CHAPTER 4

BIOLOGICAL EFFECTS OF RADIATION

INTRODUCTION

To be able to drive a car, you don't need to know how its guts work. In the same way, to protect yourself from radiation exposure, you don't need to know what radiation does to your body. Still, most people like to know, so this chapter contains a lot of "nice to know" but little "need to know" information. You do need to know the things listed in the Summary at the end of this chapter.

We'll discuss how the damage produced by ionising radiation in biological molecules affects the body cells. Then we'll use this to try to explain the biological effects of radiation on people.

We can group the biological effects of radiation on people into **somatic***) and **hereditary** effects.

SOMATIC EFFECTS are those suffered by the exposed person, whereas HEREDITARY EFFECTS don't appear until later generations are born.

We'll look at 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 specialised functional unit, it is called an **organ**.

Body cells come in two types – germ cells (spermatozoa and ova) in the reproductive system) and somatic cells everywhere else. Each cell contains a complete set of chromosomes; these are thread-like structures consisting of DNA. We met DNA on page 72, where we said that DNA carries the blueprints for life in humans.

In a human, the somatic cells contain twenty-three pairs of chromosomes. (This number varies with different species of animals.) The sperm cells in males and egg cells in females (both are called **germ cells**) contain half the usual number of chromosomes. In humans, these germ cells contain 23 single chromosomes.

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*) From the Greek *soma*, meaning body

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. These cells will grow and divide again into a total of four, then eight and so on. Billions of these cell divisions take place during the formation of the new individual. This process is illustrated in Fig. 4.1. Your parents probably told you all this when you were twelve.

Each human being consists of about seven billion cells. So it's a good thing that the cells grow before dividing, otherwise we'd all be about one thousands of an inch tall, although perfectly formed! Be tough to get jeans that fit, though.

Within a few hours of conception some of the cells have already decided what they are going to be when they grow up. Some will form the brain and spinal cord, others will become kidneys, bowel, skin, etc.

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.

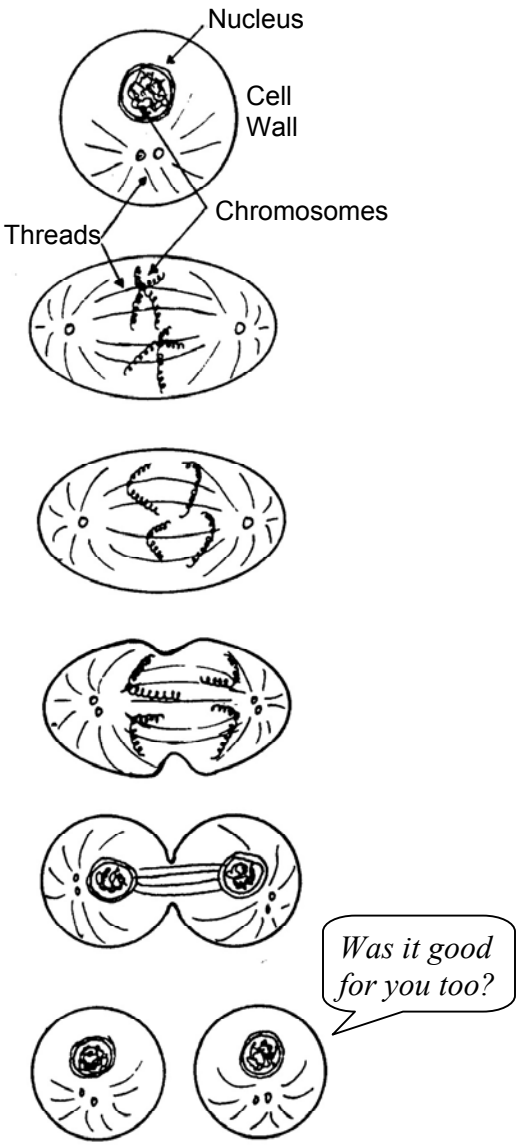

Fig. 4.1. Cell Division

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 some of us evolved to our present state.

A large number of agents have mutagenic properties (*able to produce mutations*) — 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 that 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 ionising 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.

HEREDITARY EFFECTS IN HUMANS

The descendants of those Japanese who were exposed during the nuclear bombing of Nagasaki and Hiroshima in 1945 are the largest group of irradiated humans available for study. 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.

EXPERIMENTS WITH MICE

Without firm data for humans, the best we can do is to measure the rates at which radiation causes genetic mutations in laboratory animals. Such experiments have been done (mostly in the USA and in the UK) 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 less if some time elapsed between irradiation and conception;
5. dose spread over a period of time produced a smaller effect than if delivered all at once.

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*) Why didn’t they use lawyers? I believe at that time there weren’t enough of them.

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, serious genetic mutations do not reproduce themselves well, and so 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 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% per Sv.

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 obviously has no hereditary consequences, because there are no more offspring. It is assumed that the risk is proportional to the dose; i.e., if the parents receive only 1 mSv instead of 1 Sv, the risk of producing offspring with serious hereditary ill-health in the next and all future generations is only 0.001%.

The risk for occupational exposure is only **0.6%/Sv** rather than 1%/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.

Using the best data available, exposure of the gonads to natural background radiation is thought to contribute about 0.3% of the normal incidence of serious genetic disorders in Canada.

LONG-TERM SOMATIC EFFECTS

Somatic cells are all 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 ionising radiation. The effects of the damage from ionising radiation can be **short-term** or **long-term** depending on the means and severity of the exposure. The most important long-term effect of radiation exposure is an increased chance of getting cancer. We'll deal with this long-term effect first.

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. 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. Not many people know that.

The types of cancer caused by radiation are the same as those that occur naturally. The risk of an increased incidence of cancers per unit of radiation dose can be estimated by carefully following up groups of people who were exposed to relatively high doses of radiation many years ago. These groups include:

- early radium dial painters, who swallowed radium during their work;
- patients treated with high doses of medical X-rays to cure a crippling arthritic disease of the spine;
- uranium miners who inhaled high concentrations of radon daughters in mine air when the hazards of this radiation were not understood; and
- the Japanese bomb survivors who were exposed to high doses of gamma radiation to the whole body in Hiroshima and Nagasaki.

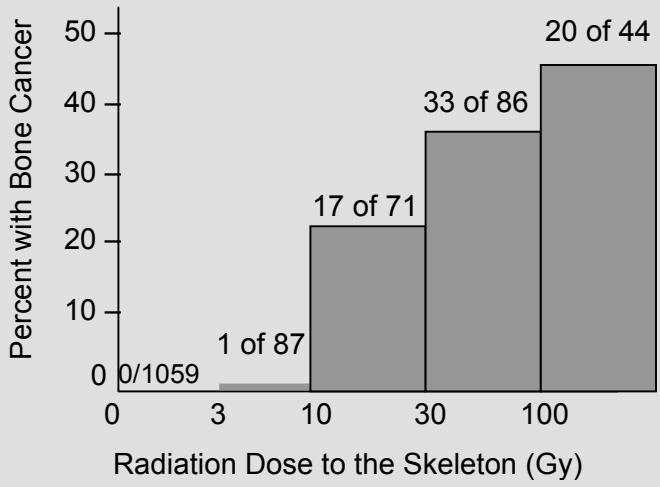

Fig. 4.2. Cancer Cases in Radium Dial Painters

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. 4.2 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.

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 painful stiffening of the joints in the backbone. Of the 6500 patients, 30 developed leukaemia compared with an expected incidence of 7 cases.

The most reliable data we have is from the atom bomb survivors in Japan. Dose estimates are available for a group of about 42,000 people of all ages and both sexes who were exposed in 1945 to a wide range of doses in a short time. There was also a control group of nearly equal size, which was too far away from the centre of the bomb explosions to receive any significant radiation dose. Follow-up of these persons from 1950 to 1985 has produced sufficient data to be statistically reliable.

TABLE 4.1. FOLLOW-UP OF BOMB SURVIVORS

Number exposed	41,719
Number not exposed	34,272
Total Deaths in both groups	28,737
Total cancer deaths In exposed group	3,435
Extra cancer deaths in exposed group due to radiation exposure in 1945	340

An international effort to reassess the radiation doses received by each of the bomb survivors resulted in improved risk estimates in 1986. It turns out that neutron doses were overestimated, and shielding effects of buildings were underestimated. Both of these factors meant that the doses received by the survivors were quite a bit lower than previously thought.

Of the 340 excess cancers, 126 were 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.

The Japanese study has several advantages over other studies, because the Japanese group contains both sexes and all ages, and because it was exposed to a wide range of doses, from trivial to fatal.

Excess cancers that are statistically significant can be found only at doses above 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.

THE DOSE RESPONSE CURVE

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 thought to be proportional to the dose. At higher dose rates, greater than 100 mGy/h, two or more ionising 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 will depend on the square of the dose, D^2, rather than just on D.

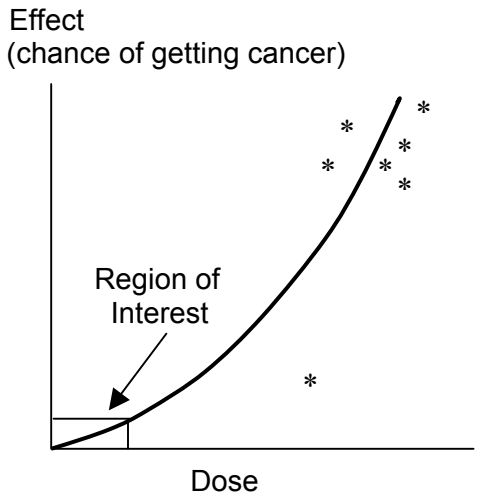

Fig. 4.3. Dose Response Curve

This relationship is shown in Fig. 4.3. 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. Animal studies yield similar curves.

The ICRP (a committee of international experts we'll meet in the next chapter) 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 when

1) absorbed doses are less than 0.2 Gy, and

2) 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 factor 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 ICRP's 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."*

The cancers we've been talking about are fatal cancers. Not all of them are. If you're still smoking, you really should quit, because unfortunately about 95% of all lung cancers are fatal. Breast cancers are 50%, thyroid cancers are 10%, and only 0.2% of skin cancers are fatal.

ICRP now says that

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

This means that if you work from age 20 to age 60 and get a dose of 10 mSv every year (this is a fairly large lifetime dose of 400 mSv), you will increase your fatal cancer risk by 1.6%, namely from 25% to 26.6%. If you average 5 mSv every year for 40 years, you'll increase your fatal cancer risk by 0.8% to 25.8%. Even so, I doubt that we'll have many people at Lepreau who will reach 200 mSv in their working lifetime. Most of them will have been promoted long before then to some desk job far away from the sharp end of radiation exposure. (By June 1999, the highest lifetime dose at Point Lepreau was 162 mSv.)

We assume 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 nobody else does either. 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 high **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/years.

If we abide by the dose limits that apply to us, we will never suffer any short-term somatic effects from high acute exposures. Still, most people are interested in what might happen for large exposures that might arise in radiation accidents. So I'll tell you. Let's look at the short-term somatic effects in five parts:

1. Effects of radiation on living cells.
2. Functions of the self-renewal tissues in the body.
3. Probable effects of high acute whole-body doses.
4. Lethal dose.
5. Treatment of radiation injury.

1. Effects of Radiation on the Cell

We have already seen that ionising radiation damages the molecules of 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.

Therefore, the tissues in our bodies most affected by an acute radiation dose are whose cells are most rapidly reproducing. These self-renewal tissues 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 said to be more **radiosensitive**. The self-renewal tissues are thus the most radiosensitive tissues in the body.

2. Function of the Self-Renewal Tissues

TABLE 4.2. FUNCTIONS OF THE SELF-RENEWAL TISSUES

Skin	Contains body fluids, protects underlying tissues, prevents bacterial invasion
Gonads	Procreation, recreation
Blood Components	
Red Blood Cells	Transport oxygen
White Blood Cells	Gobble up bacteria and germs
Antibodies	Destroy or immobilise foreign molecules and bacteria
Platelets	Assist in blood-clotting mechanism
GI Tract Lining	Secretes digestive enzymes, absorbs nourishment from food, prevents bacterial invasion

Table 4.2 shows that the most important tissues for survival are the blood-forming tissues and the GI tract lining. Some words of explanation:

Blood Components

In adults, red blood cells are manufactured only in the bone marrow located mainly in the central bones (ribs, sternum, vertebrae, and pelvic bones). During their lifetime, these red blood cells transport oxygen to all parts of the body, until, at the ripe old age of 3 months or so they become brittle and disintegrate. About 1% of the red blood cells is replenished every day.

80% of white blood cells are formed in the bone marrow. 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 that 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.

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

GI Tract Lining

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). The dividing cells are shed into the intestine, so that when they break down they will release their chemical content into the nutrient mixture to aid digestion of food.

3. Probable Effects of High Acute Whole-Body Doses

Table 4.3 opposite gives you the story. Generally speaking, very high doses of 100 Gy or so damage the central nervous system so badly that death may occur within a few hours or days.

At doses of 10 to 50 Gy to the whole body, the victim may escape this fate only to die from GI tract damage a week or two later.

Lower doses of around 5 Gy may avoid GI tract injury — or permit recovery from it — but still cause death after a month or two, mainly from damage to the red bone marrow. So the higher doses merely hasten the time of death.

The red bone marrow and the rest of the blood-forming system are one of the most radiosensitive parts of the body, and are affected by as little as 0.5 to 1 Gy. Fortunately, they also have a remarkable capacity for recovery — if the dose doesn't swamp them, they can recover completely. If only part of the body is irradiated, enough bone marrow will normally survive to replace what is damaged.

TABLE 4.3. PROBABLE EFFECTS OF ACUTE WHOLE-BODY GAMMA DOSES

Dose (Gy)	*Effect*
100	Death in hours or days from central nervous system damage
10 - 50	Death through GI tract damage in one or two weeks
3 - 6	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.
2 - 3	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.
1 - 2	Nausea and fatigue, possible vomiting. Reduction in certain blood cells with delayed recovery.
0.25 - 1	Slight blood changes with later recovery. Possible nausea. Serious delayed effects are possible but improbable.
0 - 0.25	No detectable clinical effects. Delayed effects may occur, but are highly unlikely.

4. 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 **L**ethal **D**ose 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.) We used to think that the victim's chances of survival would be improved by giving him bone marrow transplants from a compatible donor, but at Chernobyl bone marrow transplants were of no help at all.

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. Table 4.4 describes the biological effects and their symptoms in the 4 to 6 Gy range, which is lethal to about half the people exposed to it.

TABLE 4.4. EFFECTS OF AN ACUTE DOSE OF 4 - 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.	

5. Treatment of Radiation Injury

Table 4.5 lists the methods used for the treatment of people who have received an acute whole-body exposure along with the reasons for their use.

TABLE 4.5. TREATMENT OF RADIATION INJURY

Treatment	*Reason*
Complete rest	Conserve blood constituents.
Strict environmental sterility	Reduce contact with bacteria.
Antibiotics	Aid body's bug-fighting equipment.
Blood transfusions	Restore blood constituents.
Intravenous feeding	Aid or replace normal digestive processes.

EFFECTS OF ACUTE 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 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 original shrink-wrap for the body. 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, a dead surface layer about 70 μm thick covers the skin. 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 takes much longer to heal, because the damage is much deeper than for burns.

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 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 blood count. The maximum depression, however, occurs only after a period of roughly 2-5 weeks. The depression of 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 seen 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 GI 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 1 Gy will cause temporary nausea, vomiting and diarrhoea.

Reproductive System

The germ cells of the testes and ovaries 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 is relatively resistant to radiation. The threshold for severe function damage to the normal adult

thyroid is about 25 to 30 Gy. But this relative resistance to radiation 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 γ 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. Patients receiving large doses to the brain or spinal cord during radiation therapy, will develop myelitis (inflammation of the spinal cord) 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 radiosensitive tissue of the human body 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:

1. the pre-implantation period lasting from fertilisation until implantation of the embryo into the uterine wall;
2. the phase of major organ formation, which extends in man (well, woman actually) until about the 8th week after ovulation;
3. the phase of foetal development, continuing on until birth.

Much of the information about effects of prenatal irradiation comes from observations of laboratory animals. 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.

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 extremely 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 organisation and scheduling. Nevertheless it has been introduced into most hospitals, and is clearly a very desirable step.

Due to the increased risk of radiation damage to the foetus, pregnant workers are subject to lower dose limits. Women who work with radioactive material are required to inform their supervisor, in writing, as soon as they learn of their pregnancy.

If you are pregnant and work at Point Lepreau, you have to tell the Senior Health Physicist as soon as you know. Working with radioactive materials will be permitted, but restrictions may be placed on jobs that have the potential for high radiation exposure. Measures will be taken to protect confidentiality, if requested. If the woman prefers not to work with radioactive material during pregnancy, attempts will be made to obtain alternative work assignments.

Going back to the Darwin awards first mentioned on page 84: although to win an award, the candidate has to either die from his injuries or be unable to reproduce, the site describes some events for which no award can be given. Here's one that was reported in *The Times* of London, UK, and that is vaguely pertinent to this chapter.

A thief who sneaked into a hospital was scarred for life when he tried to get a suntan. After evading security staff at Odstock Hospital in Salisbury, Wiltshire, and helping himself to doctors' paging devices, the thief spotted a vertical sun-bed. He walked into the unit and removed his clothes for a 45-minute tan.

However, the high-voltage UV machine at the hospital, which is renowned for its treatment of burns victims, has a maximum dosage of ten seconds. After lying on the bed for almost 300 times the recommended maximum time the man was covered in blisters.

Hours later, when the pain of the burns became unbearable, he went to Southampton General Hospital, 20 miles away in Hampshire. Staff became suspicious because he was wearing a doctor's coat. After tending his wounds they called the police. Southampton police said: "This man broke into Odstock and decided he fancied a quick suntan. Doctors say he is going to be scarred for life."

Last night police confirmed that a man was arrested for theft.

SUMMARY

Somatic effects are those experienced by the exposed individual, whereas hereditary effects do not become apparent until subsequent generations are born.

For the general population, 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 Nuclear Energy Workers, the risk of fatal cancer is 4% per 1000 mSv. This risk was estimated from data at high doses and high dose rates, and by then using a reduction factor of 2 to allow for the fact that the risk at low doses and low dose rates is less.

Acute exposures are those delivered in a short time, i.e., within a day. Chronic exposures are those delivered over a long period of time, i.e., weeks and months.

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. Localised doses cause much less damage than whole-body doses of the same size.

"I wish you'd called me earlier, Mrs. Oaten."

PROBLEMS

1. Explain what we mean by “somatic effects” and by “hereditary effects”.

2. Has there been any evidence of an increased mutation rate among children born after their parents had received high doses?

3. My lifetime dose is 33 mSv. What is the chance that I will die of a radiation-induced cancer?

4. What is the chance of someone contracting fatal cancer as a result of receiving an acute dose of 1 sievert of gamma radiation? And what about 10 Sv of gamma radiation?

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

6. 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?