IONIZING RADIATION: BASIC PRINCIPLES

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Ionizing radiation may be thought of in terms of alpha particles, beta particles, gamma rays, and x-rays, each type having its own physical characteristics and relative biological effect (RBE). Alpha particles consist of two protons and two neutrons and are identical to the nucleus of a helium atom. Beta particles are charged particles emitted from an atomic nucleus, with a mass and charge equal to those of the electron. Gamma rays are high-energy electromagnetic radiations of short wavelength that are produced by changes occurring within the nucleus during radioactive decay of many elements. X-rays result from extranuclear transitions of electrons in the atom. The interactions of both x-rays and gamma rays are similar. These rays are similar to light or ultraviolet waves, except that they are more energetic; when they interact with cells in the body they cause atoms to become ionized.

PRODUCTION OF RADIATION

Radiation is released during decay of unstable atoms. Many atoms that occur in nature or that are produced by man are unstable because of an imbalance in the number of neutrons and protons in the nucleus. For example, if a particular atom has too many neutrons, it tends to ay by emitting a negative electron, ie, a negative beta particle, or "negatron." If, on the other hand, the unstable nucleus has too few neutrons, it tends to decay by emitting positrons (ie, positive electrons). Alpha particles are emitted by very heavy atoms such as radium, polonium, and plutonium. Gamma rays are emitted during the process of radioactive decay as the nucleus releases energy. Thus, all ionizing radiations except x-rays result from the process of radioactive decay of unstable atoms.

How are these unstable atoms produced? Some exist in nature; for example, a certain fraction of all potassium on earth is radioactive and about one ten-thousandth of one percent of all the potassium in our bodies is potassium 40. Other types of radioactive materials also occur in nature, such as radium and uranium.

Many more radioactive atoms are produced as a result of processes that man has developed. One of those processes is nuclear fission. If you use neutrons to bombard certain heavy atoms, for example, uranium 235, and add a neutron to the nucleus, it becomes unstable and splits. The resulting lighter atoms are unstable because they have too many neutrons. Therefore, they will undergo radioactive decay. In this manner, radioactive products are produced by the process of nuclear fission.

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Energy is released during fission. That energy is employed in a nuclear power reactor to produce steam to drive a turbine that produces electricity. However, radioactive by-products, such as cesium-137, iodine-131, cerium-144, and strontium-90, also are produced during fission. These natural by-products of the process of nuclear fission contributed to fallout downwind of the Chernobyl disaster.

A nuclear reactor has a number of components. One of the most important is the fissionable material, called the source material, which is either a form of uranium or plutonium. However, uranium or plutonium alone cannot be used to generate electricity. Neutrons, which result from fissioning of the uranium and plutonium atoms, also are needed. Every time a uranium nucleus fissions, for example, neutrons are released in addition to energy and the radioactive fission by-products. These neutrons cause additional uranium nuclei to fission. Thus, the fission process in a reactor is called a "chain reaction." Once these events are initiated, they continue because all the components necessary to maintain it are available.

The difficulty is that the neutrons that are released do not have the correct amounts of energy to cause efficient fissioning of additional nuclei. The released neutrons are moving very fast, but the neutrons needed for additional fissioning must be moving very slowly, so slowly that they are called "thermal neutrons." The fast neutrons must be slowed and this is accomplished with a moderator, which "moderates" the speed of the neutrons so they can produce additional fission reactions. In the Chernobyl reactor, the moderator was graphite. In most reactors in the United States, the moderator is some form of water. Almost anything will function as a moderator if it contains a high proportion of light elements against which the neutrons can bounce and transfer energy.

A great amount of heat is generated in the core of a nuclear reactor, and a way is needed to cool the core. A variety of materials, including gases, water, or other liquids, can be used for this purpose. The chain reaction in a nuclear reactor is a fairly delicate process, and the rate of reaction also must be controlled carefully. If the reaction is too fast, too much heat is generated in the reactor. If the reaction is too slow, the chain reaction will cease. The rate of the fission reaction is regulated by controlling the number of neutrons available for additional fission reactions. This is done by placing materials in the reactor that will absorb neutrons. The absorbent material is some form of cadmium or boron fabricated into "control rods" in the reactor.

The core of a reactor thus has four basic parts: the fissionable material, the moderator to slow the neutrons and sustain the fission reaction, the coolant to remove heat, and the control rods to regulate the rate of fission.

The nuclear reactor is one source of radioactive materials used in clinical medicine. Other nuclides employed in clinical medicine are supplied by a cyclotron rather than a reactor. These radioactive nuclides have some slightly different characteristics from those produced in a reactor, but they all undergo radioactive decay.

MEASURING RADIATION

Whenever we have a radioactive source, we need some way of describing how much radioactivity is present. That is done by describing how many atoms are decaying in the source at that particular time. For example, a sample can decay at the rate of a certain munber of atoms per second or minute and the decay rate can be expressed in terms of disintegrations per second or per minute. However, in the samples used in medicine or in the event of a radiation accident, we are usually discussing millions or billions of disintegrations per second. Therefore, a different unit of activity that is easier to use is needed. For many years the unit, "curie" (Ci), was used. This was defined originally as the rate at which one gram of radium decayed, and, more recently, as 37 billion disintegrations per second. The millicurie (mCi), which is one one-thousandth of a curie, and the microcurie, which is one one-millionth of a curie or 37,000 disintegrations per second, also were used. A new and simpler system of unit, the becquerel (Bq), is now replacing the curie. Bq is defined as one disintegration per second. Thus, a sample with an activity of 100 becquerels decays at a rate of 100 atoms per second. In this context, a millicurie is equal to 37 million becquerels or 37 megabecquerels. The terms curie, millicurie, and microcurie are gradually fading from use as the new system of units, called the International System of units (SI), grows in acceptance.

For many years the unit, "roentgen" (R), was used to describe how much radiation was present at a given location. If a person were present at that location, the number of roentgens would describe the amount of radiation to which the person had been exposed. The roentgen is a unit of radiation exposure. It has a rather clumsy definition, because it is defined in terms of how much ionization the radiation would produce in air. About 40 years ago, a new unit was developed, the "rad" (radiation absorbed dose). This is defined as one one-hundredth of a joule of energy deposited in a kilogram of irradiated material. For example, if a person received one rad of radiation over the entire body, then each kilogram of tissue in the body would have absorbed one one-hundredth of a joule. The rad is also equal to 100 ergs of energy per gram of irradiated material.

The rad is still employed widely; however, it also has its equivalent SI unit. The SI unit for absorbed dose is the "gray," named after a physicist. The gray has a simple definition, namely, one joule per kilogram. Conversion from rads to joules is simple: 100 rads equal one gray. For example, 5,000 rads of absorbed dose is equivalent to 50 grays.

The absorbed dose describes how much energy is deposited in tissue but does not describe its biological effect. Therefore, a third unit was developed a few years ago to describe the biologically effective dose or dose equivalent. The unit for dose equivalent is "rem." To calculate the dose equivalent, the absorbed dose in rads is multiplied by a factor that varies with the type of radiation involved. The factor varies because one type of radiation delivering a certain dose may have a different biological effect than another type of radiation delivering the same dose. If so, then the two radiation exposures would be assigned a different "quality factor." The dose in rems equals the dose in rads multiplied by the quality factor. For many familiar radiations, such as x-rays, gamma rays, and beta particles, the quality factor is one. Thus, the dose in rads is the same as the dose in rems. This is not true for neutrons, or alpha particles, however.

The SI equivalent for the rem is the sievert, which is defined as the absorbed dose in grays multiplied by the quality factor. The relationship between the dose equivalent in rems and the dose equivalent in sieverts is the same as that between rads and grays, namely, 100 to 1: 100 rems equals 1 sievert.

In a few years, the units rads and rems will be a thing of the past, and sieverts and grays will be used to describe dose and dose equivalent. The unit, roentgen, is essentially obsolete for most scientific journals and probably should be considered at this time a unit of the past.

EXPOSURE TO RADIATION

There is a relatively solid understanding of how radiation behaves on a physical basis. We understand the production of radiation quite well, and have a good concept of the dosimetry. We also understand the ways in which radiation interacts with matter, especially at the atomic level, and we know it gives rise to ionized atoms. We might imagine that, because radiation is ionizing matter, we are setting up initial chemical effects in the materials that are irradiated, including tissue.Those chemical effects would certainly have an impact of the viability of single cells.

Beyond this point, however, our understanding becomes somewhat more vague. Effects on single cells can affect tissues and these can cause effects in the whole animal that result, for example, in the clinical expression of cancer. There is much information needed before we understand the entire pathway from radiation exposure to the final manifestation of injury.

Doses: Because we do not understand all these processes, we have defined certain dose limits for individuals that should not be exceeded. In fact, exposures should be kept well below these limits when working with or near radiation sources. Three categories of dose limits have been established: an average dose limit to the whole population, a limit to individuals in the population, and a higher limit for those individuals who are exposed as a result of their occupation.

Dose limit for workers occupationally exposed to radiation is 5 rem (0.05 sievert) per year to the whole body. For selected areas of the body, the dose can be higher. For example, if a person were exposed to a cloud of beta-emitting substances and the dose were concentrated in the skin, the dose levels could be higher by a factor of three. If only the hands were exposed, the allowable dose could be up to 0.75 sievert per year. For internal organs, the limit is 15 rem (0.15 sievert) per year provided that the whole body dose or the dose to certain critical organs, such as the gonads, lens of the eye, or bone marrow, does not exceed 0.05 sievert. Because of concern over possible effects of radiation on the fetus, the dose limit to the fetus is 0.5 rem (0.005 sievert) during the nine months of pregnancy.

Only rarely would occupationally exposed individuals receive to doses close to these limits. Certainly this is true for medical workers. People who work in radiology or nuclear medicine departments should receive yearly doses far lower than the accepted dose limits; lower by a factor of approximately 50 would be a reasonable objective.

For members of the general public, the dose limit is reduced by a factor of ten: it should not exceed 0.5 rem (0.005 sievert) per year. In addition, the average dose to the population should not exceed 5 rem (0.05 sievert) in 30 years (0.0017 sievert per year).

<u>Sources</u>: How is the public exposed to radiation? There are a variety of sources. We all have lived with radiation our entire lives, just as people throughout history have been exposed to radiation. Part of that exposure results from the release of particles and electromagnetic radiation during fission processes in stars. Those cosmic rays bombard the atmosphere and produce radioactive intermediate products to which we are exposed. At sea level, we receive a dose of about 30 millirem or 0.3 millisievert per year from cosmic rays. Each of us has several radioactive materials in our body: potassium 40 and lower concentrations of other elements. These give rise to a yearly radiation dose of another 30 millirem (0.30 millisievert). Radioactive materials, such as radium, polonium, thorium, and others, exist in the earth's crust and produce an additional 30 millirem of exposure per year. In all we are exposed to 80 to 90 millirem each year from naturally occurring sources of radiation: cosmic rays, terrestrial radioactive sources, and materials within our bodies.

In the Rocky Mountain region of the United States, the cosmic ray flux is higher because there is less filtering of the radiation and less time for decay of the radioactive intermediates before they reach the earth. More importantly, the terrestrial component also is higher in that part of the nation, because radioactive materials are present at a higher concentration in the soil. For instance, in Washington, D.C. exposure is 80 to 90 millirem per year; it may be twice that value in Colorado, Wyoming, New Mexico, and Utah, and in certain parts of these states, it may be three or four times higher. In some parts of the world, such as areas of Brazil and India, the natural background radiation levels may be as much as 100 times those in most places.

Medical exposures to ionizing radiation include diagnostic x-rays, nuclear medicine procedures, and radiation therapy. Those who benefit from these procedures are exposed to radiation that results in a dose of 80 to 100 millirem per year averaged over the population of the country.

We live and work in buildings made of materials that give off radiations; this too increases our yearly exposure. Radioactive fallout from atmospheric tests of atomic weapons conducted now and in years past contributes 1 to 5 millirem per year. Thus, when all sources are added and the sum is averaged over the population, all of us are exposed on the average to approximately 150 to 200 millirem annually.

Other exposures are unusual. For example, we receive small doses from luminous wrist watches, and television sets produce 0.3 to 1 millirem per year. The coal or oil used for home heating contains naturally occurring radioactive substances that are released as it burns. This produces small radiation doses to the lung epithelium. Tobacco products have been claimed to deliver doses as high as 8,000 millirem per year to the lung epithelium of an individual who smokes one pack of cigarettes per day. This exposure is due to radioactive materials absorbed from the soil into the tobacco leaf. As the leaves are burned during smoking, the radioactive material is inhaled.

Some dental porcelain material contain uranium, which can emit fairly high doses to the superficial layers of tissue in direct contact with dentures and crowns. Some types of eyeglasses can cause radiation doses to the cornea. Many of the smoke detectors employed in homes contain radioactive sources that can contribute a small radiation dose to the whole body.

A current concern is the presence of radon in homes, which occurs because uranium is ubiquitous in the earth's crust. As the uranium decays, it forms radium and then radon, which percolates out of the soil and into the home. Fairly high doses may be delivered, especially if the home is tightly weatherproofed. In some areas of the country, the dose from radon may exceed that from all other sources of background radiation combined.

Obviously, the human race has lived with ionizing radiation over its entire history, and some of our present genetic and somatic diseases are probably caused in part by exposure to radiation. Because of man-made radiation, average exposures are somewhat higher today than in generations past. For this reason, every effort is made to keep exposures as low as possible without compromising the benefits we all enjoy from medical and societal uses of radiation.