Uses of Radiation

Although scientists have only known about radiation since the 1890s, they have developed a wide variety of uses for this natural force. Today, to benefit humankind, radiation is used in medicine, academics, and industry, as well as for generating electricity. In addition, radiation has useful applications in such areas as agriculture, archaeology (carbon dating), space exploration, law enforcement, geology (including mining), and many others.

Medical Uses

Hospitals, doctors, and dentists use a variety of nuclear materials and procedures to diagnose, monitor, and treat a wide assortment of metabolic processes and medical conditions in humans. In fact, diagnostic x-rays or radiation therapy have been administered to about 7 out of every 10 Americans. As a result, medical procedures using radiation have saved thousands of lives through the detection and treatment of conditions ranging from hyperthyroidism to bone cancer.

Nuclear medicine is a branch of medical imaging that uses small amounts of radioactive material to diagnose or treat a variety of diseases, including many types of cancers, heart disease and certain other abnormalities within the body.

Nuclear medicine or radionuclide imaging procedures are noninvasive and, with the exception of intravenous injections, are usually painless medical tests that help physicians diagnose medical conditions. These imaging scans use radioactive materials called radiopharmaceuticals or radiotracers.

Depending on the type of nuclear medicine exam you are undergoing, the radiotracer is either injected into a vein, swallowed or inhaled as a gas and eventually accumulates in the organ or area of your body being examined, where it gives off energy in the form of gamma rays. This energy is detected by a device called a gamma camera, a positron emission tomography (PET) scanner and/or probe. These devices work together with a computer to measure the amount of radiotracer absorbed by your body and to produce special pictures offering details on both the structure and function of organs and tissues.

In some centers, nuclear medicine images can be superimposed with computed tomography (CT) or magnetic resonance imaging (MRI) to produce special views, a practice known as image fusion or co-registration. These views allow the information from two different studies to be correlated and interpreted on one image, leading to more precise information and accurate diagnoses. In addition, manufacturers are now making single photon emission computed tomography/computed tomography (SPECT/CT) and positron emission tomography/computed tomography (PET/CT) units that are able to perform both imaging studies at the same time.

Therapy

Nuclear medicine also offers therapeutic procedures, such as radioactive iodine (I-131) therapy that use small amounts of radioactive material to treat cancer and other medical conditions affecting the thyroid gland, as well as treatments for other cancers and medical conditions.

Non-Hodgkin's lymphoma patients who do not respond to chemotherapy may undergo radioimmunotherapy (RIT).

Radioimmunotherapy (RIT) is a personalized cancer treatment that combines radiation therapy with the targeting ability of immunotherapy, a treatment that mimics cellular activity in the body's immune system. Physicians use radionuclide imaging procedures to visualize the structure and function of an organ, tissue, bone or system within the body in order to:

Renal

- Analyze native and transplant kidney function
- Detect urinary tract obstruction
- Evaluate for hypertension related to the kidney arteries
- Evaluate and follow-up urinary reflux in pediatric patients
Heart (Tc-99m)
- Visualize heart blood flow and function (such as a myocardial perfusion scan)
- Detect coronary artery disease and the extent of coronary stenosis
- Assess damage to the heart following a heart attack
- Evaluate treatment options such as bypass heart surgery and angioplasty
- Evaluate the results of revascularization procedures
- Detect heart transplant rejection
- Evaluate heart function before and after chemotherapy (MUGA)

Lungs
- Scan lungs for respiratory and blood flow problems
- Assess differential lung function for lung reduction or transplant surgery
- Detect lung transplant rejection

Bones (Sr- 89, Sr-90)
- Evaluate bones for fractures, infection and arthritis
- Evaluate for metastatic bone disease
- Evaluate painful prosthetic joints
- Evaluate bone tumors
- Identify sites for biopsy

Brain
- Investigate abnormalities in the brain, such as seizures, memory loss and abnormalities in blood flow
- Detect the early onset of neurological disorders such as Alzheimer disease
- Plan surgery and localize seizure foci
- Evaluate post-concussion syndrome

Thyroid (I-131)
- Radioactive iodine (I-131) therapy used to treat some causes of hyperthyroidism (overactive thyroid gland, for example, Graves' disease) and thyroid cancer

The use of x-rays — a type of radiation that can pass through our skin is also common (although x-rays do not have a nuclear origin). When x-rayed, our bones and other structures cast shadows because they are denser than our skin, and those shadows can be detected on photographic film. The effect is similar to placing a pencil behind a piece of paper and holding the pencil and paper in front of a light. The shadow of the pencil is revealed because most light has enough energy to pass through the paper, but the denser pencil stops all the light. The difference is that x-rays are invisible, so we need photographic film to "see" them for us. This allows doctors and dentists to spot broken bones and dental problems.

X-rays and other forms of radiation also have a variety of therapeutic uses. When used in this way, they are most often intended to kill cancerous tissue, reduce the size of a tumor, or reduce pain. For example, radioactive iodine (specifically iodine-131) is frequently used to treat thyroid cancer, a disease that strikes about 11,000 Americans every year.

X-ray machines have also been connected to computers in machines called computerized axial tomography (CAT) or computed tomography (CT) scanners. These instruments provide doctors with color images that show the shapes and details of internal organs. This helps physicians locate and identify tumors, size anomalies, or other physiological or functional organ problems.

In addition, hospitals and radiology centers perform approximately 10 million nuclear medicine procedures in the United States each year. In such procedures, doctors administer slightly radioactive substances to patients, which are attracted to certain internal organs such as the pancreas, kidney, thyroid, liver, or brain, to diagnose clinical conditions.
Academic and Scientific Applications

Universities, colleges, high schools, and other academic and scientific institutions use nuclear materials in course work, laboratory demonstrations, experimental research, and a variety of health physics applications. For example, just as doctors can label substances inside people's bodies, scientists can label substances that pass through plants, animals, or our world. This allows researchers to study such things as the paths that different types of air and water pollution take through the environment. Similarly, radiation has helped us learn more about the types of soil that different plants need to grow, the sizes of newly discovered oil fields, and the tracks of ocean currents. In addition, researchers use low-energy radioactive sources in gas chromatography to identify the components of petroleum products, smog and cigarette smoke, and even complex proteins and enzymes used in medical research.

Archaeologists also use radioactive substances to determine the ages of fossils and other objects through a process called carbon dating. For example, in the upper levels of our atmosphere, cosmic rays strike nitrogen atoms and form a naturally radioactive isotope called carbon-14. Carbon is found in all living things, and a small percentage of this is carbon-14. When a plant or animal dies, it no longer takes in new carbon and the carbon-14 that it accumulated throughout its life begins the process of radioactive decay. As a result, after a few years, an old object has a lower percent of radioactivity than a newer object. By measuring this difference, archaeologists are able to determine the object's approximate age.

Industrial Uses

We could talk all day about the many and varied uses of radiation in industry and not complete the list, but a few examples illustrate the point. In irradiation, for instance, foods, medical equipment, and other substances are exposed to certain types of radiation (such as x-rays) to kill germs without harming the substance that is being disinfected — and without making it radioactive. When treated in this manner, foods take much longer to spoil, and medical equipment (such as bandages, hypodermic syringes, and surgical instruments) are sterilized without being exposed to toxic chemicals or extreme heat. As a result, where we now use chlorine — a chemical that is toxic and difficult-to-handle — we may someday use radiation to disinfect our drinking water and kill the germs in our sewage. In fact, ultraviolet light (a form of radiation) is already used to disinfect drinking water in some homes.

Similarly, radiation is used to help remove toxic pollutants, such as exhaust gases from coal-fired power stations and industry. For example, electron beam radiation can remove dangerous sulphur dioxides and nitrogen oxides from our environment. Closer to home, many of the fabrics used to make our clothing have been irradiated (treated with radiation) before being exposed to a soil-releasing or wrinkle-resistant chemical. This treatment makes the chemicals bind to the fabric, to keep our clothing fresh and wrinkle-free all day, yet our clothing does not become radioactive. Similarly, nonstick cookware is treated with gamma rays to keep food from sticking to the metal surface.

The agricultural industry makes use of radiation to improve food production and packaging. Plant seeds, for example, have been exposed to radiation to bring about new and better types of plants. Besides making plants stronger, radiation can be used to control insect populations, thereby decreasing the use of dangerous pesticides. Radioactive material is also used in gauges that measure the thickness of eggshells to screen out thin, breakable eggs before they are packaged in egg cartons. In addition, many of our foods are packaged in polyethylene shrinkwrap that has been irradiated so that it can be heated above its usual melting point and wrapped around the foods to provide an airtight protective covering.

All around us, we see reflective signs that have been treated with radioactive tritium and phosphorescent paint. Ionizing smoke detectors, using a tiny bit of americium-241, keep watch while we sleep. Gauges containing radioisotopes measure the amount of air whipped into our ice cream, while others prevent spillover as our soda bottles are carefully filled at the factory.

Engineers also use gauges containing radioactive substances to measure the thickness of paper products, fluid levels in oil and chemical tanks, and the moisture and density of soils and material at construction sites. They also use an x-ray process, called radiography, to find otherwise imperceptible defects in metallic castings and welds. Radiography is also used to check the flow of oil in sealed engines and the rate and way that various materials wear out. Well-logging devices use a radioactive source and detection equipment to identify and record formations deep within a bore hole (or well) for oil, gas, mineral, groundwater, or geological exploration. Radioactive materials also power our dreams of outer space, as they fuel our spacecraft and supply electricity to satellites that are sent on missions to the outermost regions of our solar system.
**Important Concepts for Understanding Biological Effects of Radiation:**

Taken from the Princeton University’s Environmental Health and Safety webpage

The **quantity** of radioactive material present is generally measured in terms of **activity** rather than mass, where activity is a measurement of the number of radioactive disintegrations or transformations an amount of material undergoes in a given period of time. Activity is related to mass, however, because the greater the mass of radioactive material, the more atoms are present to undergo radioactive decay.

The two most common units of activity are the **Curie** or the **Becquerel** (in the SI system).

- **1 Curie (Ci)** = $3.7 \times 10^{10}$ disintegrations per second (dps)
- **1 Becquerel (Bq)** = 1 disintegration per second (dps).

Obviously, 1 Curie is a large amount of activity, while 1 Becquerel is a small amount. In the typical university laboratory, millicurie and microcurie (or kilo and MegaBecquerel) amounts of radioactive material are used.

**Intensity**: For the purposes of radiation protection, it is not always useful to describe the potential hazard of a radioactive material in terms of its activity. For instance, 1 millicurie of tritium a centimeter from the body poses a much different hazard than 1 millicurie of phosphorus-32 a centimeter from the body because of the type of decay undergone by the nuclei; therefore the type of radiation that is emitted. Gamma rays can penetrate the body, while alpha particles cannot. Consequently, it is often preferable to measure radiation by describing the effect of that radiation on the materials through which it passes. The three main quantities which describe radiation intensity are shown in the following table:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>What is measured</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure</td>
<td>Roentgen (R)</td>
<td>Amount of charge produced in 1 kg of air by x- or gamma rays</td>
<td>1 R = $2.58 \times 10^{4}$ Cb/kg</td>
</tr>
<tr>
<td></td>
<td>or Coulombs/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absorbed Dose</td>
<td>rad</td>
<td>Amount of energy absorbed in 1 gram of matter from radiation</td>
<td>1 rad = 100 ergs*/gram</td>
</tr>
<tr>
<td></td>
<td>Gray (Gy)</td>
<td></td>
<td>1 Gy = 100 rad</td>
</tr>
<tr>
<td>Dose Equivalent</td>
<td>Rem</td>
<td>Absorbed dose modified by the ability of the radiation to cause biological damage</td>
<td>rem = rad x Quality Factor</td>
</tr>
<tr>
<td></td>
<td>or Sievert (Sv)</td>
<td></td>
<td>1 Sv = 100 rem</td>
</tr>
</tbody>
</table>

* An erg is a unit of work.

Coulombs/kilogram, the Gray, and the Sievert are the SI units for these quantities.

**Somatic damage** from radiation is caused when an individual is directly exposed to radiation. Japanese citizens exposed to radiation after the 1945 atomic bomb would have suffered somatic damage.

**Genetic damage** occurs when genetic defects are passed on to offspring as a result of the parent’s radiation exposure.
Fact Sheet Regarding the Biological Effects of Radiation from the US NRC

Radiation is all around us. It is naturally present in our environment and has been since the birth of this planet. Consequently, life has evolved in an environment, which has significant levels of ionizing radiation. It comes from outer space (cosmic), the ground (terrestrial), and even from within our own bodies. It is present in the air we breathe, the food we eat, the water we drink, and in the construction materials used to build our homes. Certain foods such as bananas and brazil nuts naturally contain higher levels of radiation than other foods. Brick and stone homes have higher natural radiation levels than homes made of other building materials such as wood. Our nation's Capitol, which is largely constructed of granite, contains higher levels of natural radiation than most homes.

Levels of natural or background radiation can vary greatly from one location to the next. For example, people residing in Colorado are exposed to more natural radiation than residents of the east or west coast because Colorado has more cosmic radiation at a higher altitude and more terrestrial radiation from soils enriched in naturally occurring uranium. Furthermore, a lot of our natural exposure is due to radon, a gas from the earth's crust that is present in the air we breathe.

About half of the total annual average U.S. individual’s radiation exposure comes from natural sources. The other half is mostly from diagnostic medical procedures. The average annual radiation exposure from natural sources is about 310 millirem (3.1 millisieverts or mSv). Radon and thoron gases account for two-thirds of this exposure, while cosmic, terrestrial, and internal radiation account for the remainder. No adverse health effects have been discerned from doses arising from these levels of natural radiation exposure.

Man-made sources of radiation from medical, commercial, and industrial activities contribute about another 310 mrem to our annual radiation exposure. One of the largest of these sources of exposure is computed tomography (CT) scans, which account for about 150 mrem. Other medical procedures together account for about another 150 mrem each year. In addition, some consumer products such as tobacco, fertilizer, welding rods, exit signs, luminous watch dials, and smoke detectors contribute about another 10 mrem to our annual radiation exposure.

The pie chart on the following page shows a breakdown of radiation sources that contribute to the average annual U.S. radiation dose of 620 mrem. Nearly three-fourths of this dose is split between radon/thoron gas and diagnostic medical procedures. Although there is a distinction between natural and man-made radiation, they both affect us in the same way.

Above background levels of radiation exposure, the NRC requires that its licensees limit maximum radiation exposure to individual members of the public to 100 mrem (1mSv) per year, and limit occupational radiation exposure to adults working with radioactive material to 5,000 mrem (50 mSv) per year. NRC regulations and radiation exposure limits are contained in Title 10 of the Code of Federal Regulations, Part 20.
Biological Effects of Radiation

We tend to think of biological effects of radiation in terms of their effect on living cells. For low levels of radiation exposure, the biological effects are so small they may not be detected. The body has repair mechanisms against damage induced by radiation as well as by chemical carcinogens. Consequently, biological effects of radiation on living cells may result in three outcomes: (1) injured or damaged cells repair themselves, resulting in no residual damage; (2) cells die, much like millions of body cells do every day, being replaced through normal biological processes; or (3) cells incorrectly repair themselves resulting in a biophysical change.

The associations between radiation exposure and the development of cancer are mostly based on populations exposed to relatively high levels of ionizing radiation (e.g., Japanese atomic bomb survivors, and recipients of selected diagnostic or therapeutic medical procedures). Cancers associated with high-dose exposure (greater than 50,000 mrem) include leukemia, breast, bladder, colon, liver, lung, esophagus, ovarian, multiple myeloma, and stomach cancers. Department of Health and Human Services literature also suggests a possible association between ionizing radiation exposure and prostate, nasal cavity/sinuses, pharyngeal and laryngeal, and pancreatic cancer.

The period of time between radiation exposure and the detection of cancer is known as the latent period and can be many years. Those cancers that may develop as a result of radiation exposure are indistinguishable from those that occur naturally or as a result of exposure to other carcinogens. Furthermore, National Cancer Institute literature indicates that other chemical and physical hazards and lifestyle factors (e.g., smoking, alcohol consumption, and diet) contribute significantly to many of these same diseases.

Although radiation may cause cancers at high doses and high dose rates, currently there are no data to establish unequivocally the occurrence of cancer following exposure to low doses and dose rates – below about 10,000 mrem (100 mSv). Those people living in areas having high levels of background radiation – above 1,000 mrem (10 mSv) per year – such as Denver, Colorado, have shown no adverse biological effects.

Even so, the radiation protection community conservatively assumes that any amount of radiation may pose some risk for causing cancer and hereditary effect, and that the risk is higher for higher radiation exposures. A linear, no-threshold (LNT) dose response relationship is used to describe the relationship between radiation dose and the occurrence of cancer. This dose-response hypothesis suggests that any increase in dose, no matter how small, results in an incremental increase in risk. The LNT hypothesis is accepted by the NRC as a conservative model for determining radiation dose standards, recognizing that the model may over estimate radiation risk.

High radiation doses tend to kill cells, while low doses tend to damage or alter the genetic code (DNA) of irradiated cells. High doses can kill so many cells that tissues and organs are damaged immediately. This in turn may cause a rapid body response often called Acute Radiation Syndrome. The higher the radiation dose, the sooner the effects of radiation will appear, and the higher the probability of death. This syndrome was observed in many atomic bomb survivors in 1945 and emergency workers responding to the 1986 Chernobyl nuclear power plant accident. Approximately 134 plant workers and firefighters battling the fire at the Chernobyl power plant received high radiation doses – 80,000 to 1,600,000 mrem (800 to 16,000 mSv) – and suffered from acute radiation sickness. Of these, 28 died within the first three months from their radiation injuries. Two more patients died during the first days as a result of combined injuries from the fire and radiation.

Because radiation affects different people in different ways, it is not possible to indicate what dose is needed to be fatal. However, it is believed that 50% of a population would die within thirty days after receiving a dose of between 350,000 to 500,000 mrem (3500 to 5000 mSv) to the whole body, over a period ranging from a few minutes to a few hours. This would vary depending on the health of the individuals before the exposure and the medical care received after the exposure. These doses expose the whole body to radiation in a very short period of time (minutes to hours). Similar exposure of only parts of the body will likely lead to more localized effects, such as skin burns.

Conversely, low doses – less than 10,000 mrem (100 mSv) – spread out over long periods of time (years) don't cause an immediate problem to any body organ. The effects of low doses of radiation, if any, would occur at the cell level, and thus changes may not be observed for many years (usually 5-20 years) after exposure.

Genetic effects and the development of cancer are the primary health concerns attributed to radiation exposure. The likelihood of cancer occurring after radiation exposure is about five times greater than a genetic effect (e.g., increased still births, congenital abnormalities, infant mortality, childhood mortality, and decreased birth weight). Genetic effects
are the result of a mutation produced in the reproductive cells of an exposed individual that are passed on to their offspring. These effects may appear in the exposed person's direct offspring, or may appear several generations later, depending on whether the altered genes are dominant or recessive.

Although radiation-induced genetic effects have been observed in laboratory animals (given very high doses of radiation), no evidence of genetic effects has been observed among the children born to atomic bomb survivors from Hiroshima and Nagasaki.

NRC regulations strictly limit the amount of radiation that can be emitted by a nuclear facility, such as a nuclear power plant. A 1991 study by the National Cancer Institute, “Cancer in Populations Living Near Nuclear Facilities,” concluded that there was no increased risk of death from cancer for people living in counties adjacent to U.S. nuclear facilities. At the NRC’s request, the National Academy of Sciences is currently engaged in a state-of-the-art update to the earlier study. The new study will examine cancer rates in communities around operating and decommissioned nuclear power plants, as well as nuclear fuel cycle facilities.

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Additional Information from Princeton University’s Environmental Health and Safety

Mechanisms of Damage

Injury to living tissue results from the transfer of energy to atoms and molecules in the cellular structure. Ionizing radiation causes atoms and molecules to become ionized or excited. These excitations and ionizations can:

- Produce free radicals.
- Break chemical bonds.
- Produce new chemical bonds and cross-linkage between macromolecules.
- Damage molecules that regulate vital cell processes (e.g. DNA, RNA, proteins).

The cell can repair certain levels of cell damage. At low doses, such as that received every day from background radiation, cellular damage is rapidly repaired.

At higher levels, cell death results. At extremely high doses, cells cannot be replaced quickly enough, and tissues fail to function.

Tissue Sensitivity

In general, the radiation sensitivity of a tissue is:

- proportional to the rate of proliferation of its cells
- inversely proportional to the degree of cell differentiation

For example, the following tissues and organs are listed from most radiosensitive to least radiosensitive:

| Most Sensitive: Blood-forming organs |
| Reproductive organs |
| Skin |
| Bone and teeth |
| Muscle |
| Least sensitive: Nervous system |
This also means that a developing embryo is most sensitive to radiation during the early stages of differentiation, and an embryo/fetus is more sensitive to radiation exposure in the \textbf{first} trimester than in later trimesters.

**Prompt and Delayed Effects**

Radiation effects can be categorized by \textbf{when} they appear.

- \textbf{Prompt effects}: effects, including radiation sickness and radiation burns, seen immediately after large doses of radiation delivered over short periods of time.
- \textbf{Delayed effects}: effects such as cataract formation and cancer induction that may appear months or years after a radiation exposure.

**Prompt Effects**

High doses delivered to the whole body of healthy adults within short periods of time can produce effects such as blood component changes, fatigue, diarrhea, nausea and death. These effects will develop within hours, days or weeks, depending on the size of the dose. The larger the dose, the sooner a given effect will occur.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood count changes</td>
<td>50 rem</td>
</tr>
<tr>
<td>Vomiting (threshold)</td>
<td>100 rem</td>
</tr>
<tr>
<td>Mortality (threshold)</td>
<td>150 rem</td>
</tr>
<tr>
<td>LD$_{50/60}$,(^\ast) (with minimal supportive care)</td>
<td>320 – 360 rem</td>
</tr>
<tr>
<td>LD$_{50/60}$ (with supportive medical treatment)</td>
<td>480 – 540 rem</td>
</tr>
<tr>
<td>100% mortality (with best available treatment)</td>
<td>800 rem</td>
</tr>
</tbody>
</table>

(Adapted from NCRP Report No. 98 "Guidance on Radiation Received in Space Activities, NCRP, Bethesda, MD (1989))

\(^\ast\) The LD$_{50/60}$ is that dose at which 50% of the exposed population will die within 60 days.