3 - BIOLOGICAL EFFECTS OF IONIZING RADIATION

INTRODUCTION

This chapter deals with the effects of ionizing radiation on the body. It describes the possible and probable short-term and long-term effects produced by ionizing radiation depositing energy in living tissue.

We begin with a review of the ionization process, very briefly describe the effects of this process on the body's molecules, and then go on to explain the units we use for describing the amount of radiation absorbed by the body.

REVIEW OF IONIZATION

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 ionization, and the radiation responsible for it is called ionizing 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.

THE EFFECT OF RADIATION ON WATER MOLECULES

In the body, atoms are bonded together to form molecules. In the same way that an atom is the smallest part of an element, a molecule is the smallest part of a compound. 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 energy lost by the radiation in the collision is picked up by the molecule. If the energy gain is sufficient to overcome the bonding force holding the molecule together, the molecule will break up as shown below:

$$H_2O \longrightarrow H + OH$$

When radiation splits a chemical bond in this way, it is known as **DIRECT DAMAGE**.

This direct damage is by itself disturbing to the body's biochemistry, but further reactions of these components can damage molecules nearby to form undesirable products. For example, the H and OH components of the fractured water molecule can give a variety of reactions. Three important ones are shown below:

$H + OH \longrightarrow H_2O$	no problem, water is formed again.
$H + H \longrightarrow H_2$	no damage, a few hydrogen "gas" molecules can be tolerated.
$OH + OH \longrightarrow H_2O_2$	hydrogen peroxide is formed; this is poisonous. In fact, chemical poisoning by H_2O_2 resembles radiation sickness in many ways.

The damage produced by the charged H and OH bits drifting around before combining to form H_2O, or combining with other biologically important molecules is known as **INDIRECT DAMAGE**.

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 dose is specified in terms of the amount of energy deposited by radiation in 1 kg of material. Until it was internationally agreed in 1977 to convert to S.I. units for radiation, the most widely used unit was the rad* (an acronym for radiation absorbed dose). This has now been replaced by the gray, which is an S.I. unit (named in honour of Louis Gray, who was a very big name in the early days of radiation dosimetry). Note that100 rad = 1 gray.

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. 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).

$1\ Gy = 10^3\ mGy = 10^6\ \mu Gy$

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.

The reason is that alpha and neutron radiation damage is much more localized. The spacing between the ion pairs produced along the track of an alpha particle is much closer than for beta or gamma radiation. The same applies for neutrons, because they lose energy largely by transferring it to protons, which then also produce very dense ionization tracks.

Apparently 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, also called "radiation weighting 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 particular kind of radiation is defined as the ratio of the biological damage produced by the absorption of 1 gray of that radiation to 1 gray 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.

TABLE 3.1. QUALITY FACTORS

Radiation	Energy	Q
gamma	all	1
beta	all	1

neutrons	slow	5
neutrons	fast	20
alpha	all	20

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

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), 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 a big name in the Decathlon in the 1930s. The sievert replaces the older unit called the rem (100 rem = 1 Sv).

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

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

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.

Example:
A man is exposed to 2 mGy of gamma radiation, 0.6 mGy of slow neutrons and 0.2 mGy of fast neutrons during the course of a week. What is his equivalent dose (H)?

Solution:
For each radiation type, we have to convert D, the absorbed dose given in mGy, into H, the equivalent dose given in mSv. We do this by multiplying the absorbed dose D by the Q for that radiation. For gamma, the Q = 1: 2 mGy just becomes 2 mSv. For slow neutrons, the Q = 5, so 0.6 mGy represents 0.6 x 5 = 3 mSv. Similarly, the 0.2 mGy of fast neutrons is

equivalent to 0.2 x 20 = 4 mSv. Now just add up the individual equivalent doses to get the total: 2 + 3 + 4 = 9 mSv.

So the total biological effect corresponds to an equivalent dose of 9 mSv. Our instruments measure neutron equivalent doses in mSv, not mGy, so in practice you don't have to grunt your way through these calculations.

The units we will use throughout this course are the gray for absorbed dose D, and the sievert for equivalent dose H. 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 units are mGy or μGy, you'll know that absorbed dose D is meant. And if the "dose" is quoted in sieverts, you'll understand that we're talking about equivalent dose.

Now that we've come to grips with the radiation units, we'll go on to describe the various levels of radiation dose that we receive routinely (and unavoidably). After that we will describe the biological effects of radiation on body tissues.

The good news is that we don't expect you to remember the rest of this chapter - we have included the information because most people find it interesting and would want to know it anyway.

NATURAL BACKGROUND RADIATION

Every day since our forefathers first crawled out of the swamp, the human race has been exposed to ionizing 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.

These lower-energy particles are attenuated 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.

For example, the cosmic dose rate at Denver, the "Mile High City", is 530 μGy/year, whereas the dose rate at sea level is normally only around 330 μGy/year.

You will be gratified to hear that we have spared no expense to check out these variations a little closer to home. On a Montreal-Fredericton flight in October, 1976, we measured the dose rate with a sensitive radiation monitor. The results are given in Figure 3.1. As you can see, the ground level dose rate was about 0.10 μGy/h; whereas, at the maximum flight altitude (8.8 km or 29,000 ft), it was about 2.0 μGy/h. The total excess dose for the Montreal to Frederickton flight is only 0.7 μGy.

Fig. 3.1. Exposure Rate vs. Time on a Commercial Flight

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. However, 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 which alarm at high exposure levels (500 μGy/h) and 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, namely 0.3 Bq of C-14 activity per gram of carbon. Once the substance dies, the C-14 concentration is no longer maintained, and it 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. 53 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.

A survey in 1979 of several Canadian cities indicated that the average annual lung equivalent 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 equivalent 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 continuously.

The Health Physics Department has a Radon Meter which 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 composition of the 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 the corresponding figure 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 below. 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 (including Cosmic Rays)

Fig. 3.3. Seasonal Variation in Natural Background Radiation

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?

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 which 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 which 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 considerably from one person to another.

NATURAL HIGH RADIATION AREAS

In a few areas of the world, the dose rate from natural background radiation is considerably higher than that experienced by most of us. This high radiation background is due to the presence of larger than normal amounts of radioactive materials in the soil, drinking water, or building materials from which houses are constructed.

Inhabited areas with significantly higher than normal background radiation are found in certain regions of Brazil, France, India, Egypt and a small Pacific island called Niue Island. Annual average doses in these areas range up to 13,000 μSv, a lot greater than the average annual background of around 2,000 μSv to which most people on earth are exposed.

The people who live in these special areas of the world are obviously of considerable interest, because they and their ancestors have been exposed to abnormally high radiation levels over many generations. It would seem that if a radiation exposure of a few mSv per year is

detrimental to health, causing hereditary abnormalities or an increased risk of cancer, it should be evident in these people. As far as we can tell, it isn't.

As we shall see a few pages further on, it turns out to be futile to monitor these population groups for radiation effects, because any statistical comparison with the "normal" population is beset with too many variables other than radiation dose which could also have an effect (different life styles, working environment, climate, diet, etc.).

Most of our information on radiation effects comes from other investigations. Nevertheless, there is one important consequence of the studies that have been done: it indicates that man-made radiation, in amounts similar to natural background, is unlikely to produce a detectable number of biological disorders in the population.

MAN-MADE LEVELS OF RADIATION

The average equivalent dose received by Canadians from natural radiation sources amounts to about 2000 μSv per year. This varies with altitude, latitude, the nature of the 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 penetrating radiation from terrestrial sources, and partly from naturally occurring radioactive forms of certain of the elements in the body (see Table 3.2).

Medical Exposure

For many years now, the populations of developed countries have been exposed to substantial doses of radiation as a result of medical practice. Most of this is incurred in the form of diagnostic X-rays. For example, four or five chest X-rays amount to about 1 mSv.

A smaller part of the medical contribution (when averaged over the whole population) comes from the use of radiation to treat cancer and other diseases, and a very small additional part is incurred as the result of the diagnostic and therapeutic uses of radioisotopes, in what is known as "nuclear medicine".

For medical exposures, the equivalent dose received by the gonads is usually used for comparative purposes, because of its genetic significance. (The gonads are the reproductive glands, namely the testes and the ovaries.) We will have more to say about this later, but in the meantime, remember this: whenever you are given an X-ray, make sure that you are provided with a gonad shield, which is a light lead blanket. The average gonad equivalent dose per person from medical practice varies with different countries - medical exposures in North America give rise to an average increase of about 25% over and above natural background radiation (see Table 3.2 opposite).

Fall-Out

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

Occupational Doses (Non-Nuclear)

Occupational exposures, excluding those from the nuclear power industry, add only a further 3 μSv per year to the population average (Table 3.2).

Miscellaneous 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 another 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.

TABLE 3.2. AVERAGE POPULATION EQUIVALENT DOSE FROM NATURAL AND MAN-MADE SOURCES (μSv/YEAR)

Natural Background	Cosmic Rays	330	
	Radon Daughters	600	
	External Terrestrial	440	
	Internal Sources	200	1570
Medical Exposure (gonad dose)	Diagnostic X-Rays	300	
	Radiotherapy	50	
	Nuclear Medicine	5	355
Fall-out	Weapons Testing	10	10
Occupational Doses (non-nuclear)	Medical	2	
	Dental	0.5	
	Research & Education	0.5	
	Industry (non-nuclear)	0.3	3
Miscellaneous Sources	Colour TV, Air Travel, etc.	3	3
Nuclear Power Generation (projected)	Uranium Mining	1	
	Reactor Operation	15	
	Other Fuel Processes	3	
	Transportation	0.01	
	Accidents	0.5	20

Nuclear Power

Nuclear power generation currently contributes very little to the average radiation exposure of the general public, probably much less than 1 μSv/year. Even less in British Columbia. Ontario is the leading population directly - the other three quarters would come from the small fraction of the population generator of nuclear electricity; in 1988 it produced 47% of the electricity by nuclear power. This amounts to around one kilowatt of nuclear generation per person, much the same as in New Brunswick.

If every province were to generate half of its electricity needs by nuclear means, the end result might be an increase of 20 μSv per year to the population (see Table 3.2). Roughly one quarter of this 20 μSv might be received by the that receives relatively high dose, for example, uranium miners and reactor operators.

At present, in New Brunswick, the total radiation exposure from Point Lepreau is just under 1 μSv/year to the local population, and about 1 Sv/year spread over the operating staff. Averaged over the whole population of N.B., this comes to around 1.3 μSv/year.

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 opposite in Fig. 3.5. 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. 3.4. Background Radiation in Canada

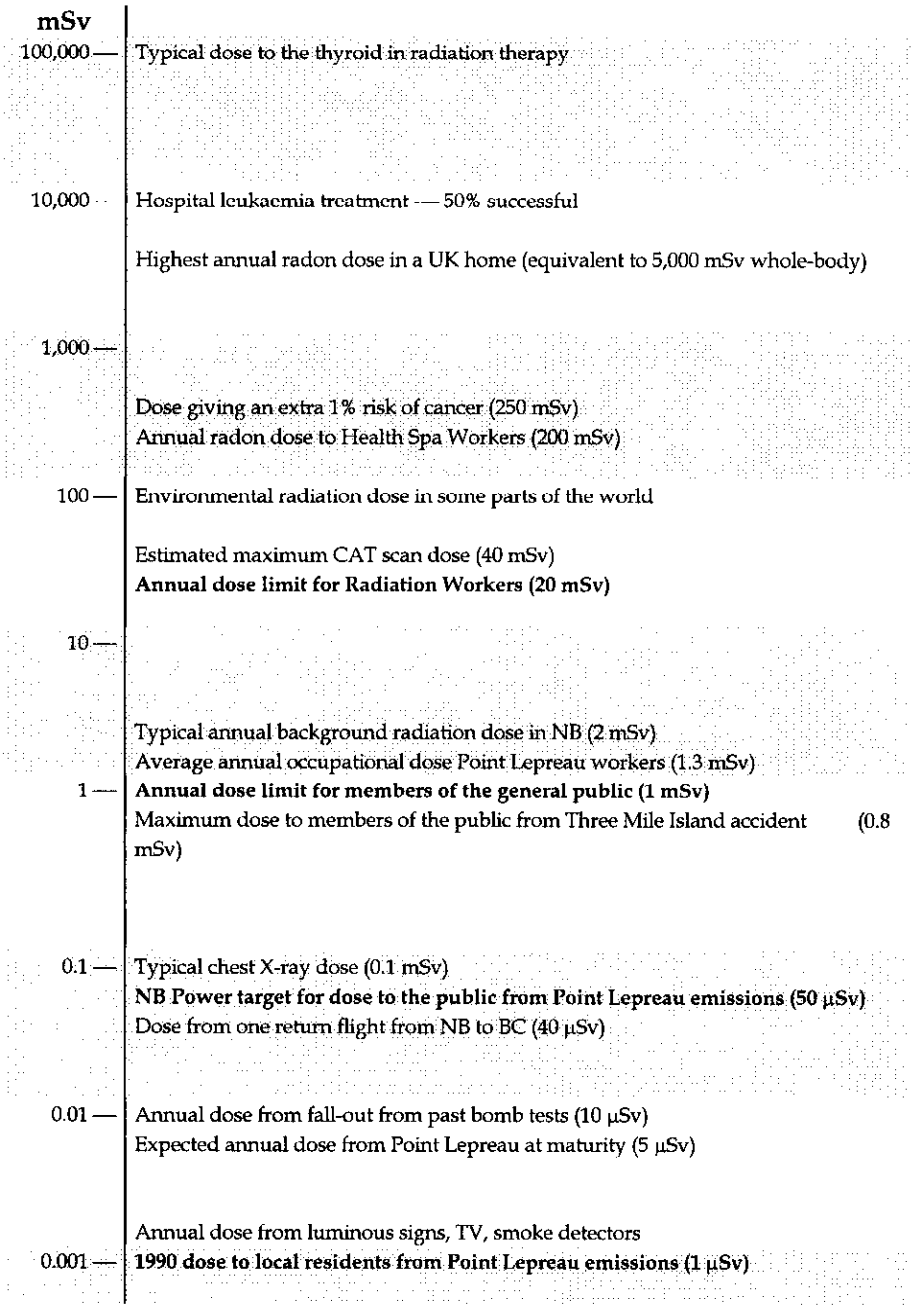

Fig. 3.5. A Log Scale of Radiation Doses in Society

SOMATIC AND HEREDITARY EFFECTS

Earlier we discussed ionization and the direct and indirect damage it produces in biological molecules. We shall now consider how this molecular damage affects the body cells, so that we can explain the biological effects of radiation on people.

The biological effects of radiation on people may be conveniently divided into somatic (from the Greek *soma,* meaning body) and hereditary effects.

SOMATIC EFFECTS are those experienced by the exposed individual, whereas HEREDITARY EFFECTS do not become apparent until subsequent generations are born.

We will consider hereditary effects first, and then somatic effects.

SOME CELLULAR BIOLOGY

All living things are composed of one or more cells. Every part of your body consists of cells or was built by them. A large number of cells of any particular type is called a tissue. If this tissue forms a specialized functional unit, it is called an organ.

In an adult organism, most mature cells contain a set of giant molecules called chromosomes. These molecules contain all the information required to create another individual organism identical to the owner of that cell. Each and every one of the billions of chromosomes in an elephant contains the blueprint to re-create an elephant.

In a human, the normal cell contains twenty-three pairs of chromosomes. (This number varies with different species of animals.) Important exceptions are the sperm cells in males and egg cells in females (both are called **GERM CELLS**), which contain half the usual number of chromosomes. In humans these germ cells contain 23 single chromosomes. The germ cells are produced in the **GONADS**, a term for the male testes or female ovaries.

The first cell of a new human being is created when a sperm cell and an egg cell unite. Both sperm and egg have 23 chromosomes which fuse to form the normal 23 pairs. This allows the offspring to have characteristics from both parents.

This single cell develops into a new individual by the process of cell division, during which the information contained by the original cell is accurately passed on to both of the "daughter" cells. Billions of these cell divisions take place during the formation of the new individual. This process is illustrated in Fig. 3.6. Your parents probably told you all this when you were twelve.

Note that the genetic blueprint contained in the chromosomes includes the instructions for making new germ cells, thus characteristics of one individual can be passed on for many generations.

Fig. 3.6. Cell Division

NATURAL MUTATION

Genetic information contained in the chromosomes is often likened to a template, or to a code, which is reproduced millions of times over with remarkable accuracy. Although there are effective repair mechanisms, it is possible to damage the genetic code permanently by means of external influences. When this is done, the garbled or distorted genetic information will be reproduced just as faithfully when the cell divides as was the original message. When this kind of alteration occurs in the germ cells, it is referred to as a hereditary mutation. If the damaged germ cell is used in conception, the defect is reproduced in all of the cells of the new organism that results from this conception, including those cells that will later become germ cells. Thus, whatever defect resulted from the original mutation can be passed on for many generations.

Hereditary mutations range from harmful to beneficial. Those with damaging effects are gradually eliminated from a population by natural means, since individuals afflicted with this damage are less likely to reproduce themselves successfully than normal individuals. The more severe the damage produced by a given mutation, the more rapidly it will be eliminated, and vice-versa; mildly damaging mutations may require a great many generations before they gradually disappear. Beneficial mutations are the mechanism by which we evolved to our present state.

A large number of agents have mutagenic (i.e. able to produce mutations) properties, and it is probable that our current knowledge includes just a fraction of these. In addition, it may be that mutations can arise within the germ cells of an organism without external insult. Among the various influences which have been found to be mutagenic are a wide variety of chemicals, certain drugs, and physical factors such as elevated temperatures of the gonads and ionizing radiation. From six to nine percent of all human live births have significant hereditary defects of some kind.

Natural background radiation is believed to cause a very small percentage of human mutations. They can't be distinguished from spontaneous or chemical mutations.

MUTATIONS - RESULTS FROM EXPERIMENTS

The mutagenic properties of ionizing radiation were discovered in 1927 during a series of experiments on insects. In more recent years, large scale experiments have been made to determine the change in mutation rates in mice after irradiation. About a million animals were needed to get meaningful results. In a nutshell, the findings were:

1. different types of mutation varied enormously in their sensitivity to radiation;
2. 100-2000 mSv was required to double the natural mutation rate;
3. the effects of a given dose were greater for the male;
4. the consequences were minimized by allowing some time to elapse between irradiation and conception;
5. dose spread over a period of time produced a smaller effect than if delivered all at once.

It is difficult to measure changes in the human mutation rate for two main reasons. First, the majority of chromosome mutations will not show themselves in an individual unless both sides of a chromosome pair have the same alteration. Secondly, most of the mutations that do occur are minor and difficult to measure. Examples are a less efficient digestive system, a predisposition to a given disease, or a tendency towards steatopygia (good word, look it up).

Such mutations are not only difficult to detect in themselves, but often they cannot be distinguished from conditions produced by other influences. For example, it would be most difficult to determine whether an individual's heart disease were the result of a subtle mutation or of environmental stresses such as diet, occupation and personality.

HEREDITARY EFFECTS IN HUMANS: MAN OR MOUSE?

The largest group of irradiated humans available for study are the descendants of those Japanese who were exposed during the nuclear bombing of Nagasaki and Hiroshima. Until now, hereditary effects such as leukaemia and mental retardation have only been seen in those children who were heavily irradiated while still in their mother's womb. Children conceived and born after the explosion have shown no change in the natural mutation rate.

However, although these negative results are encouraging, the numbers involved (30,000 children born to irradiated parents) are too small for proper statistical analyses. Also, some mutations may take several generations to show themselves.

In the absence of any firm data for humans, the best we can do is assume that radiation effects on humans are similar to the effects on mice.

HEREDITARY RISK FROM RADIATION

For the general population, the risk of serious hereditary ill-health in babies conceived after the irradiation of either parent is estimated to be 1.3% per 1000 mSv. This risk number includes not only the babies born in the first generation, but also those born in all future generations stemming from these parents. The risk applies to the total exposure of the parent from age 0 until the final child is conceived. Any exposure after that time can obviously have no hereditary consequences, because there are no offspring. It is assumed that the risk is proportional to the dose; i.e., if the parents receive only 1 mSv instead of 1000 mSv, the risk of producing offspring with serious hereditary ill-health in the next and all future generations is only 0.0013%.

The risk for occupational exposure is only 0.8%/Sv rather than 1.3%/Sv. Why? Because radiation workers (like you) can only be exposed to occupational dose of hereditary significance from age 18 until say age 45, but the general public can be exposed from age 0. For equal annual doses, the shorter time span for radiation workers results in a lower risk.

LONG-TERM SOMATIC EFFECTS

Somatic cells are those cells of your body other than the reproductive cells. They can be damaged in a variety of ways, such as by chemical, biological and physical agents or by

ionizing radiation. The effects of the damage from ionizing radiation can be short-term or long-term depending on the means and severity of the exposure. The long-term effects of radiation exposure are cataract formation and an increased chance of getting cancer.

SOMATIC CELL MUTATIONS AND CANCER

A long-term somatic effect is the damage to cells that are continually reproducing. These cells are the most sensitive to radiation because any changes made in the parent cell's chromosome structure will be transmitted to its daughters. Also, radiation can affect the delicate chemistry of the cell causing changes in the rate of cell division or even the destruction of that cell.

An event which causes a somatic cell to behave in this way is called a mutation. We have already dealt with mutations in the reproductive cells. In these, damage affects future generations. However, a mutation in a somatic cell has consequences only for the individual.

If the mutation in the somatic cell increases the rate of its reproduction in an uncontrolled manner, then the number of daughter cells may increase in large numbers in that area. When this occurs, it often happens that the daughter cells divide before reaching their mature state. The result then is an ever increasing number of cells that have no beneficial function to the body, yet are absorbing body nutrition at an increasing rate. The tissue could now be called a tumour. If the cells remain in their place of origin and do not directly invade surrounding tissues, the tumour is said to be benign. If the tumour invades neighbouring tissues and causes distant secondary growths (called metastases), it is malignant.

Cancer is a malignant tumour. Whether it is fatal or not depends on the tissue in which it is located, how rapidly it grows, and how soon it is detected.

RADIATION INDUCED CANCER IN HUMANS

There are many well documented cases of radiation induced cancer in humans. The early scientists who worked with X-rays and radioactive substances did not realise the risk. Many died from skin and bone cancers and from leukaemia. Leukaemia is a disease characterised by a great excess of immature white cells in the blood and can be likened to a "blood cancer". Marie Curie, for example, who first isolated radium from uranium ore died from leukaemia, as did her daughter-assistant. Her husband, on the other hand, died in a traffic accident - he was run over by a horse and cart.

In the 1920s, watch dials were painted with a radium-based luminous paint. The factory girls who did this work often licked their paint brushes to give them a sharp point - each time they ingested a small quantity of the paint. The radium in the paint collected in the girls' bones and for many of them, it resulted in bone tumours 8 to 40 years later.

Fig. 3.7 shows the distribution of cancers among the 1349 radium painters that were followed up. It is clear that the risk of cancer increases with the radiation dose.

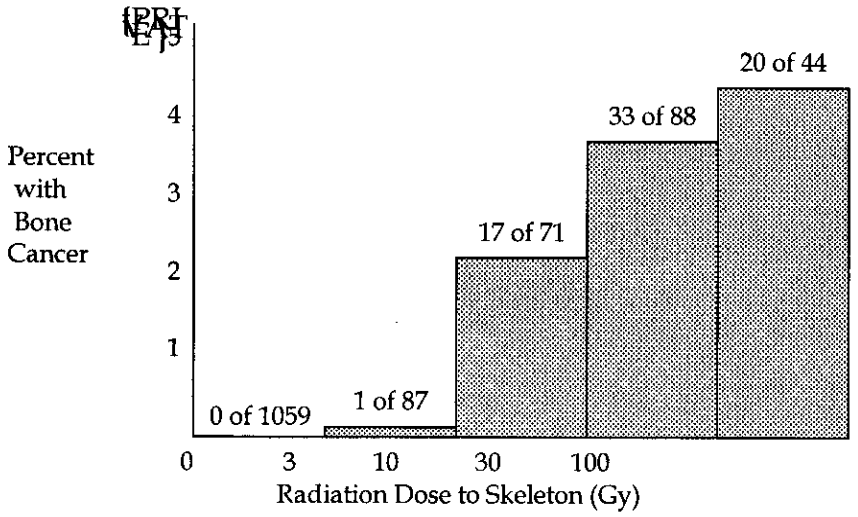

Fig. 3.7. Cancer Cases in Radium Dial Painters

In Great Britain more than 6500 patients with a certain backbone disease were treated with large doses of X-rays. The average dose was 3000 mGy. The disease was ankylosing spondylitis, which involves a painful stiffening of the joints in the backbone. Of the 6500 patients, 30 developed leukaemia compared with an expected incidence of 7 cases.

The largest group of human beings exposed to high levels of whole-body radiation are the survivors of the Nagasaki and Hiroshima atom bomb attacks. Nearly 80,000 of these people have been carefully studied in the years since the war.

Of this number of survivors (about 200,000 died in the bombing), there were about 350 excess cancer deaths. Of these, 126 died of leukaemia. This is nearly double the normal figure for this number of people. The incidence of leukaemia was related to the distance from the explosion and therefore to the radiation dose received. The highest incidence was in those survivors closest to the explosion, i.e., the higher the dose, the greater the risk. It was found that there was a delay (called the latent period) between the radiation exposure and the onset of leukaemia. The latent period for leukaemia is about eight years, and for the other cancers it is more than double.

There are some difficulties with all of these studies, when you attempt to estimate the risk of fatal cancer per sievert of dose. The data from Japan are convincing and extensive, but they relate to a study group of which 60% are still alive. This means that, apart from leukaemia, the total number of cancers eventually occurring has to be estimated. The mathematical models used for making such a prediction are uncertain.

Excess cancers that are statistically significant at the 95% level (i.e., numbers of excess cancers that would arise by chance only 5% of the time) can be found only at doses exceeding 0.2 Sv. This means we have good data for high doses and high dose rates. Yet these data tell us nothing about the lower doses and very much lower dose rates that are important for radiation

protection purposes. Still, studies on this group have several advantages over other studies. The group contains both sexes and all ages, and was exposed to a wide range of doses, from trivial to fatal.

The studies on the ankylosing spondylitis patients also pose some problems. The radiation was delivered largely to the spine and not to the whole body, and medical patients may not be representative of the general population.

The only studies on workers that have yielded any significant results at all relate to the radium dial painters mentioned a couple of pages ago and to uranium miners who inhaled radon and its daughter products. In both cases, it was difficult to estimate the amount of radioactivity taken into the body, and the doses were from alpha particles localised in bone and lung tissues. A comparison with the effects of gamma radiation is not simple.

Finally, there have been numerous studies involving the exposure of selected populations to low doses of radiation delivered over long periods of time. Some related to exposure from fall-out, to military personnel exposed at weapons tests, and to people like you and me working at nuclear power stations. Others included foetuses exposed to diagnostic X-rays, other medically irradiated populations, and still other populations living in the relatively high radiation background areas of the world that you read about on pages 104 - 105. These studies are very relevant to deciding the risks of long-term exposure to low levels of radiation (i.e., the sort of exposures we face at work). Unfortunately these studies have not produced any statistically useful results, and they have contributed very little to radiation risk estimates.

Well then, how do we translate the known effects of high doses delivered in a short time to low doses delivered over a long time? Experts believe that at low dose rates, defence mechanisms in the cells can operate to repair some of the damage caused by radiation. In this region of low dose, the effect (i.e., the probability of producing cancerous cells) is proportional to the dose. At higher dose rates, greater than 100 mGy/h, two or more ionizing events might occur in the critical parts of cells before the repair mechanism would have a chance to operate. At this point, the slope of the dose/effect curve increases and the effect depend on the square of the dose, D^2, rather than just on D. This relationship is shown in Fig. 3.8. At very high doses (greater than 4 Gy or so), the curve turns down again: here the doses are so high that some cells are being killed before they have a chance to become cancerous. Note that the curve has no threshold; in the region of interest to us the risk is assumed to be proportional to the dose. Similar curves are obtained in animal studies.

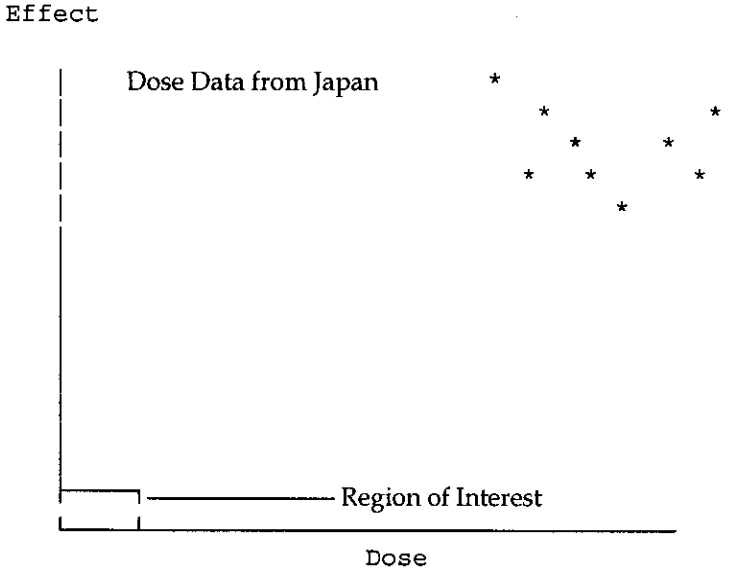

Fig. 3.8. Dose Response Curve

The ICRP (a committee of international experts we'll meet in Chapter 4) has decided that the data obtained at high dose rates and high doses will overestimate the risk at low doses and low dose rates by a factor of 2. This factor of 2 applies to our region of interest, namely at absorbed doses of less than 0.2 Gy and for higher absorbed doses when the dose rate is less than 100 mGy/h. Various committees of Big Names in the Radiation Protection business have estimated this Dose and Dose Rate Effectiveness Factor, or DDREF, to have a value ranging 2 to 10. This is another way of pointing out the uncertainties in coming up with a risk estimate. It is worth quoting from the ICRP's most recent publication on this topic (1991): "there is a wide spread in the data and the ICRP recognises that the choice of this value is somewhat arbitrary and may be conservative."

Those of you who are not new to this course will remember that the ICRP used to claim that the fatal cancer risk was about 1%/Sv. This is no longer the case. An extensive review was done in the last few years of the radiation doses that were assigned to the survivors in Hiroshima and Nagasaki. It turns out that the neutron doses were overestimated, and the shielding effects of buildings were underestimated.

Both of these factors indicate that the doses the Japanese survivors received were quite a bit lower than had been thought previously. Since the observed effects haven't changed, this means that the risk per sievert has increased. ICRP now says that the risk for occupational exposure is 4%/Sv. This was derived with the DDREF of 2.

Current estimates of fatal cancer risk for Radiation Workers are about 4%/Sv.

This means that if you work from age 18 to age 65 and receive the annual dose limit of 20 mSv every year, you will increase your cancer risk by 4%, namely from 25% to 29%. If you average 5 mSv every year for 47 years, you'll increase your cancer risk by 1% to 26%. Even so, I doubt that we'll have many people at Lepreau who will reach 250 mSv in their working lifetime.

It is assumed that there is no threshold dose for cancer, i.e., a dose below which there is zero chance of incurring a radiation related cancer. I don't know whether this is true or not, and I doubt whether we will ever know. That's why everyone recommends the cautious approach of assuming that even the smallest dose carries with it a possibility of producing a harmful effect. It is for this reason that

All unnecessary radiation exposure should be avoided.

SHORT-TERM SOMATIC EFFECTS

Short-term somatic effects are those that we would expect to see for acute exposures rather than chronic exposures.

An ACUTE exposure is one that is delivered in a short period of time, i.e., within a day.
A CHRONIC exposure is one that continues over long periods of time, i.e., months and years.

The short-term somatic effects are considered below in five parts:
1. the effects of radiation on living cells,
2. the self-renewal tissues in the body,
3. the functions of these tissues,
4. the effects of damage to these tissues, and
5. how we can treat injuries to these tissues.

1. Effects of Radiation on the Cell

We have already seen that ionizing radiation damages the molecules which compose our cells. Huge doses can kill the cell outright. For lesser doses, the big chromosome molecules in the cell nucleus present the largest target to the incoming radiation. If they are damaged, the cell's reproductive ability will be impaired or destroyed.

Thus the tissues in our bodies most affected by an acute radiation dose are those in which the cells are most rapidly reproducing. These are the skin, the blood-forming tissues, the gonads and the digestive system lining (called the gastrointestinal tract or GI tract.)

If we consider the function of these tissues, we can predict what will happen if reproduction of the cells stops. We can then determine the symptoms of an acute exposure to radiation, commonly known as radiation sickness.

If a certain tissue is more affected by radiation than another tissue, it is more radiosensitive. The self-renewal tissues are thus the most radiosensitive tissues in the body.

2. Functions of the Self-Renewal Tissues

TABLE 3.3. FUNCTIONS OF THE SELF-RENEWAL TISSUES

SKIN	Contains body fluids, protects underlying tissues, prevents bacterial invasion
GONADS	Procreation, recreation
BLOOD CONSTITUENTS:	
Red Blood Cells	Transport oxygen
White Blood Cells	Gobble up bacteria and germs
Antibodies	Destroy or immobilize foreign molecules and bacteria
Platelets	Assist in blood-clotting mechanism
GI TRACT LINING	Secretes digestive enzymes, absorbs nourishment from food, prevents bacterial invasion

From the functions listed above, the most important tissues for survival are the blood-forming tissues and the GI tract lining. For extremely high acute radiation doses, however, the damage to the cells of the brain and spinal cord may cause death to the individual before the damage to the self-renewal tissues becomes evident.

3. Blood & Guts

Before we consider what happens if self-renewal amongst these tissues stops, you must know a little about blood and guts biology.

In adults, red blood cells are manufactured only in the marrow of the bones in the head and trunk. During their lifetime, these red blood cells transport oxygen to all parts of the body, until, at the ripe old age of 4 months they become brittle and disintegrate.

80% of white blood cells are formed in the marrow of the head and trunk bones. These cells travel around the body like policemen, gobbling up any bacteria they find.

The remaining 20% of the white blood cells are formed in the lymph nodes and are known as lymphocytes. These cells manufacture antibodies which combat foreign proteins and bacteria. The lymph nodes themselves prevent the access of most bacteria to your body. The lymph cells multiply rapidly in the vicinity of an infection in order to destroy the bacteria. See Fig. 3.9.

Platelets are the final important blood constituent. They help to seal broken blood vessels by forming clots. They are also manufactured by the head and trunk bone marrow. Platelets are being used constantly to seal damage to capillaries. (This damage occurs all the time - if you flick your forearm with your fingers, the red mark is the result of bleeding capillaries - dozens would have been ruptured but will be sealed rapidly).

The GI tract is a muscular tube about 6 m long from mouth to anus (the other end). The inner lining varies according to its function. The longest section is the small intestine (about 5 m); a detailed cross-section is shown in Fig. 3.10. The dividing cells are shed into the intestine, so that when they break down they will release their chemical content into the nutrient mixture, thus aiding digestion of the food.

4. Probable Effects of High Acute Whole-Body Doses

Table 3.4 on page 125 is lifted from our Radiation Protection Regulations. It outlines the sort of unpleasantness you might anticipate for acute doses up to about 10 Gy. Table 3.5 on page 126 shows in more detail the stages of acute radiation sickness for life threatening doses of 4-6 Gy. At higher doses, in the range of 10 or more Gy, there is also gross damage to the GI tract, resulting in failure of the ability to digest food and contain bacteria. Death is certain.

Fig. 3.9. Cross-Section of Lymph Node

Fig. 3.10. Cross-Section of GI Tract

TABLE 3.4. PROBABLE EFFECTS OF ACUTE WHOLE-BODY GAMMA DOSES (mGy)

0-250	No detectable clinical effects. Delayed effects may occur, but are highly unlikely.
250-1000	Slight blood changes with later recovery. Possible nausea. Serious delayed effects are possible but improbable.
1000-2000	Nausea and fatigue, possible vomiting. Reduction in certain blood cells with delayed recovery.
2000-3000	Nausea and vomiting probable on first day. Two week latent period followed by general malaise, loss of appetite, diarrhoea, moderate loss of weight. Possible death in 2-6 weeks but for most healthy individuals recovery likely.
3000-6000	Nausea, vomiting and diarrhoea probable in first few hours. Short latent period followed by loss of appetite, general malaise, then haemorrhage, loss of weight, skin blotchiness, diarrhoea, inflammation of throat. Some deaths in first weeks, possible eventual death to 50% of individuals receiving about 3500 mGy without medical treatment.
over 6000	Nausea, vomiting and diarrhoea in first hours. Short latent period followed by diarrhoea, haemorrhage, skin blotchiness, inflammation of throat, fever by end of first week. Rapid weight loss and death as early as second week with possible eventual death of 100% of exposed individuals.

Adapted from "Medical Aspects of Radiation Accidents", Eugene L. Saenger, Editor, USAEC, 1963, p. 9.

TABLE 3.5. EFFECTS OF RADIATION EXPOSURE FROM AN ACUTE DOSE OF 4 TO 6 GRAY

Time from Exposure	Biological Effects	Symptoms Observed
Stage I 0-48 hours	Body cells killed by the radiation disintegrate, releasing irritants into the blood system. The body senses this and assumes the last meal to be at fault.	Vomiting, nausea, loss of appetite, fatigue.
Stage II 2 days - 3 weeks	Following the removal of the irritants, there is a period during which the concentrations of all blood constituents are falling.	Symptoms disappear, and patient feels well.
Stage III after 2 weeks	There is now a severe shortage of blood constituents. Shortage of red cells: - poor oxygen transport. Lack of white cells: - open to infection. Lack of platelets: - no clotting of damaged blood vessels.	Severe lethargy, fever, bleeding, and blotchy skin. Fatalities occur here.
Stage IV after 8 weeks	For the radiation victim to survive Stage III, he must have sufficient blood-forming tissue to sustain life, perhaps aided by medical treatment consisting of massive doses of antibiotics, massive blood transfusions and possibly bone marrow transplants. The patient's condition will improve but up to six months are required before full recovery.	

Following acute exposure to even higher doses (100 Gy or more) there is severe damage to all tissues of the body. The effect of damage to the brain and nervous tissue is the most severe - resulting in death to the individual in a matter of hours.

LETHAL DOSE

The greater an acute radiation dose is, the greater is the possibility of it killing the individual. An acute gamma dose of 1 Gy will kill nobody. An acute dose of 2 Gy may kill 5% of the people exposed to it; at the other extreme, a dose of 8.5 Gy will kill 100% of those exposed.

Somewhere in between is the LD_{50}, which stands for Lethal Dose for 50% of the people exposed. For a healthy adult, the LD_{50} is estimated to be somewhere between 3 and 5 Gy. Cause of death will be loss of bone marrow function. (If you survive longer than 2 months, you are almost sure to make it.) It is possible to improve the victim's chances of survival by giving him bone marrow transplants from a compatible donor, and by giving him suitable medical care. Even then, death is likely for doses in the region of 6 to 8 Gy.

At acute doses greater than about 5 Gy, severe gastrointestinal damage occurs. Combined with the bone marrow damage, this will cause death in one to two weeks. At around 10 Gy, acute inflammation of the lungs can occur and lead to death.

Above about 15 Gy, damage to the nervous system causes the victim to die of shock after a few days. For doses of 100 Gy and more, the survival time is reduced to a few hours.

The lethal dose data given above apply to acute gamma doses delivered in a short time, e.g., a few minutes. More dose is required to produce the effects listed above, if the dose is received over a period of hours or longer.

5. Treatment of Radiation Injury

The methods used for the treatment of casualties who have received an acute whole-body exposure are listed on the next page with the reasons for their use.

TREATMENT	REASON
Complete rest	Conservation of the blood constituents.
Strict environmental sterility	Reduction of contact with bacteria.
Antibiotics	To aid body's bug-fighting equipment.
Blood transfusions	Restoration of blood constituents.
Intravenous feeding	To aid or replace normal digestive processes.

RADIATION DOSE TO SPECIFIC ORGANS OR TISSUES

Radiation exposure that is confined to only one area (i.e., not the whole body) causes much less injury and risk than whole-body exposures. The reason is that, although there may be severe damage in the affected area, the high proportion of unaffected tissues will compensate for the loss of any of the blood-forming cells.

Some acute internal exposure situations can lead to damage to a specific organ if the radionuclides accumulate in that organ. Some radionuclides are intense beta ray emitters: if they are present outside the body but within range of their beta rays, they can cause skin damage leading to skin burns. Extensive skin burns from beta radiation, plus high levels of whole-body dose, led to the deaths of several fire fighters at the Chernobyl accident.

Larger doses from radionuclides entering the body by inhalation or ingestion are possible in accident situations. Such internal exposures may be uniform in the body, or they may affect particular body organs. Inhalation of tritiated air moisture, or ingestion of tritiated food or water, leads to uniform irradiation of the soft tissues of the body. For extremely large intakes, the effects would be similar to those of whole-body gamma exposures.

Since radioiodines are concentrated in the thyroid gland, exposures to radioiodines which give little whole-body exposure can nevertheless cause large doses to the comparatively small thyroid gland and surrounding tissues. In extreme cases, the thyroid may be destroyed. The sections to follow provide further details for specific organs.

Skin

The skin damage from high gamma doses is irrelevant, because a whole-body dose sufficient to kill you may only redden your skin and cause loss of hair. If you are going to drop dead anyway, these minor cosmetic blemishes probably aren't high on your list of items to get excited about. (That is not to say that the skin isn't a pretty important organ. Just think: if the holes for the eyes were a couple of cm higher, we'd all be blind.)

If you should suffer an acute exposure to beta radiation, only the skin is affected because the vast majority of beta particles do not have enough energy to penetrate any deeper.

In fact, skin is covered by a dead surface layer about 70 μm thick. Yeah, even yours. The radiation must have enough energy to penetrate this dead layer of skin to do any harm. That's why even high doses from alpha emitters and low energy beta emitters cause little skin damage (betas need at least 70 keV to penetrate the dead layer).

The skin damage depends upon the dose received, and can be quite nasty. The effects range from temporary erythema (reddening of the skin at around 5 Gy) through moist desquamation (the surface layer peeling off) to necrosis (death of the skin) at about 30 to 50 Gy, depending on the period of time over which the doses are received. For such acute exposures, the effects would show up about three weeks later.

The treatment required for high local skin doses is similar to the treatment given to thermal burns. However, injury caused by radiation heals slowly, owing to damage of the underlying tissue.

Hair follicles are more sensitive to radiation than the cells of the skin. An acute dose of 3 to 5 Gy leads to a temporary loss of hair, and this loss becomes permanent after an acute dose of around 7 Gy.

If the doses are spread out over a period of time (like weeks), they have less effect. That is, they might have to be 3 or more times greater than the acute dose to produce the same effect.

Blood-Forming System

We've already mentioned that the dividing cells of the haematopoietic (blood-forming) system are amongst the most radiosensitive in the body. After the acute whole-body dose of 1 Gy, changes can be observed within hours in the bone marrow and lymphoid follicles, and in the peripheral blood count. The maximum depression, however, occurs only after a period of roughly 2-5 weeks. The depression of leucocytes (white blood cells) leads to a marked weakening of the immune response, and of resistance to infection. A decrease in blood platelets (elements necessary to prevent bleeding) will be observed at about the same time.

After whole-body doses of several Gy, infection and haemorrhage are the main causes of death. Although we said earlier that the acute dose necessary to cause death in 50 percent of exposed persons is around 3 to 5 Gy, the outcome depends strongly on the medical support available during this critical phase. (Some of the fire fighters at Chernobyl survived doses believed to be approaching 7 to 8 Gy.) If the patient survives the relatively short critical period of two months, recovery is essentially complete and no lasting long-term effects are expected.

Gastrointestinal Tract

The sensitivity of the cells of the gastrointestinal tract is similar to that of the skin cells. Ulceration, followed by fatal dysentery, is what happens to you if a large part of your intestine is exposed to acute doses greater than 10 Gy. Doses greater that 0.5 Gy will cause temporary nausea, vomiting and diarrhoea.

Reproductive System

The germs cells of the testis and ovary are highly radiosensitive. In the testes, the primitive cells that differentiate into sperm are the most sensitive: a loss of fertility could be observed several weeks after a single acute exposure as low as 0.15 Gy. This loss is temporary, and recovery will occur over a period of months. After doses of 3.5 to 5 Gy, however, sterility will be permanent.

Acute exposure of both ovaries to doses greater than 0.7 to 1.5 Gy leads to a prompt loss of fertility. At doses below 2 to 3 Gy, the loss is temporary, and fertility is recovered. This threshold, however, depends strongly on age. It is in the range of 2.5 to 6 Gy, with older women being more sensitive. A dose of 3 Gy to the ovaries of a woman aged 40 would almost certainly cause permanent sterility.

Thyroid

One of the main concerns with regard to accidental releases from nuclear facilities is the exposure of the thyroid which could result from intakes of radioiodines. The adult thyroid, however, is relatively resistant to radiation. The threshold for severe function damage to the normal adult thyroid is about 25 to 30 Gy. On the other hand, this relative radioresistance is

strongly age-dependent. Marked thyroid depression, with accompanying retardation of growth, has been observed in children under ten years of age following thyroid doses of only 7 to 14 Gy.

Eye

The lens of the eye is fairly radiosensitive. At high doses, lens opacities (or cataracts) develop within months, progress rapidly and eventually cloud the lens completely. At lower doses, opacities may take years to develop, remain microscopic in size, and cause no notable loss of vision.

Based on several studies, it seems that a dose of more than 8 Gy of X- or g radiation is required to produce a vision impairing cataract under the exposure conditions typical of radiation workers (i.e., small doses spread out over long periods of time).

Central Nervous System

The central nervous system is relatively radiation resistant. In patients receiving large doses to the brain or spinal cord during radiation therapy, myelitis (inflammation of the spinal cord) will develop over several years, but only after exposures greater than about 30 Gy. Acute exposures above about 50 Gy, however, will cause severe acute damage leading to death in a day or so.

Developing Embryo and Foetus

The most sensitive tissue of the human body with respect to induction of damage by ionizing radiation is the developing embryo or foetus. A lot of complex things have to happen at the right time and in the right order, and there is much opportunity for outside agents to make things go fubar.

Briefly the development of the human conceptus can be divided into three phases: the pre-implantation period lasting from fertilization until implantation of the embryo into the uterine wall; the phase of major organogenesis, which extends in man (well, woman actually) until about the 8th week after ovulation; and the phase of foetal development, continuing on until birth.

Much of the quantitative information concerning effects of prenatal irradiation is derived from laboratory observations of other species. The major effect of irradiation during the first phase is death of the conceptus, but those that survive appear unimpaired with respect to morphology (shape), size, long-term survival and reproductive fitness. In humans the effect would simply be noted as a temporary failure to conceive. You might be interested to know that about 40% of human embryos are lost after conception to spontaneous abortions, and most of these occur before the pregnancy has been diagnosed.

The following is a summary of what is presently known about the risks of prenatal radiation exposure:

1. **Mortality**
   This depends on when the exposure occurs. The LD_{50} could be as low as 1 Gy.

2. **Malformations**
   Malformations may be caused in organs developing at the time of the exposure. In humans, there is a threshold of about 50 mGy, below which this won't happen.

3. **Severe Mental Retardation**
   The developing human brain is very vulnerable to radiation damage between the 8th and 15th weeks of the pregnancy. The risk of severe mental retardation is high at 40%/Gy, with a threshold of a few hundred mGy. This is based on the Japanese data at high dose rates. No DDREF is used, because there are no data for low dose rates.

4. **Reduced Intelligence**
   I.Q. testing of Japanese born after the A-bomb explosions suggests a loss of 30 I.Q. points for those who were exposed to 1 Gy at 8 - 15 weeks after conception. The loss was smaller for weeks 16 - 25, and there was no evidence of any effect after the 26th week.

5. **Childhood Cancer**
   There is disagreement between the Japanese data at high doses and large populations of children who received small doses of prenatal radiation for medical reasons. The estimated risk of childhood cancer and leukaemia range from 2% to 6% per sievert.

THE 10-DAY RULE

From what was said above, you can see that the developing embryo and foetus are uniquely sensitive, and suffer serious consequences after doses of only a few hundred mSv, depending on when the exposure occurs.

A serious practical problem occurs from time to time when a woman receives a series of X-ray exposures involving the stomach or pelvis, and later discovers that she is pregnant. The worst time is during the 8th to 15th week of the pregnancy, although it is not a good idea at any time during the pregnancy.

The only completely satisfactory solution to this problem is to ensure that it never happens in the first place. This may be achieved by ensuring that women of childbearing age receive X-rays of the stomach or pelvis only during the first 10 days after the start of a menstrual period when it is reasonably certain that they cannot be pregnant. This is called the 10-day rule, and causes some problems of organization and scheduling. Nevertheless it has been introduced into several large hospitals, and is clearly a very desirable step.

At Point Lepreau, we have adopted the policy that women who are pregnant shall not do any radiation work. If you are a woman and you know that you are pregnant, you must inform your supervisor so that you may be reassigned to work with no radiation exposure. Even if you normally do no radiation work, you are still required to tell your supervisor, so that you won't be put in a radiation job while you are pregnant.
Telling your supervisor of your pregnancy is a legal requirement.

"Are you serious? How the hell do I know if I'm the same penguin whom you mated with last year?"

SUMMARY

Radiation produces damage by breaking up the body's molecules. The S.I. units of radiation dose are:

(a) absorbed dose D is measured in grays (Gy) —— it is based on energy deposition;

(b) equivalent dose H is measured in sieverts (Sv) —— it is based on the biological effects of absorbed dose D.

Quality factors (Q) are used to convert from 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.

Somatic effects are those experienced by the exposed individual, whereas hereditary effects do not become apparent until subsequent generations are born. The risk of serious hereditary ill-health as a result of radiation exposure is highest in the first two generations. The risk for all generations is estimated at about 1% per 1000 mSv received by either parent before conception.

Long-term somatic effects of radiation exposure are cancers and cataracts. For Radiation Workers, the risk of fatal cancer is 4% per 1000 mSv. Dose limits are based on the assumption that the results of high doses received in a short period of time can be used to predict the results of small doses received over a long period of time by using a DDREF (Dose and Dose Rate Effectiveness Factor) equal to 2. Most experts believe that this is a cautious approach.

Short-term somatic effects are caused by acute high exposures. Acute doses below 250 mGy are unlikely to have any observable effects. Acute doses of about 3 to 5 Gy have a 50% chance of killing you some weeks after the exposure, if you receive no medical treatment.

Radiation injury is treated by conserving and augmenting the blood constituents and by assisting the body's anti-bacterial mechanisms. Localized doses cause much less damage than whole-body doses of the same size.

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?

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?

6. Calculate the total equivalent dose to tissue from 3 mGy of gamma radiation, and 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. What is the chance of contracting a fatal cancer as the result of receiving an acute gamma radiation dose of 1 Gy? And after 10 Gy?

9. 4.2 joules of energy are needed to heat 1 g of water by 1 °C. 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?

10. Following a radiation accident the dosimeters worn by each of two individuals are analyzed and indicate whole-body doses of 2500 and 9000 mGy respectively.
    Outline the short-term and long-term effects that can be expected from each of these acute doses.

11. To get a perspective on how you view the risks from radiation exposure, let me ask you this question:
    If you had to choose between losing a thumb (relatively painlessly) or receiving an acute whole-body dose of gamma radiation, what is the highest dose you would accept instead of the loss of the thumb?

    What would your answer be for the loss of a hand?

    And how much is an "arm and a leg" worth to you?

"I was hoping we'd have someone new this year."