Learning Objectives

• Understand how radiation is used in agriculture and various industries.
• Understand the difference between diagnostic and therapeutic radiation.

Radioactive isotopes have the same chemical properties as stable isotopes of the same element, but they emit radiation, which can be detected. If we replace one (or more) atom(s) with radioisotope(s) in a compound, we can track them by monitoring their radioactive emissions. This type of compound is called a radioactive tracer (or radioactive label). Radioisotopes are used to follow the paths of biochemical reactions or to determine how a substance is distributed within an organism.

Radioisotopes in Industry and Agriculture

Radioisotopes (radioactive isotopes or radionuclides or radioactive nulcides) are used in two major ways: either for their radiation alone (irradiation, nuclear batteries) or for the combination of chemical properties and their radiation (tracers, biopharmaceuticals).

Tracer Applications

Radioactive isotopes are effective tracers because their radioactivity is easy to detect. A tracer is a substance that can be used to follow the pathway of that substance through some structure. For instance, leaks in underground water pipes can be discovered by running some tritium (H-3)-containing water through the pipes and then using a Geiger counter to locate any radioactive tritium subsequently present in the ground around the pipes. (Recall that tritium is a radioactive isotope of hydrogen.)

Tracers are used in diverse ways to study the mechanisms of chemical reactions in plants and animals. These include labeling fertilizers in studies of nutrient uptake by plants and crop growth, investigations of digestive and milk-producing processes in cows, and studies on the growth and metabolism of animals and plants.

For example, the radioisotope C-14 was used to elucidate the details of how photosynthesis occurs. The overall reaction is:

$$\ce{6CO2(g)+6H2O(l) -> C6H12O6(s)+6O2(g)}$$

but the process is much more complex, proceeding through a series of steps in which various organic compounds are produced. In studies of the pathway of this reaction, plants were exposed to CO$_2$ containing a high concentration of $\ce{^{14}_6C}$. At regular intervals, the plants were analyzed to determine which organic compounds contained carbon-14 and how much of each compound was present. From the time sequence in which the compounds appeared and the amount of each present at given time intervals, scientists learned more about the pathway of the reaction.

**Phosphorus-32** is used in plant sciences for tracking a plant's uptake of fertilizer from the roots to the leaves. The phosphorus-32-labelled fertilizer is given to the plant hydroponically or via water in the soil and the usage of the...
phosphorus can be mapped from the emitted beta radiation. The information gathered by mapping the fertilizer uptake show how the plant takes up and uses the phosphorus from fertilizer.

Irradiation of Food and Mail

Co-60 (gamma source) and x-rays are use to irradiate many foods in the United States. Ionizing radiation can be used to kill food borne illnesses like salmonella and e coli. Irradiating food can also prolong shelf-life, delay ripening, and destroy insects. In addition, gamma/x-ray can sterilize foods making refrigeration unnecessary. Often, sterilized food is served to hospital patients who have impaired immune systems.

In the United States, irradiation of food is regulated by the FDA (Food and Drug Administration). Foods that have been irradiated must display the symbol called the radura on their packaging. Some foods that could display this symbol are: meats (beef, pork, chicken), shrimp, lobster, fruits, vegetables, shellfish, and spices. Contrary to the belief of some people, irradiation of food does not make the food itself radioactive.

Figure \(\PageIndex{1}\) The preservation of strawberries with Ionizing Radiation.

In the fall of 2001, anthrax laced letters (Figure \(\PageIndex{2}\)) were sent to various new agencies and two United States senators. Anthrax is an infectious disease caused by bacteria. It exists naturally in some soils and can be isolated in a laboratory.
To combat this form of bioterrorism, the United States Postal Service (USPS) and the Federal Bureau of Investigation (FBI) installed x-ray generators to irradiate suspicious-looking mail sent to some governmental facilities. X-rays will kill the majority of this bacteria and some viruses as well. Once irradiated, mail (packages and letters) might change in color, texture, and smell. This ionizing radiation chemically alters the composition of the mail's paper component. The x-rays do not leave the mail radioactive.

Smoke Detectors

Americium-241, an α emitter with a half-life of 458 years, is used in tiny amounts in ionization-type smoke detectors (Figure \(\PageIndex{3}\)). The α emissions from Am-241 ionize the air between two electrode plates in the ionizing chamber. A battery supplies a potential that causes movement of the ions, thus creating a small electric current. When smoke enters the chamber, the movement of the ions is impeded, reducing the conductivity of the air. This causes a marked drop in the current, triggering an alarm.

![Smoke Detectors](credit a: modification of work by “Muffet”/Wikimedia Commons)

Other Applications

Commercial applications of radioactive materials are equally diverse. They include determining the thickness of films, paper, and thin metal sheets by exploiting the penetration power of various types of radiation (Figure \(\PageIndex{4}\)).
Flaws in metals used for structural purposes can be detected using high-energy gamma rays from cobalt-60 in a fashion similar to the way X-rays are used to examine the human body. In one form of pest control, flies are controlled by sterilizing male flies with γ radiation so that females breeding with them do not produce offspring.

**Figure (PageIndex{4})** Using radiation to control the thickness of a material. Because the amount of radiation absorbed by a material is proportional to its thickness, radiation can be used to control the thickness of plastic film, tin foil, or paper. As shown, a beta emitter is placed on one side of the material being produced and a detector on the other. An increase in the amount of radiation that reaches the detector indicates a decrease in the thickness of the material and vice versa. The output of the detector can thus be used to control the thickness of the material.

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**Radioisotopes in Medicine**

Radioactive tracers are also used in many medical applications, including both diagnosis and treatment. They are used to measure engine wear, analyze the geological formation around oil wells, and much more.

Radioisotopes have revolutionized medical practice, where they are used extensively. Over 10 million nuclear medicine procedures and more than 100 million nuclear medicine tests are performed annually in the United States.

**Diagnostic Medical Applications**

Diagnostic medical applications involve testing for a disease or condition. In nuclear medicine, this could involve using PET scans, or isotopic studies. The radiation involved for each of these types of tools will vary in mrem or mSv amounts.

**PET Scanning**

Positron Emission Tomography or PET scan is a type of nuclear medicine imaging. Depending on the area of the body being imaged, a radioactive isotope is either injected into a vein, swallowed by mouth, or inhaled as a gas. When the radioisotope is collected in the appropriate area of the body, the gamma ray emissions are detected by a PET scanner (often called a gamma camera) which works together with a computer to generate special pictures, providing details on
both the structure and function of various organs. Watch this informational video on how this technique works.

PET Scan

**Video** PET scans: What to expect.

PET scans are used to:

- Detect cancer
- Determine the amount of cancer spread
- Assess the effectiveness of treatment plans
- Determine blood flow to the heart muscle
- Determine the effects of a heart attack
- Evaluate brain abnormalities such as tumors and memory disorders
Mild cognitive impairment (MCI) is a state between normal ageing and dementia, where someone’s mind is functioning less well than would be expected for their age. This image is for illustrative purposes only. Image used with permission (Public Domain; Center For Functional Imaging, Lawrence Berkeley National Laboratory. Alzheimer’s Disease Neuroimaging Initiative (ADNI)).

PET Scanning, is used to image the physiological aspects of the body rather than the anatomy (Figures \(\PageIndex{5}\)) and \(\PageIndex{6}\)). It images the function of the body rather than the form, such as where tagged molecules go and how they are used. For instance, if you were to image the brain of a deceased person, nothing would show up on a PET scan opposed to a CAT scan, as the brain is no longer functional. Pet Scanning is very useful in imaging tumors, which can be done when patients are injected with certain tracers. Often times PET scanners are used in collaboration with CAT scanners to create a composite image that shows both the function and form of the body. The animation below is a whole-body PET scan using the radioisotope of \(^{18}\text{F}\) \((t_{1/2} = 110 \text{ min})\). Using this tracer, doctors can determine if cancer has metastasized by looking at the metabolic activity of glucose.
Other Isotopic Tests

Radioisotopes have revolutionized medical practice, where they are used extensively. Over 10 million nuclear medicine procedures and more than 100 million nuclear medicine tests are performed annually in the United States. Four typical examples of radioactive tracers used in medicine are technetium-99 $^{99}_{43}\text{Tc}$, thallium-201 $^{201}_{81}\text{Tl}$, iodine-131 $^{131}_{53}\text{I}$, and sodium-24 $^{24}_{11}\text{Na}$. Damaged tissues in the heart, liver, and lungs absorb certain compounds of technetium-99 preferentially. After it is injected, the location of the technetium compound, and hence the damaged tissue, can be determined by detecting the $\gamma$ rays emitted by the Tc-99 isotope. Thallium-201 (Figure 7) becomes concentrated in healthy heart tissue, so the two isotopes, Tc-99 and Ti-201, are used together to study heart tissue. Iodine-131 concentrates in the thyroid gland, the liver, and some parts of the brain. It can therefore be used to monitor goiter and treat thyroid conditions, such as Grave's disease, as well as liver and brain tumors. Salt solutions containing compounds of sodium-24 are injected into the bloodstream to help locate obstructions to the flow of blood.
Small doses of $^{131}$I (too small to kill cells) are used for purposes of imaging the thyroid. Once the iodine is concentrated in the thyroid, the patient lays down on a sheet of film and the radiation from the $^{131}$I makes a picture of the thyroid on the film. The half-life of iodine-131 is approximately 8 days so after a few weeks, virtually all of the radioactive iodine is out of the patient's system. During that time, they are advised that they will set off radiation detectors in airports and will need to get special permission to fly on commercial flights.

Some isotopes that are used to diagnose diseases are shown in Table 1. All of these nuclear isotopes release one form of ionizing radiation (either particle or ray). In addition, each isotopic application would involve a specific amount of mrem/mSv radiation.

<table>
<thead>
<tr>
<th>Symbol-mass</th>
<th>Half-Life ($t_{1/2}$)</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe-133</td>
<td>5.27 days</td>
<td>Lung imaging</td>
</tr>
<tr>
<td>H-3</td>
<td>12.26 years</td>
<td>Analyzing total body water</td>
</tr>
<tr>
<td>Tl-201</td>
<td>73 hours</td>
<td>Stress tests for heart problems</td>
</tr>
<tr>
<td>Fe-59</td>
<td>44.5 days</td>
<td>Detection of anemia</td>
</tr>
<tr>
<td>Symbol-mass</td>
<td>Half-Life ($t_{1/2}$)</td>
<td>Application</td>
</tr>
<tr>
<td>------------</td>
<td>----------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>Gd-153</td>
<td>242 days</td>
<td>Analyzing bone density</td>
</tr>
<tr>
<td>Cr-51</td>
<td>27.8 days</td>
<td>Determining blood volume</td>
</tr>
<tr>
<td>C-11</td>
<td>20.4 minutes</td>
<td>Brain scans</td>
</tr>
<tr>
<td>Tc-99m</td>
<td>6.0 hours</td>
<td>Heart, lung, kidney, bone marrow, brain, or bone marrow imaging</td>
</tr>
<tr>
<td>Pu-238</td>
<td>86 years</td>
<td>Powering pacemakers</td>
</tr>
<tr>
<td>I-131</td>
<td>8.0 days</td>
<td>Imaging Thyroid</td>
</tr>
</tbody>
</table>

The “m” in Tc-99m stands for “metastable,” indicating that this is an unstable, high-energy state of Tc-99. Metastable isotopes emit $\gamma$ radiation to rid themselves of excess energy and become (more) stable.

Keep in mind that x-rays, CT scans, PET scans, and isotopic studies involve ionizing radiation. In contrast, MRI (magnetic resonance imaging) and ultrasounds do not utilize ionizing forms of radiation.

**Therapeutic Radiation**

There are many techniques used to treat cancer. Surgery can be used to remove cancerous tumors inside or on the body. With chemotherapy, ingested or injected chemicals are used to kill rapidly dividing cells (cancerous and noncancerous). Other cancer treatment methods include immunotherapy, stem cell replacement, hormone therapy, and targeted therapy.

Radiation therapy and Chemotherapy: Two different treatment procedures

Patients diagnosed with cancer might be required to do chemotherapy or radiation therapy. Sometimes, both of these methods are used for a patient. In this picture, a female patient is receiving chemotherapy through an IV. She is participating in cooling therapy while receiving her treatment. By placing her hands and feet in cooling devices, this will lower her chances of losing her finger and toenails. Cold cap therapy is also now available for chemotherapy patients. Wearing this type of device could enable a patient to keep his/her hair during chemotherapy.
Current therapeutic radiation applications involve the use of gamma, x-rays, or protons. Recently, some research facilities are investigating the use of alpha and beta tagged molecules to kill cancer cells. These radioisotopes will first locate a cancer related molecule on a tumor cell. Then, the alpha or beta tagged species will inject its radiation into the tumor. Sr-89 (beta emitter) and Ra-223 (alpha emitter) have been used in clinical research trials of certain types of bone cancers.

Radiation Therapy is used as a treatment to control malignant cells within cancer patients. Oncologists (specialists that deal with cancer) utilize radiation frequently to help slow or cure the spread of cancer within individuals. Radiation is specifically applied to malignant tumors in order to shrink them in size. Medical professionals, mainly radiation oncologists, administer a variety of dosages to patient, contingent to the patients current health, as well as other treatments such as chemotherapy, success of surgery, etc.

**External Beam Therapy (Photon and Proton Therapy)**

External Beam Therapy (EBT) is a method of delivering a high energy beam of radiation to the precise location of a patient's tumor. These beams can destroy cancer cells and with careful planning, NOT kill surrounding cells. The concept is to have several beams of radiation, each of which is sub-lethal, enter the body from different directions. The only place in the body where the beam would be lethal is at the point where all the beams intersect. Before the EBT process, the patient is three-dimensionally mapped using CT scans and x-rays. The patient receives small tattoos to allow the therapist to line up the beams exactly. Alignment lasers are used to precisely locate the target. The radiation beam is usually
generated with a linear accelerator. The video below illustrates the basic preparation and administration of external beam therapy.

**Radiation Therapy**

Video \(PageIndex(2)\) Targeting cancer - Radiation therapy treatment process.

Photon EBT utilizes either x-ray or gamma rays. An x-ray source would require a linear accelerator to produce high energy electrons. In contrast, a gamma source incorporates a radioactive isotope (like Co-60). Keep in mind both of these technologies use ionizing radiation. As a result, cancer patients must be monitored throughout their life to ensure they do not develop other cancers, like leukemia. EBT is used to treat the following diseases as well as others:

- Breast cancer
- Colorectal cancer
- Head and neck cancer
- Lung cancer
- Prostate cancer

The majority of radiation patients receive photon EBT. The smaller size of this machine makes this therapy an option for all sizes of hospitals and cancer treatment centers. Photon EBT equipment costs approximately three million dollars. The size and the price of this technology enables smaller facilities to keep their patients closer to home during treatment.
Another method of radiation treatment involving protons is not as commonly used in the United States. **Photon therapy** requires a cyclotron to generate proton beams (recall, a proton is an ionized H-1 isotope). Unlike x-ray or gamma rays (photon therapy), protons are extremely heavy.

At this time, research facilities are working on miniaturizing proton generators. An ideal technology would reduce the cost from hundreds of millions of dollars to about twenty to thirty million per device. This would make proton therapy more available and convenient for patients.

**Proton Therapy vs Radiation Therapy**

There are many advantages to choosing proton therapy over photon therapy. Unlike photon radiation, proton beams will only penetrate to the depth of the tumor and not pass through the entire body. This reduces the overall toxicity dose. In addition, fewer treatments are required for proton therapy patients than photon therapy. Unfortunately, proton therapy is more expensive than photon therapy and less common. Once approved by a facility and medical insurance, a patient may have to move temporarily to a larger city to receive treatment. Some forms of cancer have never been clinically treated with proton therapy (namely, breast cancer). Patients desiring proton therapy might not be able to receive type of therapy due to lack of research.

**Brachtherapy**

**Brachytherapy** involves placing ionizing pellets(seeds) or rods directly at the tumor. Photons (in the form of x-ray or gamma ray) are produced inside the body and will penetrate throughout this particular area localizing the radiation.
Pellets are surgically implanted while rods can be temporarily inserted to produce radiation internally. With pellets/seeds, the patient will remain radioactive as long as these devices remain inside the body. People undergoing this type of radiotherapy need to be aware of their constant emission of radiation. Radiation that is administered through rods connected to a photon device will disperse energy immediately and not leave the patient radioactive.

![Image](https://c1.staticflickr.com/8/7254/7...74d83b7058.jpg)

**Figure \(\PageIndex{9}\)** The picture on the left shows a brachytherapy rod. This device would be connected to a gamma source and connected inside a human body. The second image shows radioactive pellets or seeds that can be surgically implanted near a tumor. Note how small the pellets are when compared to an American penny. Image taken from: [https://c1.staticflickr.com/8/7254/7...74d83b7058.jpg](https://c1.staticflickr.com/8/7254/7...74d83b7058.jpg)

Brachytherapy is widely used in the treatment of cancers involving reproductive organs. Because the radiation is isolated internally, patients are less likely to experience side effects when receiving this type of treatment. Cancers that have been treated with brachytherapy are shown below:

- Prostate
- Breast
- Esophageal
- Lung
- Uterine
- Anal/Rectal
- Sarcomas
- Head and neck

Table \(\PageIndex{2}\) list commonly used radionuclides for brachtherapy.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Type</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cesium-131 ((^{131})Cs)</td>
<td>Electron Capture, (\varepsilon)</td>
<td>9.7 days</td>
</tr>
<tr>
<td>Cesium-137 ((^{137})Cs)</td>
<td>(\beta^-) particles, (\gamma)-rays</td>
<td>30.17 years</td>
</tr>
<tr>
<td>Cobalt-60 ((^{60})Co)</td>
<td>(\beta^-) particles, (\gamma)-rays</td>
<td>5.26 years</td>
</tr>
<tr>
<td>Iridium-192 ((^{192})Ir)</td>
<td>(\gamma)-rays</td>
<td>73.8 days</td>
</tr>
<tr>
<td>Radionuclide</td>
<td>Type</td>
<td>Half-life</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Iodine-125 ((^{125})I)</td>
<td>Electron Capture, (\epsilon)</td>
<td>59.6 days</td>
</tr>
<tr>
<td>Palladium-103 ((^{103})Pd)</td>
<td>Electron Capture, (\epsilon)</td>
<td>17.0 days</td>
</tr>
<tr>
<td>Ruthenium-106 ((^{106})Ru)</td>
<td>(\beta^-) particles</td>
<td>1.02 years</td>
</tr>
<tr>
<td>Radium-226 ((^{226})Ra)</td>
<td>(\beta^-) particles</td>
<td>1599 years</td>
</tr>
</tbody>
</table>

**Side Effects of Radiation Therapy**

Patients receiving radiation therapy can experience a variety of side effects. For example, sterility could occur if reproductive organs are irradiated. Skin that has been irradiated can appear dry and feel itchy. Some patients will lose sensation in the irradiated area. Radiation can affect the production of white and red blood cells. A reduction of white blood cells results in immunity disorders. Red blood cell lose causes anemia. Gastrointestinal issues such as diarrhea and nausea are common during radiation therapy. Some patients will lose hair as well. Lastly, dry mouth and tooth decay are prevalent during radiation treatments.

Medications are available to alleviate symptoms of radiation therapy. Narcotics can be prescribed to help alleviate intense pain. Prescription medications like zofran (Figure \(\PageIndex{10}\)) and phenergan can help with nausea. Special mouthwashes have been formulated to reduce dry mouth and cavities.

*Figure*

\(\PageIndex{10}\)(left) Zofran is a medication used to prevent nausea and vomiting caused by cancer chemotherapy, radiation therapy, or surgery. (right) A vial of Zofran 4 mg containing ondansetron for intravenous injection. This medicine is a controlled substance and is used for nausea. Images used with permission (left: Public domain;
Hair loss is a side effect of radiation, but only locally

Radiation therapy can cause hair loss, but hair is only lost in the area being treated. For instance, radiation to your head may cause you to lose some or all the hair on your head (even eyebrows and lashes), but if you get treatment to your hip, you won’t lose the hair on your head.

Summary

- Compounds known as radioactive tracers can be used to follow reactions, track the distribution of a substance, diagnose and treat medical conditions, and much more.
- Other radioactive substances are helpful for controlling pests, visualizing structures, providing fire warnings, and for many other applications.
- Hundreds of millions of nuclear medicine tests and procedures, using a wide variety of radioisotopes with relatively short half-lives, are performed every year in the US.
- Radiation therapy uses high-energy radiation to kill cancer cells by damaging their DNA. The radiation used for this treatment may be delivered externally or internally.

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