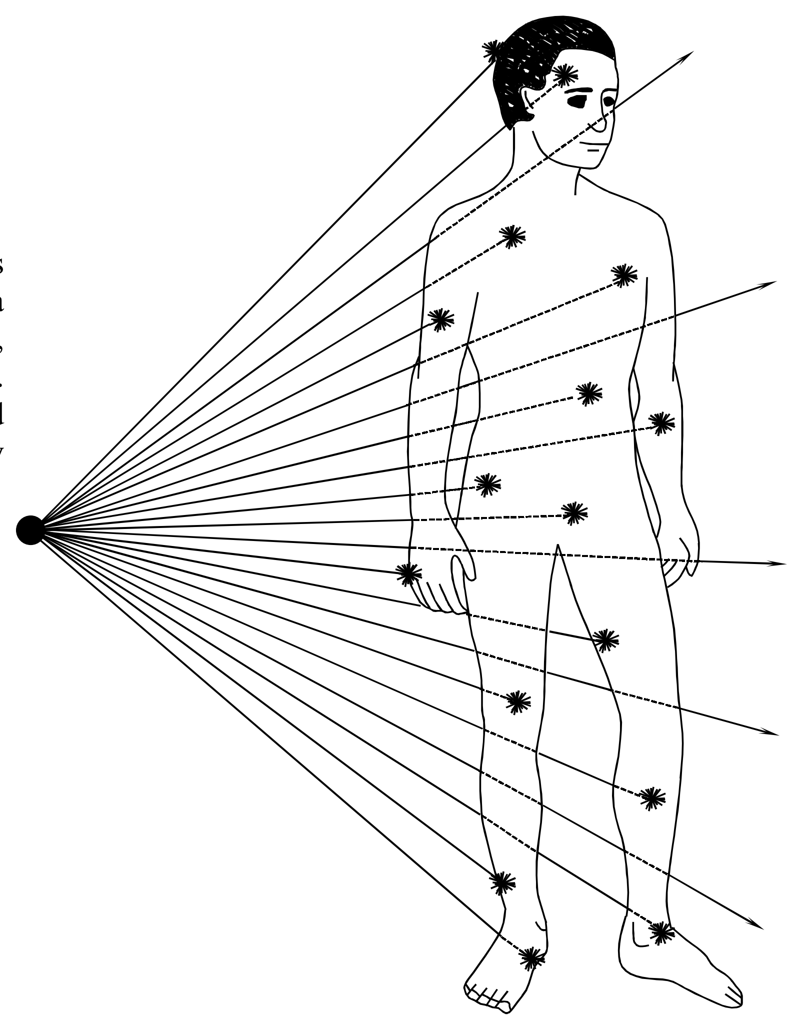
Biological Effects of Radiation

Whether the source of radiation is natural or man-made, whether it is a small dose of radiation or a large dose, there will be some biological effects. This chapter summarizes the short and long term consequences which may result from exposure to radiation.



Radiation Causes Ionizations of:

ATOMS

which may affect

MOLECULES

which may affect

CELLS

which may affect

TISSUES

which may affect

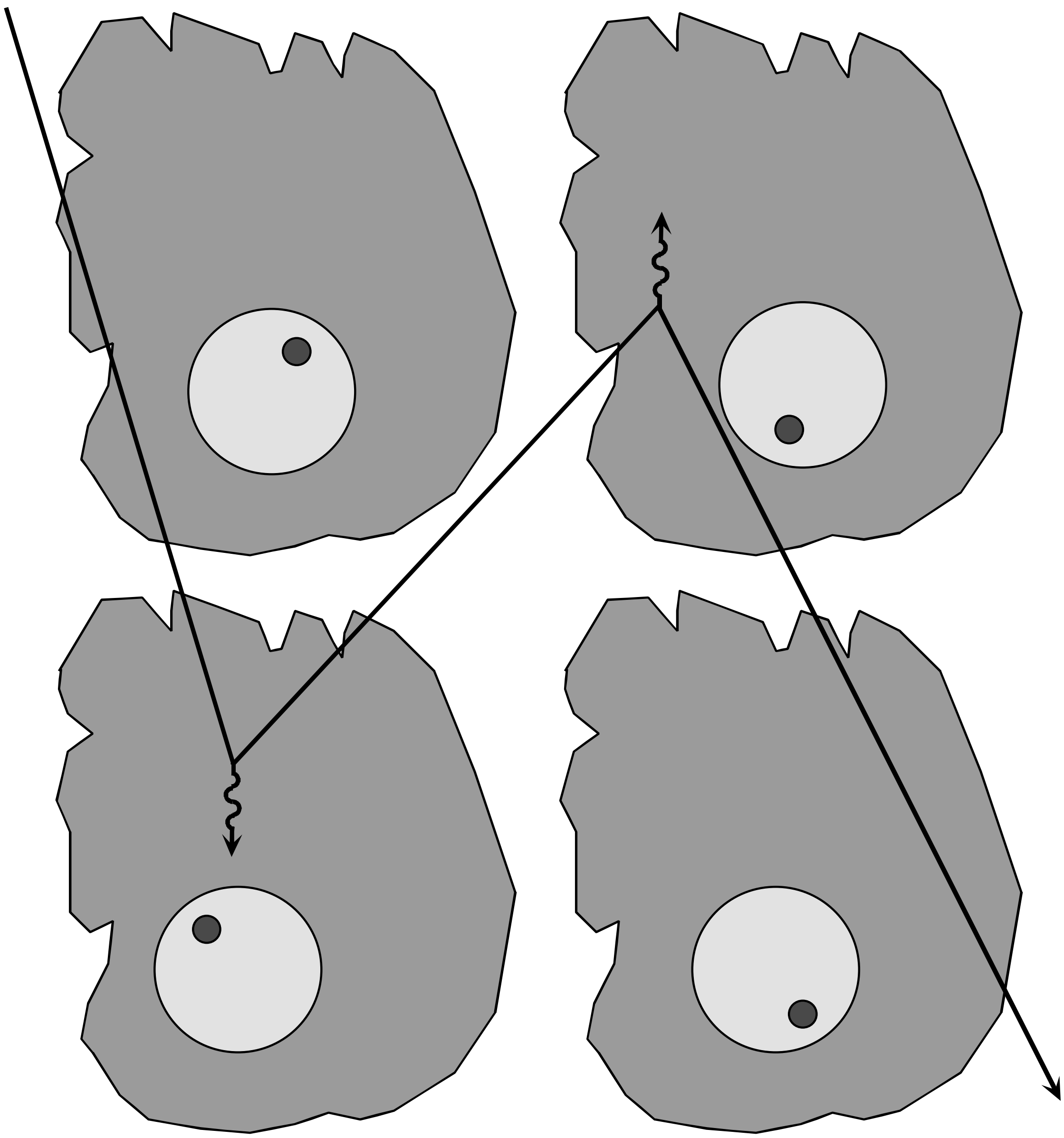
ORGANS

which may affect

THE WHOLE BODY

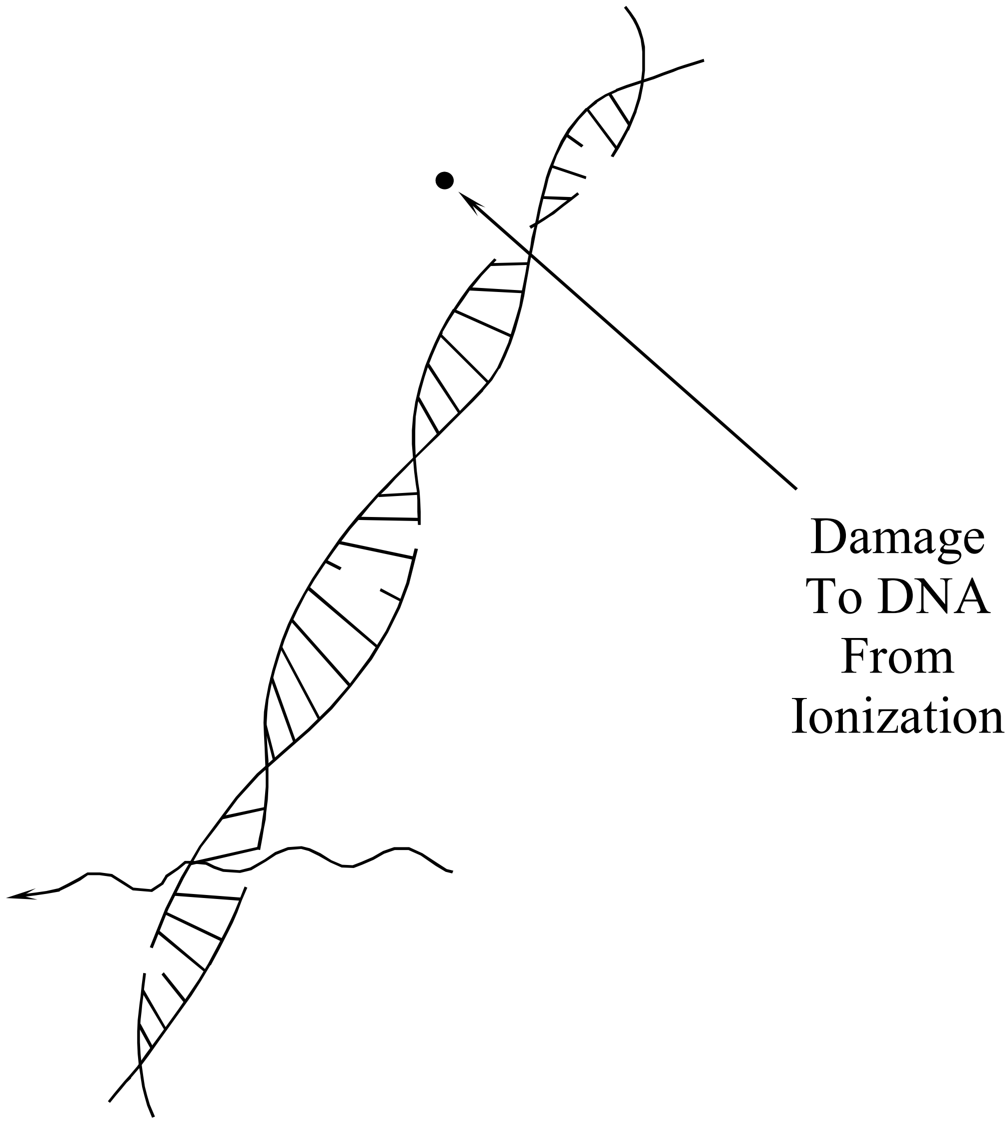
Although we tend to think of biological effects in terms of the effect of radiation on living cells, in actuality, ionizing radiation, by definition, interacts only with atoms by a process called ionization. Thus, all biological damage effects begin with the consequence of radiation interactions with the atoms forming the cells. As a result, radiation effects on humans proceed from the lowest to the highest levels as noted in the above list.

CELLULAR DAMAGE



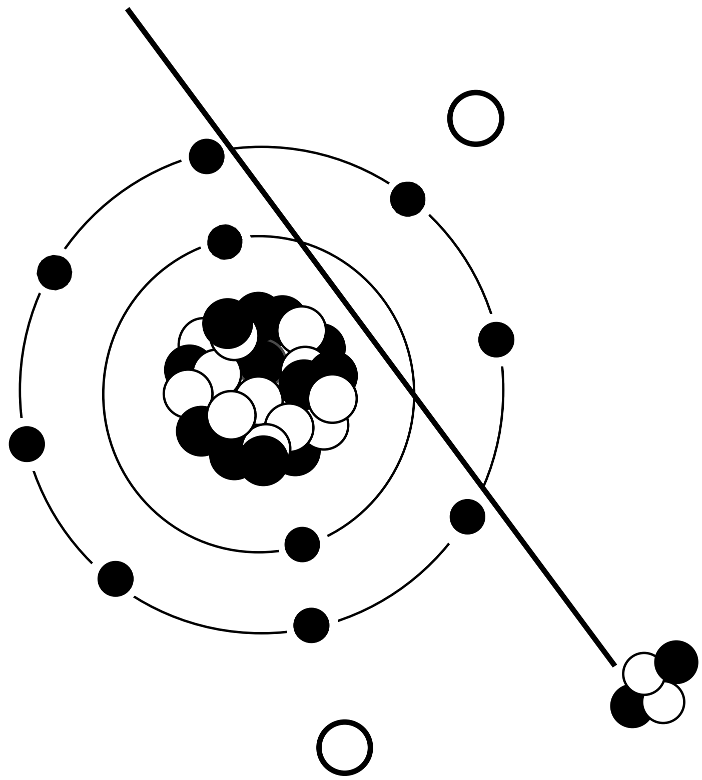
Even though all subsequent biological effects can be traced back to the interaction of radiation with atoms, there are two mechanisms by which radiation ultimately affects cells. These two mechanisms are commonly called direct and indirect effects.

Direct Effect



If radiation interacts with the atoms of the DNA molecule, or some other cellular component critical to the survival of the cell, it is referred to as a direct effect. Such an interaction may affect the ability of the cell to reproduce and, thus, survive. If enough atoms are affected such that the chromosomes do not replicate properly, or if there is significant alteration in the information carried by the DNA molecule, then the cell may be destroyed by "direct" interference with its life-sustaining system.

Indirect Effect



Radiolytic Decomposition of Water in a Cell

If a cell is exposed to radiation, the probability of the radiation interacting with the DNA molecule is very small since these critical components make up such a small part of the cell. However, each cell, just as is the case for the human body, is mostly water. Therefore, there is a much higher probability of radiation interacting with the water that makes up most of the cell's volume.

When radiation interacts with water, it may break the bonds that hold the water molecule together, producing fragments such as hydrogen (H) and hydroxyls (OH). These fragments may recombine or may interact with other fragments or ions to form compounds, such as water, which would not harm the cell. However, they could combine to form toxic substances, such as hydrogen peroxide (H_2O_2), which can contribute to the destruction of the cell.

Cellular Sensitivity to Radiation

(from most sensitive to least sensitive)

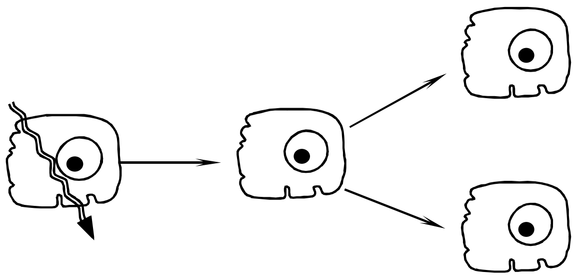
Lymphocytes and Blood Forming Cells

Reproductive and Gastrointestinal (GI) Cells

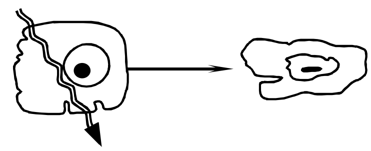
Nerve and Muscle Cells

Not all living cells are equally sensitive to radiation. Those cells which are actively reproducing are more sensitive than those which are not. This is because dividing cells require correct DNA information in order for the cell's offspring to survive. A direct interaction of radiation with an active cell could result in the death or mutation of the cell, whereas a direct interaction with the DNA of a dormant cell would have less of an effect.

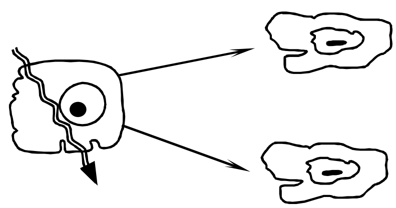
As a result, living cells can be classified according to their rate of reproduction, which also indicates their relative sensitivity to radiation. This means that different cell systems have different sensitivities. Lymphocytes (white blood cells) and cells which produce blood are constantly regenerating, and are, therefore, the most sensitive. Reproductive and gastrointestinal cells are not regenerating as quickly and are less sensitive. The nerve and muscle cells are the slowest to regenerate and are the least sensitive cells.



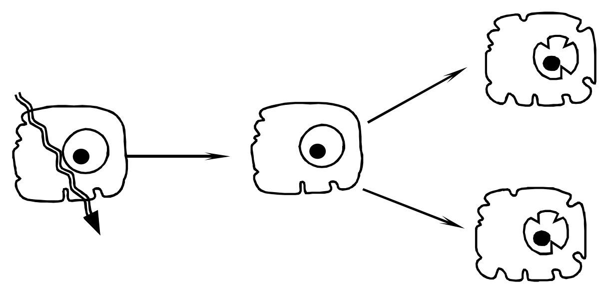
NORMAL REPAIR OF DAMAGE



CELL DIES FROM DAMAGE



DAUGHTER CELLS DIE



NO REPAIR OR NON-IDENTICAL REPAIR BEFORE REPRODUCTION

Cells, like the human body, have a tremendous ability to repair damage. As a result, not all radiation effects are irreversible. In many instances, the cells are able to completely repair any damage and function normally.

If the damage is severe enough, the affected cell dies. In some instances, the cell is damaged but is still able to reproduce. The daughter cells, however, may be lacking in some critical life-sustaining component, and they die.

The other possible result of radiation exposure is that the cell is affected in such a way that it does not die but is simply mutated. The mutated cell reproduces and thus perpetuates the mutation. This could be the beginning of a malignant tumor.

Organ Sensitivity

(from most sensitive to least sensitive)

Blood Forming Organs

Reproductive and Gastrointestinal Tract Organs

Skin

Muscle and Brain

The sensitivity of the various organs of the human body correlate with the relative sensitivity of the cells from which they are composed. For example, since the blood forming cells were one of the most sensitive cells due to their rapid regeneration rate, the blood forming organs are one of the most sensitive organs to radiation. Muscle and nerve cells were relatively insensitive to radiation, and therefore, so are the muscles and the brain.

Sensitivity

Rate of Reproduction

Oxygen Supply

The rate of reproduction of the cells forming an organ system is not the only criterion determining overall sensitivity. The relative importance of the organ system to the well being of the body is also important.

One example of a very sensitive cell system is a malignant tumor. The outer layer of cells reproduces rapidly, and also has a good supply of blood and oxygen. Cells are most sensitive when they are reproducing, and the presence of oxygen increases sensitivity to radiation. Anoxic cells (cells with insufficient oxygen) tend to be inactive, such as the cells located in the interior of a tumor.

As the tumor is exposed to radiation, the outer layer of rapidly dividing cells is destroyed, causing it to "shrink" in size. If the tumor is given a massive dose to destroy it completely, the patient might die as well. Instead, the tumor is given a small dose each day, which gives the healthy tissue a chance to recover from any damage while gradually shrinking the highly sensitive tumor.

Another cell system that is composed of rapidly dividing cells with a good blood supply and lots of oxygen is the developing embryo. Therefore, the sensitivity of the developing embryo to radiation exposure is similar to that of the tumor, however, the consequences are dramatically different.

Whole Body Sensitivity Factors

Total Dose
Type of Cell
Type of Radiation
Age of Individual
Stage of Cell Division
Part of Body Exposed
General State of Health
Tissue Volume Exposed
Time Interval over which Dose is Received

Whole body sensitivity depends upon the most sensitive organs which, in turn, depend upon the most sensitive cells. As noted previously, the most sensitive organs are the blood forming organs and the gastrointestinal system.

The biological effects on the whole body from exposure to radiation will depend upon several factors. Some of these are listed above. For example, a person, already susceptible to infection, who receives a large dose of radiation may be affected by the radiation more than a healthy person.

Radiation Effects

High Doses (Acute)

Low Doses (Chronic)

Biological effects of radiation are typically divided into two categories. The first category consists of exposure to high doses of radiation over short periods of time producing acute or short term effects. The second category represents exposure to low doses of radiation over an extended period of time producing chronic or long term effects.

High doses tend to kill cells, while low doses tend to damage or change them. High doses can kill so many cells that tissues and organs are damaged. This in turn may cause a rapid whole body response often called the Acute Radiation Syndrome (ARS). High dose effects are discussed on pages 6-12 to 6-16.

Low doses spread out over long periods of time don't cause an immediate problem to any body organ. The effects of low doses of radiation occur at the level of the cell, and the results may not be observed for many years. Low dose effects are discussed on pages 6-17 to 6-23.

Occupation High Dose Exposures

Chernobyl
Irradiators
Inadvertent Criticalities

Non-Occupational High Dose Exposures

Chernobyl (firefighters)
Nagasaki and Hiroshima
Therapy source in Goiania, Brazil

Although we tend to associate high doses of radiation with catastrophic events such as nuclear weapons explosions, there have been documented cases of individuals dying from exposure to high doses of radiation resulting from workplace accidents and other tragic events.

Some examples of deaths which have occurred as a result of occupational (worker related) accidents are:

Inadvertent criticality (too much fissionable material in the right shape at the wrong time)
Irradiator (accidental exposure to sterilization sources, which can be more than 10 million curies)
Chernobyl (plant workers)

An example of a nonoccupational accident occurred in 1987 in Goiania, Brazil. An abandoned medical therapy source (cesium) was found and cut open by people who did not know what it was. This resulted in the deaths of several members of the public and the spread of radioactive contamination over a large area.

A recent inadvertent criticality event occurred in a fuel processing plant in Japan.

High Dose Effects

Dose (Rad)	Effect Observed
15 - 25	Blood count changes in a group of people
50	Blood count changes in an individual
100	Vomiting (threshold)
150	Death (threshold)
320 - 360	LD 50/60 with minimal care
480 - 540	LD 50/60 with supportive medical care
1,100	LD 50/60 with intensive medical care (bone marrow transplant)

Every acute exposure will not result in death. If a group of people is exposed to a whole body penetrating radiation dose, the above effects might be observed. The information for this table was extracted from NCRP Report No. 98, *Guidance on Radiation Received in Space Activities,* 1989.

In the above table, the threshold values are the doses at which the effect is first observed in the most sensitive of the individuals exposed. The LD 50/60 is the lethal dose at which 50% of those exposed to that dose will die within 60 days.

It is sometimes difficult to understand why some people die while others survive after being exposed to the same radiation dose. The main reasons are the health of the individuals at the time of the exposure and their ability to combat the incidental effects of radiation exposure, such as the increased susceptibility to infections.

Other High Dose Effects

Skin Burns
Hair Loss
Sterility
Cataracts

Besides death, there are several other possible effects of a high radiation dose.

Effects on the skin include erythema (reddening like sunburn), dry desquamation (peeling), and moist desquamation (blistering). Skin effects are more likely to occur with exposure to low energy gamma, X-ray, or beta radiation. Most of the energy of the radiation is deposited in the skin surface. The dose required for erythema to occur is relatively high, in excess of 300 rad. Blistering requires a dose in excess of 1,200 rad.

Hair loss, also called epilation, is similar to skin effects and can occur after acute doses of about 500 rad.

Sterility can be temporary or permanent in males, depending upon the dose. In females, it is usually permanent, but it requires a higher dose. To produce permanent sterility, a dose in excess of 400 rad is required to the reproductive organs.

Cataracts (a clouding of the lens of the eye) appear to have a threshold of about 200 rad. Neutrons are especially effective in producing cataracts, because the eye has a high water content, which is particularly effective in stopping neutrons.

Acute Radiation Syndrome (ARS)

Hematopoietic
Gastrointestinal
Central Nervous System

If enough important tissues and organs are damaged, one of the Acute Radiation Syndromes could result.

The initial signs and symptoms of the acute radiation syndrome are nausea, vomiting, fatigue, and loss of appetite. Below about 150 rad, these symptoms, which are no different from those produced by a common viral infection, may be the only outward indication of radiation exposure.

As the dose increases above 150 rad, one of the three radiation syndromes begins to manifest itself, depending upon the level of the dose. These syndromes are:

Syndrome	Organs Affected	Sensitivity
Hematopoietic	Blood forming organs	Most sensitive
Gastrointestinal	Gastrointestinal system	Very sensitive
Central Nervous System	Brain and muscles	Least sensitive

Summary of Biological Response to High Doses of Radiation

< 5 rad	-	No immediate observable effects
~ 5 rad to 50 rad	-	Slight blood changes may be detected by medical evaluations
~ 50 rad to 150 rad	-	Slight blood changes will be noted and symptoms of nausea, fatigue, vomiting, etc. likely
~ 150 rad to 1,100 rad	-	Severe blood changes will be noted and symptoms appear immediately. Approximately 2 weeks later, some of those exposed may die. At about 300 - 500 rad, up to one half of the people exposed will die within 60 days without intensive medical attention. Death is due to the destruction of the blood forming organs. Without white blood cells, infection is likely. At the lower end of the dose range, isolation, antibiotics, and transfusions may provide the bone marrow time to generate new blood cells and full recovery is possible. At the upper end of the dose range, a bone marrow transplant may be required to produce new blood cells.
~ 1,100 rad to 2,000 rad	-	The probability of death increases to 100% within one to two weeks. The initial symptoms appear immediately. A few days later, things get very bad, very quickly since the gastrointestinal system is destroyed. Once the GI system ceases to function, nothing can be done, and medical care is for comfort only.
> 2,000 rad	-	Death is a certainty. At doses above 5,000 rad, the central nervous system (brain and muscles) can no longer control the body functions, including breathing blood circulation. Everything happens very quickly. Nothing can be done, and medical care is for comfort only.

As noted, there is nothing that can be done if the dose is high enough to destroy the gastrointestinal or central nervous system. That is why bone marrow transplants don't always work.

In summary, radiation can affect cells. High doses of radiation affect many cells, which can result in tissue/organ damage, which ultimately yields one of the Acute Radiation Syndromes. Even normally radio-resistant cells, such as those in the brain, cannot withstand the cell killing capability of very high radiation doses. The next few pages will discuss the biological effects of low doses of radiation.

Annual Exposure to Average U.S. Citizen

Exposure Source	Average Annual Effective Dose Equivalent (millirems)
Natural:	
Radon	200
Other	100
Occupational	0.90
Nuclear Fuel Cycle	0.05
Consumer Products:	
Tobacco	?*
Other	5 - 13
Environmental Sources	0.06
Medical:	
Diagnostic X-rays	39
Nuclear Medicine	14
Approximate Total	360

* The whole body dose equivalent from tobacco products is difficult to determine. However, the dose to a portion of the lungs is estimated to be 16,000 millirems/year.

Everyone in the world is exposed continuously to radiation. The average radiation dose received by the United States population is given in the table above. This data was extracted from material contained in NCRP Report No. 93, *Ionizing Radiation Exposure of the Population of the United States*, 1987.

Radiation workers are far more likely to receive low doses of radiation spread out over a long period of time rather than an acuate dose as discussed previously. The principal effect of low doses of radiation (below about 10 rad) received over extended periods of time is non-lethal mutations, with the greatest concern being the induction of cancer.

The next few pages will discuss the biological effects of low doses of radiation.

Categories of Effects of Exposure to Low Doses of Radiation

Genetic
Somatic
In-Utero

There are three general categories of effects resulting from exposure to low doses of radiation. These are:

Genetic - The effect is suffered by the offspring of the individual exposed.

Somatic - The effect is primarily suffered by the individual exposed. Since cancer is the primary result, it is sometimes called the Carcinogenic Effect.

In-Utero - Some mistakenly consider this to be a genetic consequence of radiation exposure, because the effect, suffered by a developing embryo/fetus, is seen after birth. However, this is actually a special case of the somatic effect, since the embryo/fetus is the one exposed to the radiation.

Genetic Effects

Mutation of the reproductive cells passed on to the offspring of the exposed individual

The Genetic Effect involves the mutation of very specific cells, namely the sperm or egg cells. Mutations of these reproductive cells are passed to the offspring of the individual exposed.

Radiation is an example of a physical mutagenic agent. There are also many chemical agents as well as biological agents (such as viruses) that cause mutations.

One very important fact to remember is that radiation increases the spontaneous mutation rate, but does not produce any new mutations. Therefore, despite all of the hideous creatures supposedly produced by radiation in the science fiction literature and cinema, no such transformations have been observed in humans. One possible reason why genetic effects from low dose exposures have not been observed in human studies is that mutations in the reproductive cells may produce such significant changes in the fertilized egg that the result is a nonviable organism which is spontaneously resorbed or aborted during the earliest stages of fertilization.

Although not all mutations would be lethal or even harmful, it is prudent to assume that all mutations are bad, and thus, by USNRC regulation (10 CFR Part 20), radiation exposure SHALL be held to the absolute minimum or As Low As Reasonably Achievable (ALARA). This is particularly important since it is believed that risk is directly proportional to dose, without any threshold.

Somatic Effects

Effect is suffered by the individual exposed
Primary consequence is cancer

Somatic effects (carcinogenic) are, from an occupational risk perspective, the most significant since the individual exposed (usually the radiation worker) suffers the consequences (typically cancer). As noted in the USNRC Regulatory Guide 8.29, this is also the NRC's greatest concern.

Radiation is an example of a physical carcinogenic, while cigarettes are an example of a chemical cancer causing agent. Viruses are examples of biological carcinogenic agents.

Unlike genetic effects of radiation, radiation induced cancer is well documented. Many studies have been completed which directly link the induction of cancer and exposure to radiation. Some of the population studied and their associated cancers are:

Lung cancer - uranium miners
Bone cancer - radium dial painters
Thyroid cancer - therapy patients
Breast cancer - therapy patients
Skin cancer - radiologists
Leukemia - bomb survivors, in-utero exposures, radiologists, therapy patients

In-Utero Effects

Effects of radiation on embryo/fetus

Intrauterine Death
Growth Retardation
Developmental Abnormalities
Childhood Cancers

The in-utero effect involves the production of malformations in developing embryos.

Radiation is a physical teratogenic agent. There are many chemical agents (such as thalidomide) and many biological agents (such as the viruses which cause German measles) that can also produce malformations while the baby is still in the embryonic or fetal stage of development.

The effects from in-utero exposure can be considered a subset of the general category of somatic effects. The malformation produced do not indicate a genetic effect since it is the embryo that is exposed, not the reproductive cells of the parents.

The actual effects of exposure in-utero that will be observed will depend upon the stage of fetal development at the time of the exposure:

Weeks Post Conception	Effect
0 - 1 (preimplantation)	Intrauterine death
2 - 7 (organogenesis)	Developmental abnormalities/growth retardation/cancer
8 - 40 (fetal stage)	Same as above with lower risk plus possible functional abnormalities

Radiation Risk:

With any exposure to radiation, there is some risk

The approximate risks for the three principal effects of exposure to low levels of radiation are:

Effect	Excess Cases per 10,000 exposed per rad
Genetic	2 to 4
Somatic (cancer)	4 to 20
In-Utero (cancer)	4 to 12
In-Utero (all effects)	20 to 200

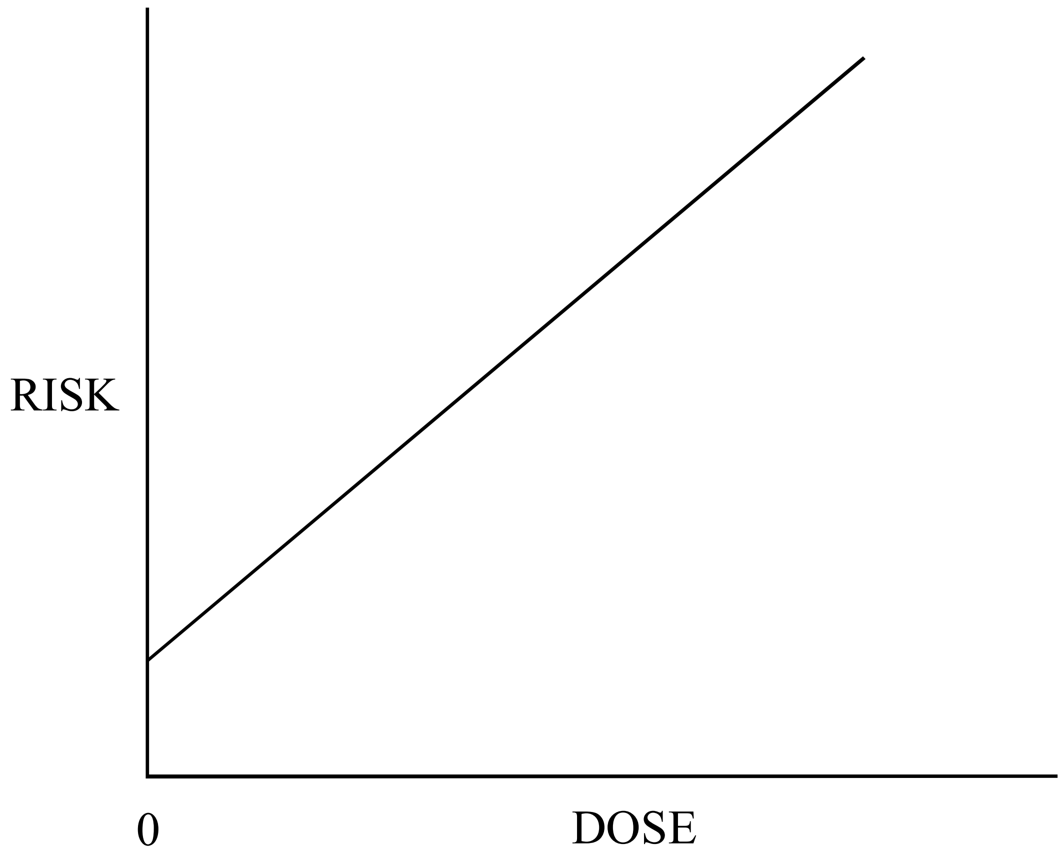
Genetic - Risks from 1 rem of radiation exposure to the reproductive organs are approximately 50 to 1,000 times less than the spontaneous risk for various anomalies.

Somatic - For radiation induced cancers, the risk estimate is small compared to the normal incidence of about 1 in 4 chances of developing any type of cancer. However, not all cancers are associated with exposure to radiation. The risk of dying from radiation induced cancer is about one half the risk of getting the cancer.

In-Utero - Spontaneous risks of fetal abnormalities are about 5 to 30 times greater than the risk of exposure to 1 rem of radiation. However, the risk of childhood cancer from exposure in-utero is about the same as the risk to adults exposed to radiation. By far, medical practice is the largest source of in-utero radiation exposure.

Because of overall in-utero sensitivity, the NRC, in 10 CFR Part 20, requires that for the declared pregnant woman, the radiation dose to the embryo/fetus be maintained less than or equal to 0.5 rem during the entire gestation period. This limit is one-tenth of the annual dose permitted to adult radiation workers. This limit applies to the worker who has voluntarily declared her pregnancy in writing. For the undeclared pregnant woman, the normal occupational limits for the adult worker apply (as well as ALARA).

Linear No-Threshold Risk Model



General consensus among experts is that some radiation risks are related to radiation dose by a linear, no-threshold model. This model is accepted by the NRC since it appears to be the most conservative.

LINEAR - An increase in dose results in a proportional increase in risk
NO-THRESHOLD - Any dose, no matter how small, produces some risk

The risk does not start at 0 because there is some risk of cancer, even with no occupational exposure. The slope of the line just means that a person that receives 5 rems in a year incurs 10 times as much risk as a person that receives 0.5 rems in a year.

Exposure to radiation is not a guarantee of harm. However, because of the liner, no-threshold model, more exposure means more risk, and there is no dose of radiation so small that it will not have some effect.