Theme 17. Ionizing radiation: diagnosis and treatment applications; methods of their impact protection and prevention on human body

Problem
Ionizing radiation: How to protect yourself

Attendance prerequisite
Note! Answer in writing to perform

1. Define or explain: nuclides, radioactivity, radiation types

References

№	Author(s)	Name of the source (textbook, manual, monograph, etc)	City, Publishing house	Year of edition, vol., issue	Number of pages
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4.	N. V. Pronina	Medical Physics The First Module Lectures	Simferopol	2006	68
5.	Douglas C. Giancoli	Physics Principles with Applications	Prentice Hall, INC. Englewood Cliffs, New Jersey		
6.	Martin Hollins	Medical Physics	Tomas Nelson & Sons	1992	222
7.	I. Tarjan	An Introduction to Physics with Medical Orientation	Akademiai Kiado, Budapest	1987	425
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Introduction

Passage of radiation through matter. Ionizing radiation includes α, β, γ and X rays, as well as protons, neutrons, and other particles. Charged particles (α-, β-particles and protons) cause ionization because of the electric force. Passing through a material they can attract or repel electrons strongly enough to remove them from the atoms of the material. The α- and β-rays emitted by radioactive substances have energies much higher than energies required for ionization of atoms and molecules, therefore a single α-, or β-particle can cause thousands of ionizations. Neutral particles also give rise to ionization. X-ray and γ-ray photons can ionize atoms knocking out electrons by means of the photoelectric and Compton effects. If a γ-ray has sufficient energy (greater than 1.02 MeV), it can undergo pair production: an electron and a positron are produced. The charged particles produced in all three of these processes themselves can go on to produce further ionization. Neutrons interact with matter mainly by collisions with nuclei breaking them apart. It leads to the alteration of molecules.

Radiation passing through matter can cause considerable damage, particularly to biological tissue. Ions or radicals are produced which are highly reactive and take part in chemical reactions that interfere with the normal operation of cells. For example free radicals H^+ and OH^- are produced from water, which is the major constituent of cells: these free radicals are very reactive and cause chemical reactions that may break chemical bonds in vital molecules such as proteins.

All forms of radiation can ionize atoms by knocking out electrons. If these are bonding electrons, the molecule may break apart; or its structure may be altered so that it does not perform its normal function or performs a harmful function. In the case of proteins, the loss of one molecule is not serious if there are other copies of that particular one in the cell, and additional ones can be made from its gene. However, large doses of radiation may damage too many molecules so that new copies cannot be made quickly enough, and the cell dies. Damage to the DNA is more serious, since a cell may have only one copy. Each alteration in the DNA affects a gene and can alter the molecule it codes for, and the cell may die. The death of a single cell is not normally a problem, since the body can replace it with a new one. (There are exceptions, such as neurons, which are ***not*** replaceable.) But if many cells die, the organism may not be able to recover. On the other hand, a cell may survive but be defective. It may go on dividing and produce many more defective cells. Thus radiation can cause cancer — the rapid production of defective cells.

Radiation damage to biological organisms is often separated into categories according to its location in the body: "somatic" and "genetic."

Somatic damage refers to that in any part of the body except the reproductive organs. Somatic damage can seriously affect that particular organism, causing cancer and at high doses radiation sickness (characterized by nausea, fatigue, loss of body hair, and other symptoms) or even death.

Genetic damage refers to damage to the reproductive apparatus and so affects an individual's offspring. Damage to the genes results in mutation, the majority of which are harmful; and mutations, if they occur in the reproductive organs, are transmitted to future generations. Radiation, including that from diagnostic use of X-rays, is commonplace, and its effect on the future of the human race is a cause of great concern.

We are constantly exposed to low-level radiation from natural sources: cosmic rays, natural radioactivity in rocks and soil, and naturally radioactive isotopes occurring in our food (${}_{19}K^{40}$). The recommended upper limit of allowed radiation for an individual in the general populace at about 0.5 rem per year, exclusive of natural sources.

People who work around radiation - in hospitals, in power plants, in research, are subjected to much higher doses than 0.5 rem/year. Large doses of radiation can cause reddening of the skin, drop in white-blood-cell count, nausea, fatigue, and loss of body hair (radiation sickness). Large doses can be fatal. A short dose of 1000 rem is nearly always fatal. A 400-rem dose in a short period of time is fatal in 50 percent of the cases. However, the body possesses remarkable repair processes so that a 400-rem dose spread over several weeks is not usually fatal. It will, nonetheless, cause considerable damage to the body.

Biological Effects of Radiation. The increased use of radioisotopes has led to increased concerns over the effects of these materials on biological systems (such as humans). All radioactive nuclides emit high-energy particles or electromagnetic waves. When this radiation encounters living cells, it can cause heating, break chemical bonds, or ionize molecules. The most serious biological damage results when these radioactive emissions fragment or ionize molecules. For example, alpha and beta particles emitted from nuclear decay reactions possess much higher energies than ordinary chemical bond energies. When these particles strike and penetrate matter, they produce ions and molecular fragments that are extremely reactive. The damage this does to biomolecules in living organisms can cause serious malfunctions in normal cell processes, taxing the organism’s repair mechanisms and possibly causing illness or even death. Radiation can harm biological systems by damaging the DNA of cells. If this damage is not properly repaired, the cells may divide in an uncontrolled manner and cause cancer (fig. 1).

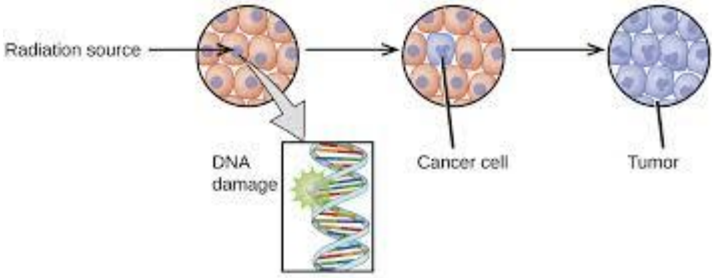

Figure 1

Ionizing and Nonionizing Radiation. There is a large difference in the magnitude of the biological effects of **nonionizing radiation**, for example, light and microwaves, and **ionizing radiation**, emissions energetic enough to knock electrons out of molecules, for example, α- and β-particles, γ-rays, X-rays, and high-energy ultraviolet radiation. Lower frequency, lower-energy electromagnetic radiation is nonionizing, and higher frequency, higher-energy electromagnetic radiation is ionizing (fig. 2).

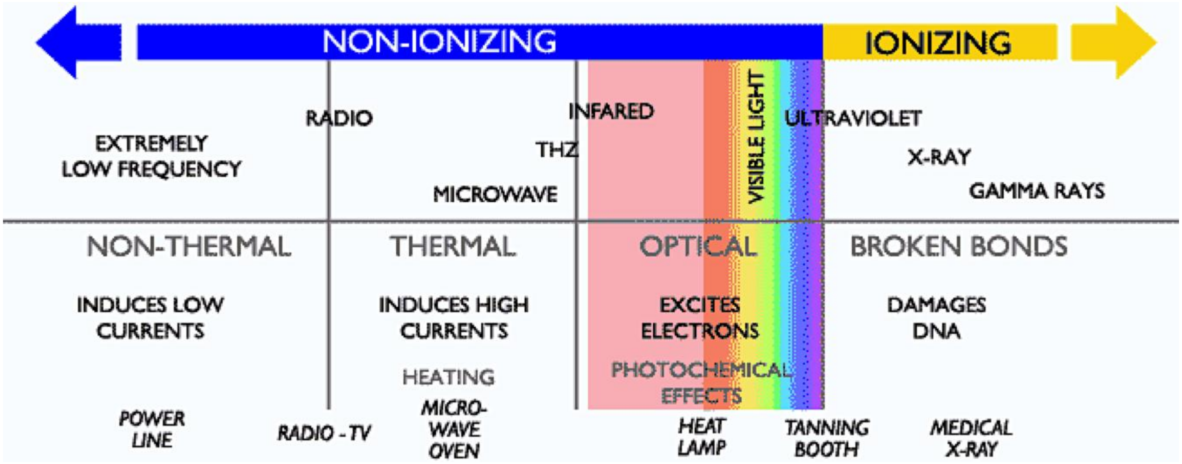

Figure 2

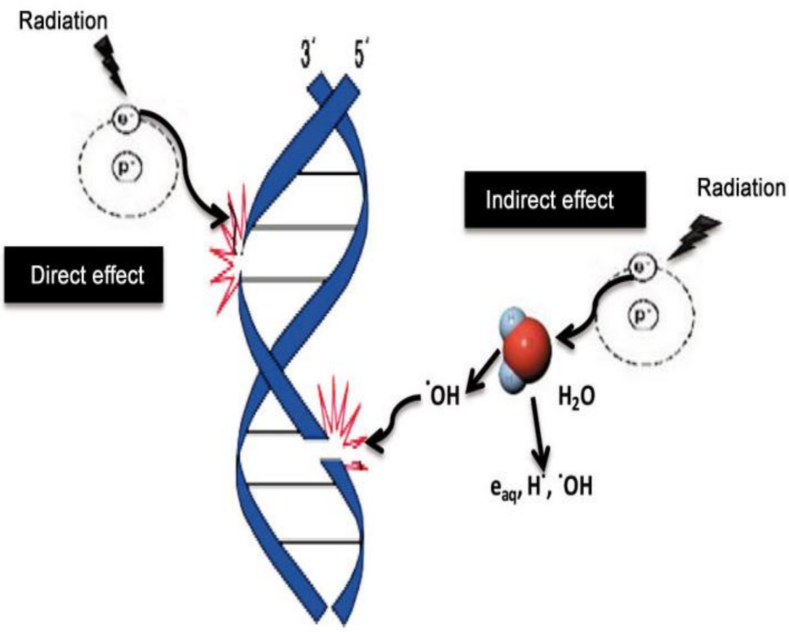

Figure 3

Energy absorbed from nonionizing radiation speeds up the movement of atoms and molecules, which is equivalent to heating the sample. Although biological systems are sensitive to a large amount of nonionizing radiation is necessary before dangerous levels are reached. Ionizing radiation, however, may cause much more severe damage by breaking bonds or removing electrons in biological molecules, disrupting their structure and function. The damage can also be done indirectly, by first ionizing H_2O that is the most abundant molecule in living organisms, which forms a H_2O^+-ion that reacts with water, forming a hydronium ion and a hydroxyl radical:

$$H_2O + \text{radiation} \xrightarrow{e^-} H_2O^+ + H_2O \Rightarrow H_3O^+ + OH^-$$

Because the hydroxyl radical has an unpaired electron, it is highly reactive. This is true of any substance with unpaired electrons, known as a free radical. This hydroxyl radical can react with all kinds of biological molecules - DNA, proteins, enzymes, and so on, causing damage to the molecules and disrupting physiological processes. Examples of direct and indirect damage are shown in figure 3. A damage stages are illustrated in figure 4.

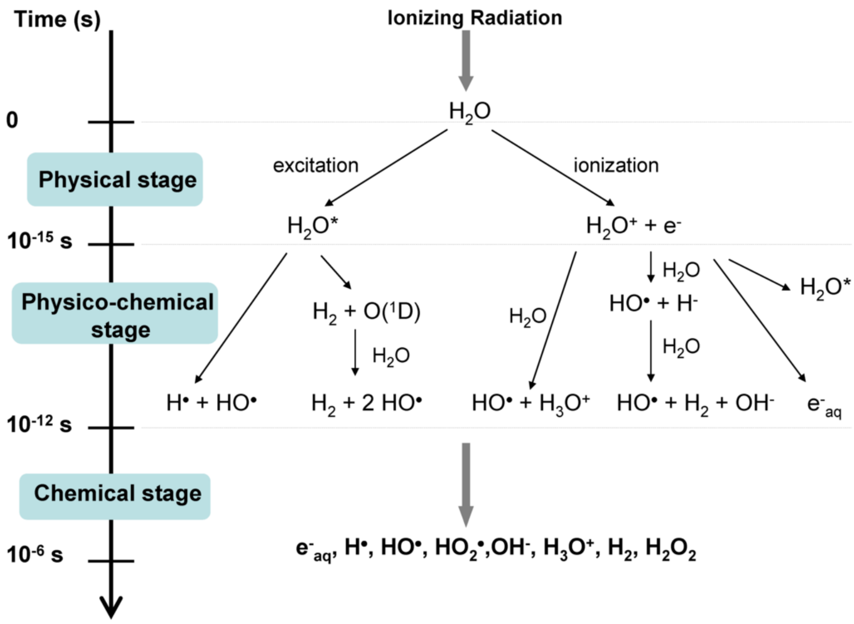

Figure 4

Biological Effects of Exposure to Radiation. Radiation can harm either the whole body - somatic damage, or eggs and sperm - genetic damage. Its effects are more pronounced in cells that reproduce rapidly, such as the stomach lining, hair follicles, bone marrow, and embryos. This is why patients undergoing radiation therapy often feel nauseous or sick to their stomach, lose hair, have bone aches, and so on, and why particular care must be taken when undergoing radiation therapy during pregnancy.

Different types of radiation have differing abilities to pass through material (fig. 4). A very thin barrier, such as a sheet or two of paper, or the top layer of skin cells, usually stops alpha particles. Because of this, alpha particle sources are usually not dangerous if outside the body, but are quite hazardous if ingested or inhaled.

Beta particles will pass through a hand, or a thin layer of material like paper or wood, but are stopped by a thin layer of metal.

Gamma radiation is very penetrating and can pass through a thick layer of most materials. Some high-energy gamma radiation is able to pass through a few feet of concrete. Certain dense, high atomic number elements such as lead can effectively attenuate gamma radiation with thinner material and are used for shielding.

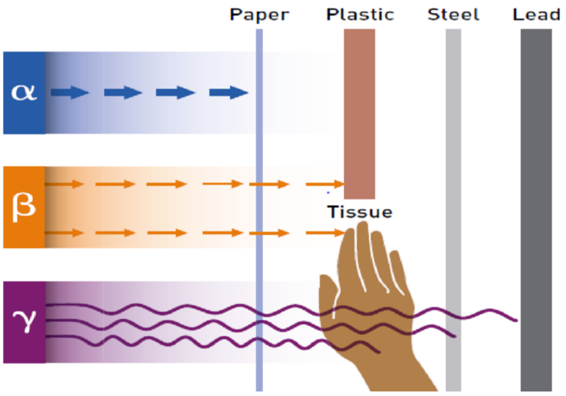

Figure 5

The ability of various kinds of emissions to cause ionization varies greatly, and some particles have almost no tendency to produce ionization. Alpha particles have about twice the ionizing power of fast-moving neutrons, about 10 times that of β particles, and about 20 times that of γ rays and X-rays (fig. 5).

Radon Exposure. For many people, one of the largest sources of exposure to radiation is from radon gas (Rn-222). Radon-222 is an α emitter with a half–life of 3.82 days.

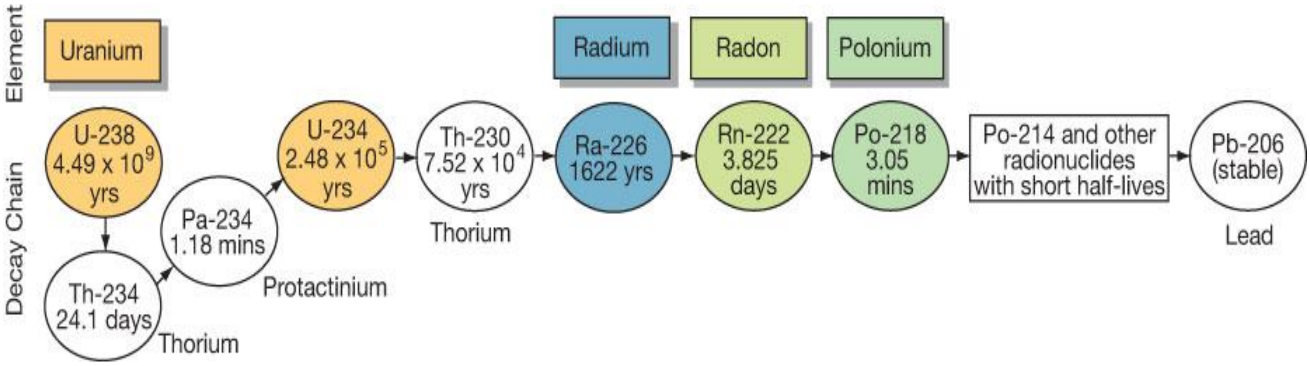

Figure 6

It is one of the products of the radioactive decay series of U-238 (fig. 6), which is found in trace amounts in soil and rocks. The radon gas that is produced slowly escapes from the ground and gradually seeps into homes and other structures above. Since it is about eight times more dense than air, radon gas accumulates in basements and lower floors, and slowly diffuses throughout buildings (fig. 7).

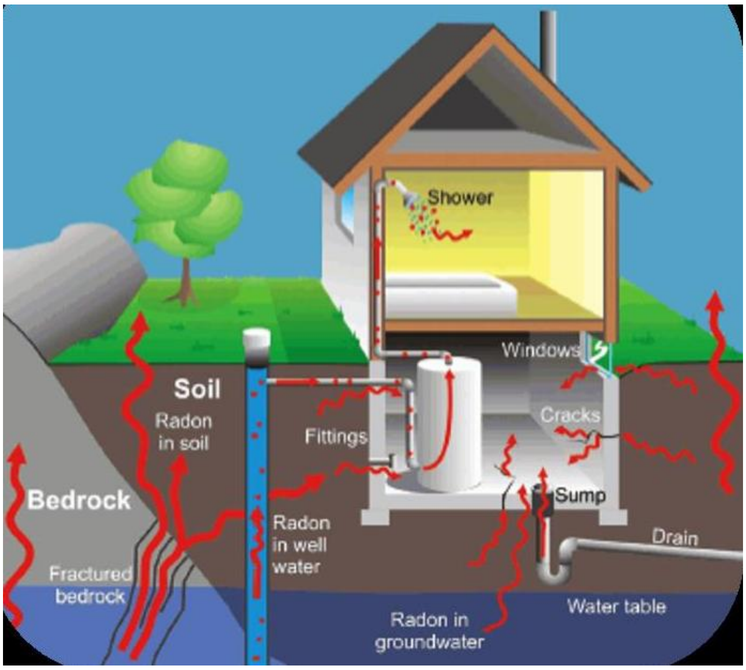

Figure 7

The radon enters through cracks in concrete foundations and basement floors, stone or porous cinderblock foundations, and openings for water and gas pipes.

Radon is found in buildings across the countries, with amounts depending on where you live. The average concentration of radon inside houses in the US (1.25 pCi/L) is about three times the levels found in outside air, and about one in six houses have radon levels high enough that remediation efforts to reduce the radon concentration are recommended.

Exposure to radon increases one's risk of getting cancer especially lung cancer, and high radon levels can be as bad for health as smoking a carton of cigarettes a day. Radon is the number one cause of lung cancer in nonsmokers and the second leading cause of lung cancer overall. Radon exposure is believed to cause over 20,000 deaths in the US per year.

Measuring Radiation Exposure. Several different devices are used to detect and measure radiation, including Geiger counters, scintillation counters (scintillators), and radiation dosimeters.

Probably the best-known radiation instrument, the Geiger counter also called the Geiger-Müller counter (fig. 7) detects and measures radiation.

A Geiger counter consists of a Geiger-Müller tube - the sensing element which detects the radiation and the processing electronics, which displays the result.

The Geiger-Müller tube is filled with an inert gas such as helium, neon, or argon at low pressure, to which a high voltage is applied. The tube briefly conducts electrical charge when a particle or photon of incident radiation makes the gas conductive by ionization. The ionization is considerably amplified within the tube by the Townsend discharge effect to produce an easily measured detection pulse, which is fed to the processing and display electronics. This large pulse from the tube makes the Geiger counter relatively cheap to manufacture, as the subsequent electronics are greatly simplified. The electronics also generate the high voltage, typically (400 –

900) V, that has to be applied to the Geiger-Müller tube to enable its operation. Radiation causes the ionization of the gas in a Geiger-Müller tube. The rate of ionization is proportional to the amount of radiation.

To stop the discharge in the Geiger-Müller tube a little halogen gas or organic material alcohol is added to the gas mixture.

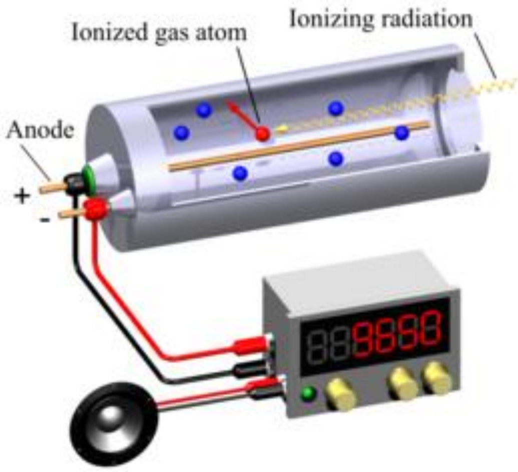

Figure 8

A scintillation counter contains a scintillator - a material that emits light (luminesces) when excited by ionizing radiation - and a sensor that converts the light into an electric signal.

A scintillator is a material that exhibits scintillation - the property of luminescence (sparkles of light), when excited by ionising radiation.

Scintillation crystal surrounded by various scintillation detector

Figure 9

Scintillation detectors (fig. 9) are usually water clear crystalline materials and work better if they contain heavy elements, which are more likely to intercept a gamma ray within the material and absorb its energy. Sodium iodide doped with thallium is one of the oldest known scintillation crystals, and is still in common use today. Its high sensitivity is very desirable.

After absorbing a gamma ray, a scintillation crystal emits a pulse of light, usually in the visible spectrum. Various types of sensitive photo-detectors are closely coupled to the crystal so the tiny sparkles produced can be fed to the optical sensing part. For lower sensitivities, there are quite a few semiconductor light sensors that can be used. But for maximum sensitivity, nothing can beat the photomultiplier tube (PMT) for performance. Despite being fragile, bulky and needing very high voltages, PMTs are still found in the highest sensitivity scintillation detectors.

Modern developments in PMTs have led to fairly small tubes with excellent light to current gain, much better than semiconductor optical detectors.

The RadEye PRD from Thermo Scientific is an excellent example. It's easily held in your palm, yet it contains a sodium iodide crystal with a miniature photomultiplier tube.

Despite being popular, sodium iodide is very hygroscopic and can absorb humidity from the air and turn from a water clear crystal into a sloppy yellow sludge. To avoid that problem, there are some exotic new and expensive scintillation crystals available, Bismuth Germinate, Cadmium Tungstate, Lutetium Yttrium Oxyorthosilicate, Lanthanum Bromide and Caesium Lithium Yttrium Chloride (CLYC).

The CLYC crystal has been incorporated into the Thermo Scientific RIIDEye X-GN isotopic identifier.

Figure 10

Radiation dosimeters also measure ionizing radiation and are often used to determine personal radiation exposure. Commonly used types are electronic, film badge, thermoluminescent, and quartz fiber dosimeters (fig. 10)

A variety of units are used to measure various aspects of radiation. The SI unit for rate of radioactive decay is the **becquerel Bq**, with 1 Bq = 1 disintegration per second. The **curie Ci** and **millicurie mCi** are much larger units and are frequently used in medicine 1 curie Ci = $3.7 \cdot 10^{10}$ disintegrations per second.

The SI unit for measuring radiation dose is the **gray Gy**, with 1 Gy = 1 J of energy absorbed per kilogram of tissue. In medical applications, the **radiation absorbed dose rad** is more often used 1 rad = 0.01 Gy; 1 rad results in the absorption of 0.01 J/kg of tissue. The SI unit measuring tissue damage caused by radiation is the **sievert Sv**. This takes into account both the energy and the biological effects of the type of radiation involved in the radiation dose. The **roentgen equivalent for man rem** is the unit for radiation damage that is used most frequently in medicine 1 rem = 1 Sv. Note that the tissue damage units rem or Sv includes the energy of the radiation dose rad or Gy along with a biological factor referred to as the **RBE** for **relative biological effectiveness** that is an approximate measure of the relative damage done by the radiation. These are related by: number of rems = RBE·number of rads with RBE approximately 10 for α radiation, 2(+) for protons and neutrons, and 1 for β and γ radiation.

Table 1. Units of Radiation Measurement

Measurement Purpose	Unit	Quantity Measured	Description
activity of source	becquerel Bq	radioactive decays or emissions	amount of sample that undergoes 1 decay/second
	curie Ci		amount of sample that undergoes $3.7 \cdot 10^{10}$ decays/second
absorbed dose	gray Gy	energy absorbed per kg of tissue	1 Gy = 1 J/kg tissue
	radiation absorbed dose, rad		1 rad = 0.01 J/kg tissue
biologically effective dose	sievert Sv	tissue damage	Sv = RBE·Gy
	roentgen equivalent for man, rem		Rem = RBE· rad

Effects of Long-term Radiation Exposure on the Human Body. The effects of radiation depend on the type, energy, and location of the radiation source, and the length of exposure. As shown in figure 11, the average person is exposed to background radiation, including cosmic rays from the sun and radon from uranium in the ground; radiation from medical exposure, including CAT scans, radioisotope tests, X-rays, and so on; and small amounts of radiation from other human activities, such as airplane flights which are bombarded by increased numbers of cosmic rays in the upper atmosphere, radioactivity from consumer products, and a variety of radionuclides that enter our bodies when we breathe, for example, carbon-14, or through the food chain for example, potassium-40, strontium-90, and iodine-131.

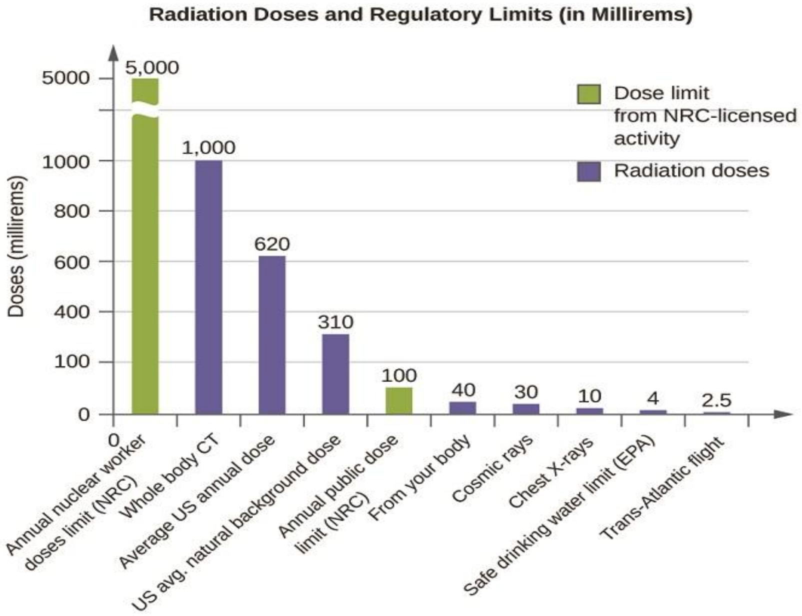

Figure 11

A short-term, sudden dose of a large amount of radiation can cause a wide range of health effects, from changes in blood chemistry to death. Short-term exposure to tens of rems of radiation will likely cause very noticeable symptoms or illness; a dose of about 500 rems is estimated to have a 50% probability of causing the death of the victim within 30 days of exposure. Exposure to radioactive emissions has a cumulative effect on the body during a person's lifetime, which is another reason why it is important to avoid any unnecessary exposure to radiation. Health effects of short-term exposure to radiation are shown in table 2.

Table 2. Health Effects of Radiation

Exposure (rem)	**Health Effect**	**Time to Onset (without treatment)**
5–10	changes in blood chemistry	—
50	nausea	hours
55	fatigue	—
70	vomiting	—
75	hair loss	2–3 weeks
90	diarrhea	—
100	hemorrhage	—
400	possible death	within 2 months
1000	destruction of intestinal lining	—
	internal bleeding	—
	death	1–2 weeks
2000	damage to central nervous system	—
	loss of consciousness;	minutes
	death	hours to days

It is impossible to avoid some exposure to ionizing radiation. We are constantly exposed to background radiation from a variety of natural sources, including cosmic radiation, rocks, medical procedures, consumer products, and even our own atoms. We can minimize our exposure by blocking or shielding the radiation, moving farther from the source, and limiting the time of exposure.

How to Protect Yourself

1. **If you work around radioactive materials it is good to have a radiation detector.** Things change from day to day. Other workers can forget to replace shielding around sources. X-ray machines can be be inadvertently activated. Things can get spilled. It‘s good to review your environment on a regular basis.
2. **Counting on a Dosimeter can leave you Vulnerable.** Dosimeters generally tell you what dose you have received after the fact. While this may be useful for regulatory compliance and limiting your lifetime dose, it does not help you keep your dose minimized on a day to day basis.
3. **Use Time Distance and Shielding to Protect Yourself.** Putting distance and shielding between you and a radiation source is an immediately effective way of reducing your exposure. Reducing the time you are being exposed is another way.
4. **Use a Respirator or Face Mask** if You are exposed to airborne sources.
5. **Properly Label Sources and keep them Shielded.**
6. **Be Aware of All Sources of Radiation Exposure.** We are all exposed to radiation every day from natural sources, outer space, the earth, radon gas in our homes and businesses. We are also exposed inadvertently to sources that can include people undergoing medical procedures, radioactive antiques such as Fiestaware, and diagnostic medical procedures.
7. **Be Thoughtful and Informed about Medical X-rays.** Medical imaging can provide important and life saving diagnostic information. It is also sometimes used unnecessarily. Sometimes the same diagnostic information can be obtained by using techniques that reduce dose. If you have concerns about the dose and benefits you may receive from a proposed procedure, take time to inform your self and also have a conversation with your health care professional with any concerns you might have. If you continue to have reservations or concerns, you can always ask for a second opinion.
8. **Things to Think About**

Risk Reduction is usually an automatic process for most potential hazards. It is something that we do every day, whether we are conscious about it or not. When we pull our car out from a side street onto a main road our eyes, ears and brain are at heightened awareness. We are sensing, observing, listening, internally calculating the speed of oncoming vehicles, making judgements about when it is safe to proceed and how rapidly or slowly to do so. With radiation we are limited in what we can see, so we need instruments, knowledge and awareness to navigate.

Knowledge and Instrumentation can form the basis for awareness in the invisible world of ionizing radiation. A good radiation detector will help you learn what is hot and what is not. Many people will find that things are pretty normal around them. Every person with a good instrument will also find that we are surrounded by naturally occurring radiation all of the time. Whether it is the muons raining on the surface of the earth from outer space, or the naturally occurring radiation in the soil beneath our feet, there is always some radiation present in our lives. We can‘t do anything about that. **What we want to do is limit the extra and unnecessary exposures that are preventable, and relax. Stress can also cause health problems.**