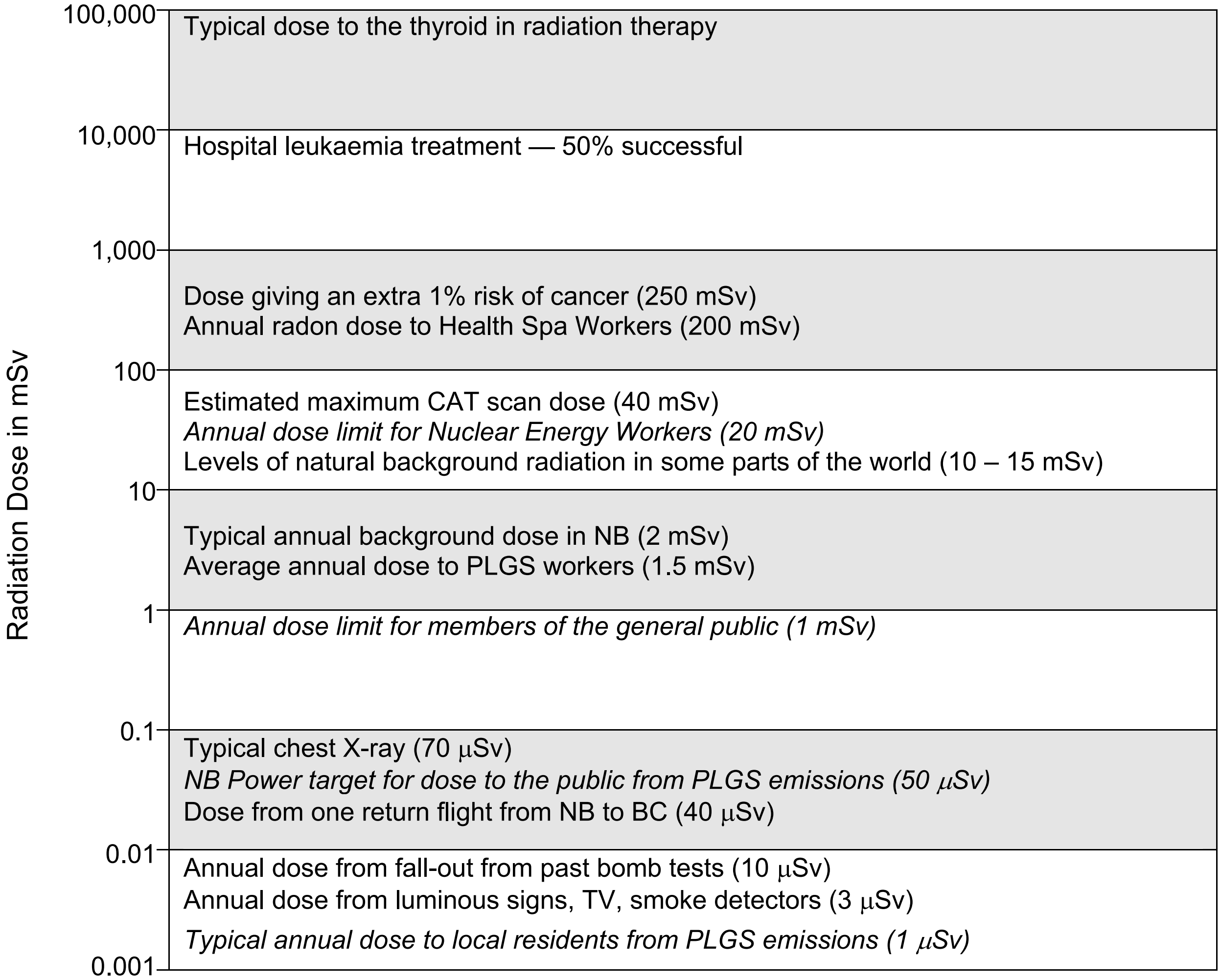


Fig. 3.5. A Log Scale of Radiation Doses in Society

SUMMARY

Radiation produces damage by breaking up the body's molecules.

The S.I. units of radiation dose are absorbed dose and equivalent dose.

Absorbed dose D is measured in grays (Gy). It is based on energy deposition: an absorbed dose of 1 Gy represents the deposition of 1 joule of energy in 1 kg of material.

Equivalent dose H is measured in sieverts (Sv). It is based on the biological effects of the absorbed dose D: an equivalent dose of 1 Sv is that amount of radiation that produces the same amount of biological damage as an absorbed dose of 1 Gy of X or gamma radiation.

Quality factors (Q) are used to convert absorbed dose D to equivalent dose H:

$$H\ (Sv) = D\ (Gy) \times Q$$

For radiation dose measurement, equivalent doses H are additive, but absorbed doses D are not.

The gray is a very small unit of energy deposition, but it corresponds to a very large amount of biological damage in man.

Background radiation comes from natural and man-made radiation and amounts to about 2 mSv per year.

We don’t want this book to be too serious all the time, so I’m going to introduce you to the “Darwin Awards”. In case you haven’t heard of them, they are given (posthumously) to the individuals who remove themselves from the gene pool in the most spectacular fashion. If you find yourself at a loose end one evening, check out some hilarious stories at Wendy Northcutt’s site at http://www.darwinawards.com

Here is the 1997 Darwin Award Winner:

Police said a lawyer demonstrating the safety of windows in a downtown Toronto skyscraper crashed through a pane with his shoulder and plunged 24 floors to his death.

A police spokesman said Garry Hoy, 39, fell into the courtyard of the Toronto Dominion Bank Tower early Friday evening as he was explaining the strength of the building's windows to visiting law students.

Hoy previously had conducted demonstrations of window strength according to police reports. Peter Lauwers, managing partner of the firm Holden Day Wilson, told the Toronto Sun newspaper that Hoy was ``one of the best and brightest'' members of the 200-man association.

PROBLEMS

1. Define a gray.

2. What is a microgray, mGy, milligray, µGy?

3. In your own words, explain the difference between absorbed dose and equivalent dose.

4. Why is 1 mGy of alpha radiation considered to be more damaging to tissue than 1 mGy of beta radiation? What about 1 mSv of alpha radiation compared to 1 mSv of beta radiation?

5. A man has been exposed to 1 mGy each of alpha, beta and gamma radiation from a source outside his body. What is the total equivalent dose to his whole body? (Do not include any dose that is delivered to skin alone.)

6. Calculate the total equivalent dose to tissue from separate doses of 3 mGy of gamma radiation, 0.6 mGy of slow neutrons, and 1 mGy of beta radiation.

7. Frank weighs 112 kg and John weighs 56 kg. Both are exposed to 5 mGy of gamma radiation. Do they receive the same equivalent dose?

8. 4.2 joules of energy are needed to heat 1 g of water by 1 ºC. If you receive an acute absorbed dose of 4.2 Gy, what kind of a temperature increase would you expect for the tissues in your body?

9. A gamma source used in radiography sits in a cylindrical shielded container of lead. The wall thickness is 22 cm, and a gamma field of 10 µSv/h above background can be detected on the outside wall of the container. The HVL of lead for this source is 11 mm. What radiation field would you expect at the same distance from the source if it were not shielded?
   a) about 200 µSv/h,
   b) about 10 mSv/h,
   c) about 10 Sv/h,
   d) none of the above.

10. Gamma radiation has deposited 10 joules of energy in a 100-kg man. He has received a radiation dose of:
    a) 10 Gy,
    b) 1 Gy,
    c) 0.1 Gy,
    d) none of the above.