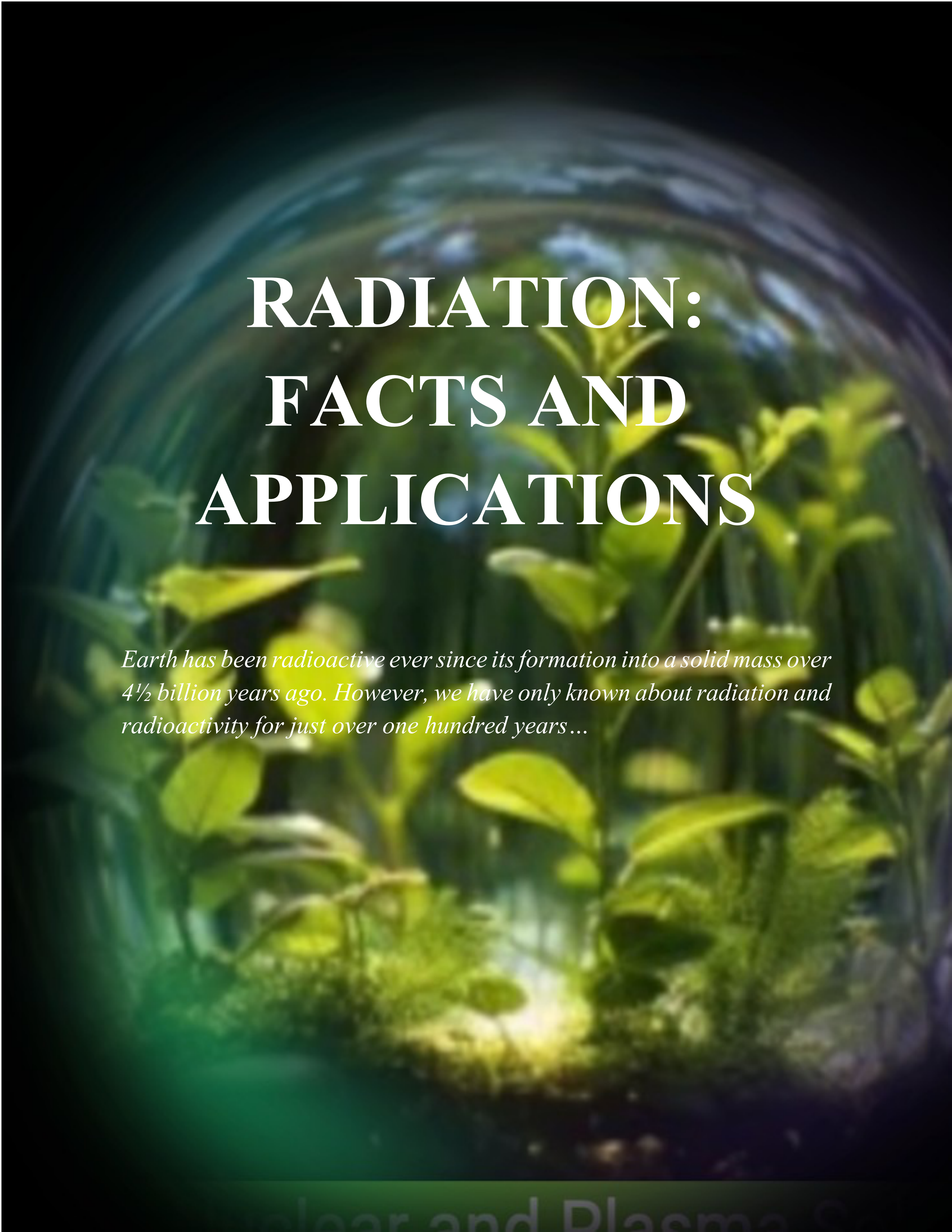

RADIATION: FACTS AND APPLICATIONS

Earth has been radioactive ever since its formation into a solid mass over 4½ billion years ago. However, we have only known about radiation and radioactivity for just over one hundred years…

Introduction

This document intends to provide a simple overview of "radiation" and its use, with its main purpose being for information and education.[1]

1. Our world is bathed in radiation

Humans have been exposed to radiation since their first appearance on Earth. For example, we are exposed to radiation coming from the Sun and from space. This is known as cosmic radiation or cosmic rays. Cosmic radiation manifests as particles, including muons and neutrons, with very high energies capable of passing through thick layers of rock and other materials. Electromagnetic radiation includes visible light, plus parts of the spectrum not visible to the human eye, including ultraviolet and infrared radiation, radio waves, X-rays and gamma radiation.

Nuclear radiation refers to the energetic particles or rays emitted from an unstable nucleus as it decays into a more stable form, while x-rays originate from atomic electrons de-exciting or from free electrons decelerating in the vicinity of atoms. Together, "radiation" can take the form of alpha particles, beta particles, x-rays, and gamma rays, each with distinct characteristics and levels of penetration. While alpha particles can be stopped by a sheet of paper, beta particles require denser materials like plastic or glass; x-rays can vary in energy and be stopped or attenuated by the human body, and gamma rays, typically being the most penetrating, often require dense materials such as lead or concrete for shielding.

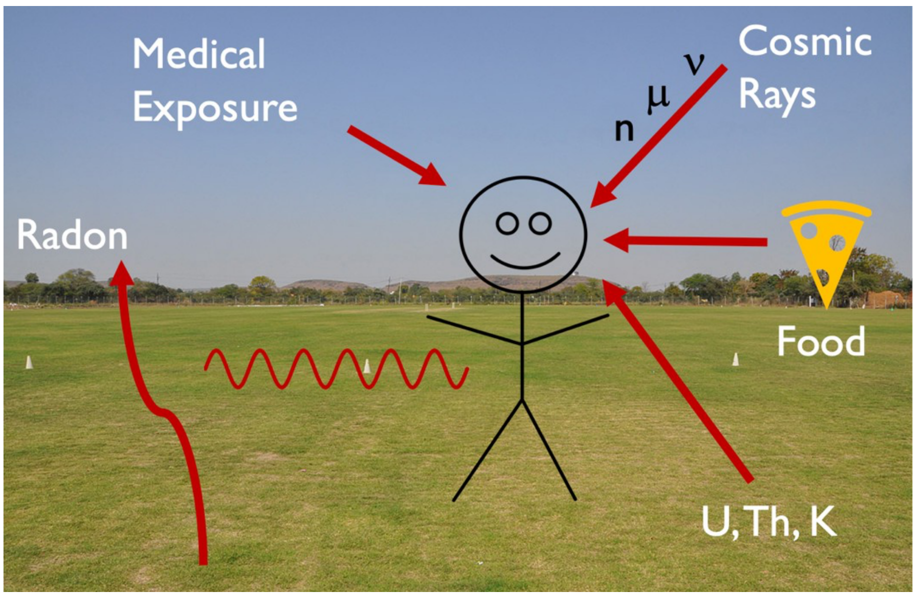

Figure 1-1: Sources of background radiation in the environment.

Nuclear radiation is a natural phenomenon occurring in various environments, ranging from cosmic rays

[1] This booklet was developed for the IEEE Nuclear and Plasma Sciences Society by C. Da Via, S. Cherry, R. Kouzes, and P. LeDu in 2025.

from space to radioactive elements in the Earth's crust. Radiation is also artificially produced in nuclear reactors, medical equipment, and other technologies. Radon is produced by nuclear decays in soil and can percolate up into houses, causing exposure (mostly to the lungs) to radiation that is very dependent on the local geology. We are exposed to radiation every day from the surrounding materials and even from the food we eat, as illustrated in Figure 1-1.

Historical Context and Discovery

The discovery of atomic radiation dates to 1895 when Wilhelm Roentgen discovered that the invisible radiation he produced by bombarding an anode with electrons emitted from a cathode caused a photographic plate to be fogged by an invisible radiation. He called this radiation “X-rays” from X, the unknown. Physicians immediately saw the usefulness of this type of radiation and began to use it in medical research. This was the birth of radiology. Similarly, in 1896, the French physicist Henri Becquerel accidentally discovered nuclear radioactivity while experimenting with uranium salts, which emitted radiation capable of fogging photographic plates. Following this, Marie and Pierre Curie conducted extensive research, leading to the discovery of two new radioactive elements, polonium and radium, decay products of uranium. Their groundbreaking work not only deepened the understanding of atomic structure but also laid the foundation for the development of nuclear physics. The 20th century witnessed significant advancements, from the harnessing of nuclear energy to the development of nuclear medicine, fundamentally altering both science and society.

In the following years, many technological discoveries were made, including:

- 1923 – The Tracer principle of G.V. Hevesy- the father of nuclear medicine
- 1932 – The invention of the cyclotron by E. Lawrence enabling the production of radioisotopes
- 1934 – The radioactivity discovered by Irène and Fréderic Jolio Curie in combination with the cyclotron opened the door to the production of useful radioactive indicators.
- 1938-1942 – The discovery of the fission of uranium (O. Hahn, E. Fermi, L. Meitner, O. Frisch) led to the production of long-lived radioisotopes; and the first graphite reactor in Chicago initiated the production of nuclear energy

Importance of Nuclear Radiation in Modern Society

Nuclear radiation plays a pivotal role in modern society, with applications spanning various fields. In medicine, it is used in diagnostic imaging techniques such as X-rays, CT scans, and PET scans, as well as in radiation therapy for cancer treatment. Nuclear energy, generated through controlled nuclear fission, provides a significant portion of the world's electricity, offering a low-carbon alternative to fossil fuels. Additionally, nuclear radiation is crucial in scientific research, helping scientists understand atomic structures and the fundamental forces of nature. Despite its benefits, the use of nuclear radiation also poses challenges, particularly in terms of safety, waste disposal, and the potential for nuclear weapons proliferation, necessitating careful regulation and international cooperation.

2. Basic types of nuclear and atomic radiation

By virtue of their high energy, ionizing radiation is penetrating, that is, it can pass through matter, ionizing atoms as it passes. However, different types of radiation can penetrate matter to different depths. This defines the thickness of the material needed to provide protection.

- **Alpha particles:** These are two neutrons and two protons, i.e., a helium nucleus. Emitted from nuclei, they have a range of 1 – 3 cm in air. A single sheet of paper, however, is thick enough to stop them.
- **Beta minus particles (electrons)**: Emitted from nuclei, beta minus particles are electrons and are more penetrating than alpha particles, with ranges up to a few meters in air. A sheet of aluminum a few millimeters thick is enough to stop electrons.
- **Beta plus particles (positrons):** Emitted from nuclei, these electron antiparticles are effectively absorbed immediately. A positron is annihilated as soon as it meets an electron, emitting two gamma ray photons. The interaction process then becomes one of gamma radiation scattering and absorption.
- **X-rays and gamma rays**: Emitted from atoms and nuclei, respectively, these photons can have very deep penetration in a material depending on their energy, and the atomic number and density of the material. Ranges can be centimeters to many meters in air. Protection is usually provided by layers of high atomic number, dense materials, such as concrete, lead, and tungsten.
- **Neutrons**: Emitted from nuclei, their penetration depends on the energy and the material they are traversing. Generally, low-Z materials, concrete, water or paraffin, barrier can moderate (slow down) and stop neutrons.

When radiation penetrates matter, it interacts with it and transfers energy to the matter. The amount of energy transferred depends on the type of interaction, resulting in an absorbed dose by the matter.

Measuring and Detecting Radiation

Radiation units provide a way to quantify the amount of radiation and its impact on matter.

- <u>Radioactivity</u> represents the number of decays of a nucleus per second: the Becquerel (Bq) is 1 decay / second and replaces the historical Curie (Ci) which is 37 GBq.
- <u>Dose</u> is the amount of radiation absorbed in any material or absorbed energy / mass: the Gray (Gy) is 1 joule of absorbed energy / kilogram of absorbing matter.
- <u>Effective Dose</u> is the estimated biological effect from the absorbed radiation and is an indication of risk: the Sievert (Sv) is 1 joule / kilogram of tissue. It a combination of the absorbed dose times a weighting factor accounting for the radiation type, times a weighting factor for the specific organ tissue.

Example of Sources of Radiation

According to the standard worldwide evaluation, the main sources of ionizing radiation that impact humans are:

- Cosmic ray 7%
- Radon 34%

- Water and food 6%
- Soils 11%
- Medical 41%
- Nuclear industry 1%

Cosmic radiation

Cosmic rays originate from energetic particles impinging on the Earth's atmosphere producing muons, neutrons and gamma rays that can reach the Earth's surface. The effective dose from cosmic radiation varies by location and altitude:

- Average 0.9 mSv / year
- Sea level 0.25 mSv / year
- Mexico (2240 m) 0.80 mSv / year
- La Paz (3900 m) 2.00 mSv / year

External radiation exposure due to earth and rocks emission

- Average 0.9 mSv / year
- Espirito Santo, Brazil 35 mSv / year
- Maximum value in Iran[2] 260 mSv / year
- Paris, France 0.20 mSv / year
- Clermont Ferrand, France 1.20 mSv / year

Internal exposure due to water (France)

- Evian water 0.03 mSv / year
- St Alban water 1.25 mSv / year

Typical exposure from radiological X rays for various organs in USA

- Thorax, face 0.015 - 0.15 mSv / year
- Lumbar region 4 - 1.5 mSv / year
- Urography 3 mSv / year
- Brain scan 1 mSv / year
- Whole Body scan 4 - 10 mSv / year
- Mammography 0.5 - 1 mSv / year

The effects of radiation on humans depends on the effective dose. The impact of an effective whole-body dose is:

- 10000 mSv: high irradiation / rapid death
- 1000 mSv: moderate irradiation / clinical visible signs such as burns

[2] Health Phys 82 (2002) p. 87

3. Nuclear Radiation in Energy Production

Nuclear Power Plants

The purpose of a nuclear reactor in a power plant is to generate heat that can be used to create steam that is used to drive a turbine to produce electrical power. Nuclear power reactors use the uranium isotope uranium-235 (^{235}U), which is naturally occurring (0.72% of uranium on Earth) and decays by alpha particle emission with a half-life of 704 million years. Upon absorption of a slow neutron, this isotope will fission 86% of the time and create two lighter fission fragments, some gamma rays, plus 2 – 3 neutrons. The neutrons make it possible to create a "chain reaction" where the fission of one ^{235}U nucleus induces one or more other ^{235}U nuclei to fission (see Figure 3-1). If uncontrolled, this chain reaction process can lead to a nuclear explosion, but if controlled, the chain reaction can reach a steady state, releasing energy in a controlled manner that can be used to heat water into steam.

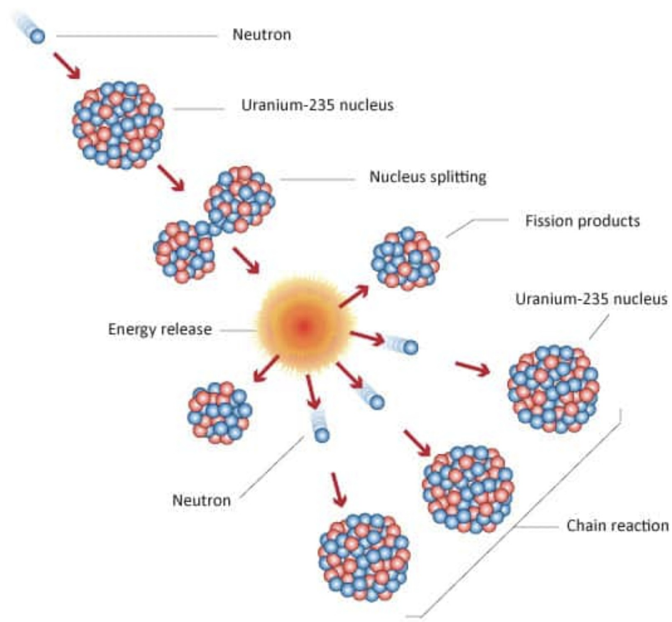

Figure 3-1. A nuclear chain reaction. A neutron induces fission in a ^{235}U nucleus, creating two daughters and more neutrons that sustain the chain reaction.
(From *Nuclear Fission Chain Reaction*, nuclear- power.com)

Electrical power generation from nuclear reactors begins with the ^{235}U fission process. The ^{235}U is contained in nuclear fuel rods which consist of mostly ^{238}U (which is not easily fissioned) and typically less than 20% ^{235}U. To maintain a steady state reaction, "control rods," consisting of a material that absorbs neutrons (such as cadmium) so that the chain reaction does not run away, are used. The fuel rods and control rods are typically immersed in a bath of water which acts as a "moderator" to slow down the fission neutrons so they can more readily fission another ^{235}U nucleus. This water is heated by the energy released in the fission reactions and is pumped to a heat exchanger to create steam in a secondary water loop to drive the turbine that generates electricity, as seen schematically in Figure 3-2. This keeps any contaminants in the primary water circuit from escaping into the secondary water circuit. The steam coming from the turbine is then converted back to water in a "condenser" that utilizes a "cooling tower" as a 3rd water circuit heat exchanger cooled by water from a nearby natural source.

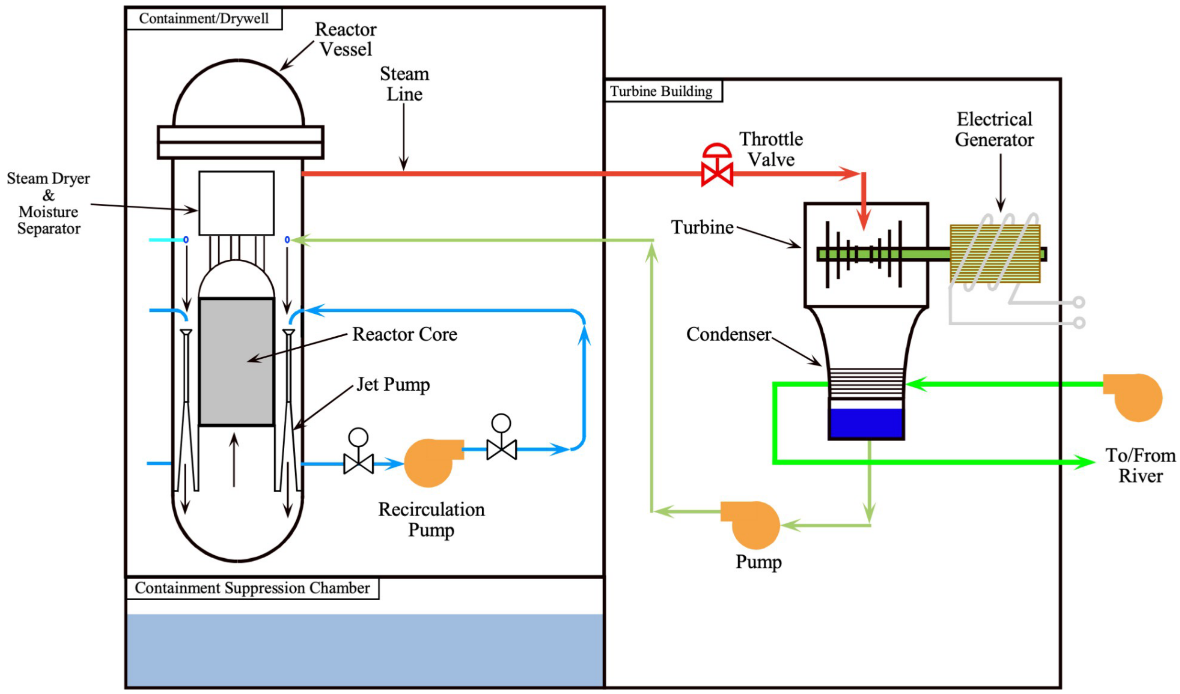

Figure 3-2. Schematic of a BWR nuclear power plant system (US NRC Technical Training Manual).

Nuclear power reactors come in a variety of forms, the most common being light (ordinary) water reactors, either boiling water reactors (BWR) or pressurized water reactors (PWR). In the former, the hot water in the pressure vessel containing the fuel assembly is allowed to boil, whereas in the latter, the pressure is high enough to keep the hot water as a liquid.

Another reactor design is based on "heavy water" which is water where the hydrogen atoms in H_2O are replaced with deuterium atoms. Deuterium is naturally occurring isotope hydrogen in which there is one proton and one neutron in the nucleus rather than just the single proton that forms normal hydrogen. The advantage of this reactor design is that the ^{235}U in the fuel does not need to be enriched so natural uranium can be used, reducing the cost and effort to enrich the ^{235}U that is used in most reactors. This is because heavy water absorbs many fewer neutrons that normal water, so the chain reaction is not damped by neutron absorption in the water.

The nuclear reactors on submarines and aircraft carriers that provide electricity and propulsion power use more highly enriched ^{235}U, varying from 20% to 95%. This allows these reactors to be smaller and to operate at full power for many years.

Benefits of Nuclear Energy

Nuclear power reactors are highly efficient and reliable. A typical reactor in the United States generates about 1 GW of electricity and operates at a high enough temperature to have an efficiency of 33-37%, comparable to fossil fueled power plants. The next Generation IV of nuclear power plants could have an efficiency above 45%. This typical plant can power about one million homes. Nuclear reactors are typically refueled every 18-24 months where 1/3 of the fuel rods are replaced, requiring a shutdown of about a few weeks. During the normal operation period, the nuclear plant produces power continuously and can adjust easily to changes in power demand by adjusting the control rods.

Nuclear power plant operation does not produce carbon dioxide or any other greenhouse gasses (such as methane). This makes nuclear power a "green" energy source along with hydro, solar, and wind power, except nuclear power provides continuous power production since it does not depend on the sun or wind or water flow. Some greenhouse gases are produced during construction of the nuclear plant, the same as construction of fossil fuel plants, and during the mining of ore and the production of the nuclear fuel used in the reactor.

Challenges and Risks

Nuclear power produces waste, starting with mining operations though a much smaller volume than coal mining. Used fuel elements removed from power plants during refueling are highly radioactive and still physically hot from the decay of fission products in the fuel, so they are placed into water cooling ponds for about five years. After that time, they are put into concrete dry storage casks (see Figure 3-3) where they may remain permanently. The U.S. does not have a permanent storage site for spent fuel; there are 85 sites in the U.S. where dry storage casks are located. Similar situations exist around the world, which raises concerns about safety and security of nuclear material.

Figure 3-3. Dry Storage of Spent Nuclear Fuel (2004. U.S. Nuclear Regulatory Commission, Rockville, MD. Flickr. JPEG image).

It is possible to reprocess spent nuclear fuel to separate out the remaining ^{235}U for reuse in new fuel elements, and the highly radioactive heavy waste products for storage. This is done[3] in France, Russia, the U.K., and India, but U.S. policy does not allow such reprocessing. Reprocessing has the advantage of removing unburned ^{235}U and reducing the volume of the highly radioactive waste components in the spent fuel. The disadvantage of reprocessing is the possibility that some component materials in the waste could be used to make nuclear weapons, which is why the U.S. does not currently allow reprocessing. In the future, reprocessing of nuclear fuel may be implemented in the U.S. if the process can be adequately secured. Japan, for example, is investing in reprocessing technology at the Rokkashu Mura facility to help reduce their nuclear waste problem.

There have been 3 notable nuclear power reactor accidents in all the years of reactor operation. The first was the Three Mile Island reactor accident in 1979 in Pennsylvania, USA. In this accident, there were a series of malfunctions due largely to human error, starting with a valve being left closed and a pressure relief valve that stuck open, resulting in a loss of coolant accident (LOCA) condition. Poor response by the operators resulted in a meltdown in the core, destroying the usefulness of the reactor. The only external consequence was a release of radioactive gas into the environment that was found to have no long-term impact on the surrounding population. The cleanup after the accident cost about $1B.

The second accident was the disastrous fire at the Chernobyl plant in the Ukraine in 1986 that released large quantities of radioactivity into the environment impacting multiple countries. The several reactors at Chernobyl are a water cooled, and graphite moderated Russian RBMK reactors. The accident resulted from human error while performing a test of the steam turbine's ability to power the emergency feedwater pumps if there were a simultaneous coolant pipe rupture and a loss of external power. A series of operator actions then resulted in a LOCA leading to a fire in the graphite moderator that destroyed the reactor and released huge quantities of radionuclides into the air. The cost of cleanup was many lives lost, and the cleanup cost has been over $700B, the costliest disaster in human history.

The third accident was the Fukushima reactor meltdown in 2011 in Japan, when a tsunami following an earthquake swamped critical backup power systems at the plant. The resulting loss of external electrical power allowed the reactor to overheat, melting the core, followed by an explosion of hydrogen gas in the reactor, thus releasing radionuclides into the area surrounding the plant. The consequence of the accident has resulted in evacuation of the nearby population and cost well over $100B to date.

Advances in Nuclear Technology

Typical nuclear power reactors are of the scale of 3 GW thermal, resulting in 1 GW of electrical power. The latest trend in nuclear power reactor design is what is the small modular reactor (SMR), where a plant may contain multiple reactors that are on the scale of 300 MW electrical output, with a variety of designs. These new designs incorporate several passive safety features that prevent reactor accidents such as in the case of loss of external power. It should be possible to construct such reactors more quickly and at a lower cost than previous conventional designs. The SMRs should require less frequent refueling,

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[3] World Nuclear Assoc. report, https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel, from 8/2024.

every 3-7 years rather than the 1-2 years for conventional reactors.

A future nuclear energy option is the application of fusion. Fusion is the process of merging certain light nuclei, resulting in the release of energy; there is no chain reaction involved. Fusion is the process that releases energy in the center of our Sun. If fusion can be produced in a controlled manner on Earth, it could lead to a safe and clean power source. Scientists have been working on methods to create fusion in the laboratory for decades. It is challenging since it requires very high temperatures for fusion to occur. The current reaction being investigated is the fusion of a deuterium nucleus (one proton and one neutron) with a tritium nucleus (one proton and two neutrons) resulting in a helium nucleus (two protons and two neutrons) and a neutron, with the release of a significant amount of energy. Once this reaction can be produced in a continuous manner and applied to power production, other possible reaction fuels beyond deuterium and tritium might become feasible with advantages in the power produced with less accompanying radiation. Fusion is the great hope for a clean nuclear power future.

4. Radiation in Medicine

Ionizing radiation, which includes radiation emitted from the atomic nucleus as well as x-rays that originate from atomic transitions, plays a critical role in the diagnosis of a wide range of medical injuries, diseases and disorders, and is one of the most effective options for treating cancer. In this section, we discuss how different types of radiation are used to produce diagnostic images, and how external radiation beams or administered radiopharmaceuticals can be used for treatment.

X-rays

Within a few months of the discovery of x-rays by Wilhelm Roentgen in 1895, physicians were already exploiting the ability to see deep into the human body with this penetrating form of radiation and the medical discipline of Radiology was born. X-rays were transformative in medicine - for the first time, the skeleton and internal organs of the body were visible, without surgery. 130 years later, x-rays are still the most common diagnostic imaging methodology, with more than 1 billion scans being performed annually across the world. Many of us are familiar with routine uses of x-rays that include dental x-rays, chest x-rays, and mammograms used to screen for breast cancer. X-rays are often the first line of diagnostics for sports injuries, joint or muscular pain, persistent cough or breathing problems. Modern x-ray imaging systems are highly flexible, offering the ability to image many different parts of the body with highly sensitive and high-resolution digital detectors that produce exquisite images at very low radiation doses. Figure 4-1 shows an example of a clinical x-ray imaging system and some representative x-ray images. There also are several specialized forms of x-ray imaging systems including mammography (to screen for breast cancer), fluoroscopy (real-time continuous x-ray imaging for guiding interventions such as placing a stent in a coronary artery) and angiography (uses a similar set-up to fluoroscopy but with the addition of a contrast agent to allow blood vessels to be clearly visualized).

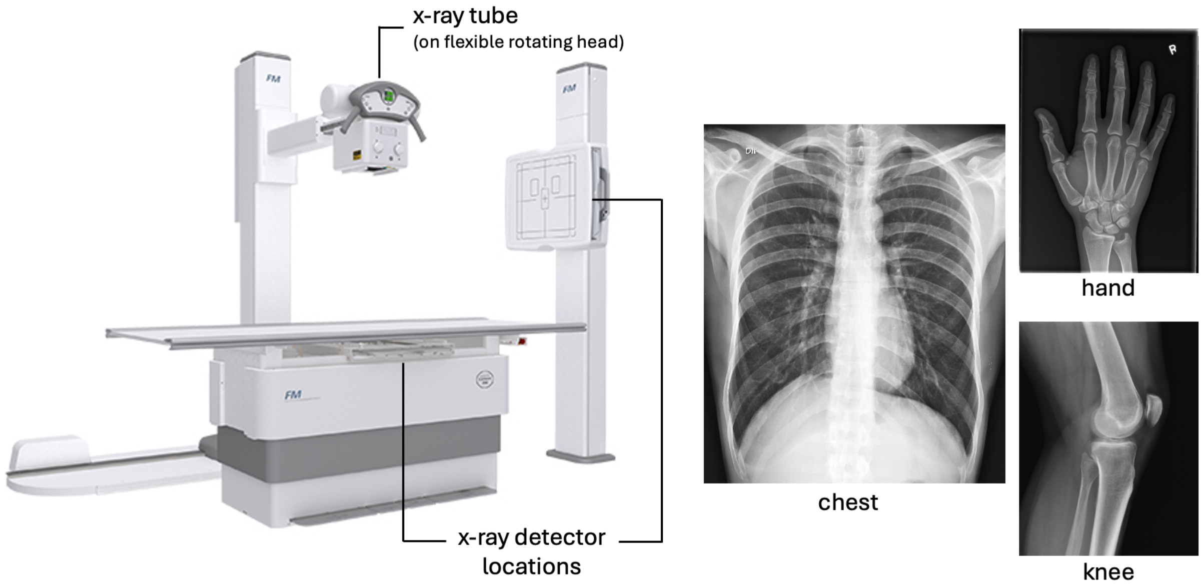


Figure 4-1: Typical clinical digital x-ray radiography system showing the x-ray tube which generates high-energy x-rays that pass through the patients onto a digital detector (Courtesy United Imaging Healthcare). An image is formed based on the differential scattering and absorption of x-rays by different tissues of the body. The x-ray tube and detectors can be positioned flexibly to image different parts of the body as shown by the example images on the right (cases courtesy of Dr. B. Di Muzio, Radiopaedia.org, rID: 37906 and rID: 38755; and Dr. A. Murphy, Radiopaedia.org, rID: 48333)

CT Scans

A major limitation of conventional x-rays is that the images correspond to a projection of the three-dimensional body onto a two-dimensional imaging detector. This causes structures that lie along the direction of the x-ray beam and are located either in front or behind the organ or tissue of interest, to overlap. In the lungs and extremities, this may not be a problem, because there is little overlapping tissue, but in the abdomen, where there are multiple organs at different depths, conventional x-ray images can be very hard to interpret.

The solution is to acquire multiple x-ray images at different angles around the patient and then use mathematical algorithms to "reconstruct" a stack of cross-sectional images, or "slices" across the body. This is known as computed tomography (CT), where "tomo-" is the Greek word for slice. CT scanners are based on rotating x-ray systems and tomographic reconstruction methods largely developed in the early 1970s (although the mathematics used dates to Johann Radon in 1917). The concept behind CT is shown in Figure 4-2. Scans of large numbers of slices covering tens of cm along the length of the body can be acquired in just seconds.

CT scanning has major uses in medicine, including detection of tumors in many organs of the body, assessing musculoskeletal disorders and pain. Just as with conventional x-rays, differences in image intensity reflect the fact that different types of tissue vary in their ability to scatter or absorb x-rays. The ability to visualize blood can also be augmented by the injection of contrast agents that circulate in the blood and increase the absorption and scattering of x-rays compared to surrounding tissue. Contrast-enhanced CT scans enable restrictions or blockages in blood vessels to be observed and also are important for determining if vessels have ruptured allowing blood to infiltrate surrounding tissues (e.g. in hemorrhagic stroke). Figure 4-3 shows a CT scanner and a CT scan in a patient with liver cancer. Godfrey Hounsfield and Allan Cormack were awarded the Nobel Prize for Medicine in 1979 for their contributions to developing the CT scanner. CT has evolved into one of the most important diagnostic tools in medicine, producing high-quality images, in very short scan times, and contemporary systems do this at much reduced radiation doses (see Table 4-1).

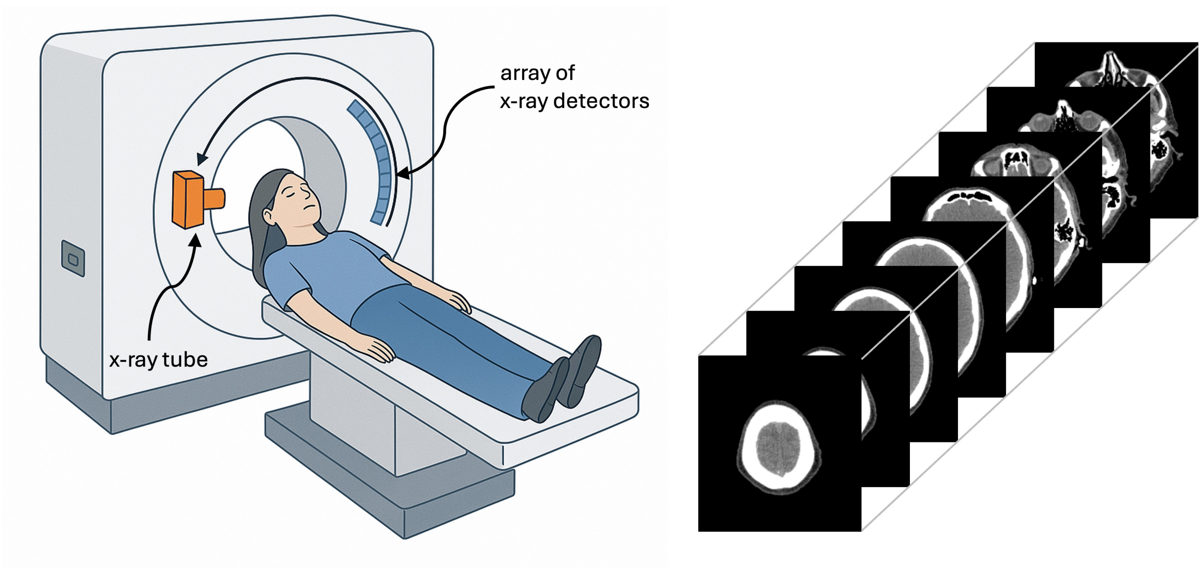


Figure 4-2: Left: Schematic of a CT scanner. The x-ray tube and detector rotate around the body capturing views at multiple angles which are reconstructed into cross-sectional images. Right: Multiple slices are stacked to form a 3-D image volume.

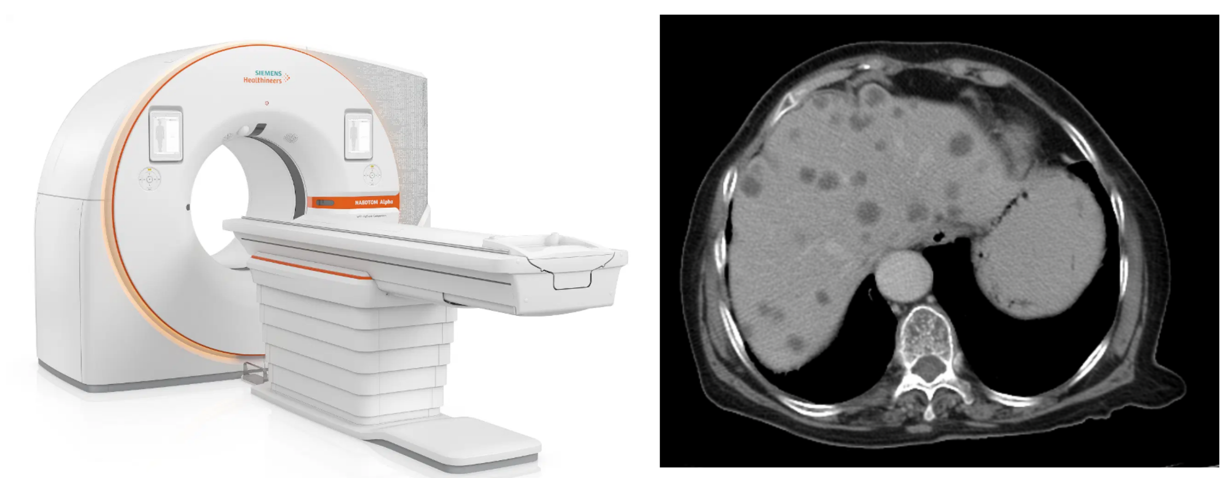
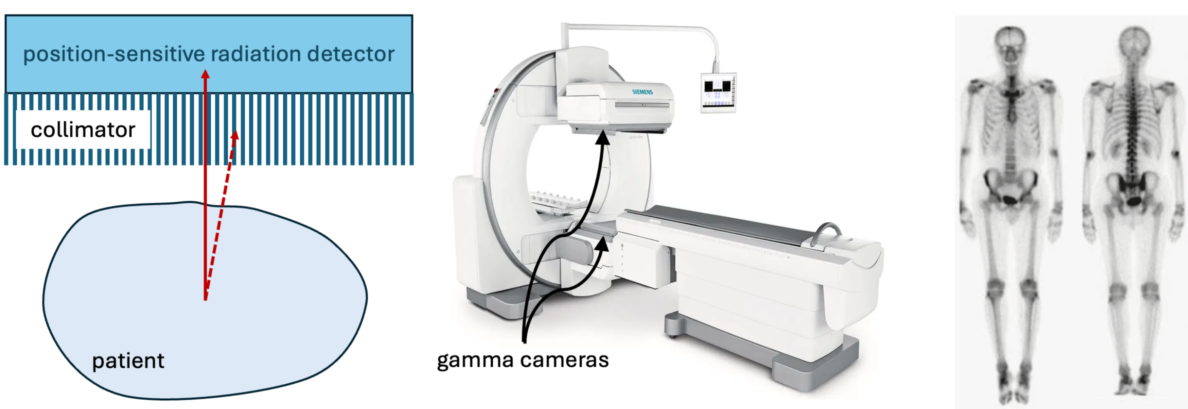


Figure 4-3: Left: Photograph of a CT scanner (Courtesy Siemens Healthineers). Right: Single CT slice at the level of the liver showing multiple cancerous lesions (dark spots) (case courtesy of Dr. A. BinNuhaid, Radiopaedia.org, rID-197788).

Nuclear Medicine: Scintigraphy, SPECT and PET Scans

In a nuclear medicine scan, minute amounts of a compound are labeled with a radioactive isotope and this "radiotracer" is introduced into the body, typically by intravenous injection. The radioactive isotope is chosen to be one that emits high-energy photons (typically gamma rays) when it decays, and these high-energy photons can pass through the tissues of the body and escape with relatively high probability and be imaged using an array of external detectors. This is known as emission imaging, because the signal source is inside the body, compared to imaging with x-rays, which is transmission imaging, where radiation is transmitted through the body from an external signal source. Nuclear medicine also fundamentally differs from x-ray imaging in that it can used to measure function in the body, rather than anatomy. The administered radiotracer defines what is measured, and a wide array of radiotracers are approved for clinical use, measuring a diverse range of parameters that include blood flow, kidney function, glucose metabolism, or the presence or absence of specific receptors on the cell surface, to name but a few. Careful consideration is given to the radioisotope used for labeling in terms of its half-life (time for the radioactivity to diminish by half) and decay products (emission of photons and particles) to maximize diagnostic image quality while minimizing radiation dose. These radioisotopes are produced in nuclear reactors, or by particle accelerators such as a cyclotron.

Scintigraphy: The most basic form of nuclear medicine is scintigraphy or also known as planar imaging. This is analogous to a standard x-ray, in that is provides a single 2-D image which is a projection of the radioactivity distributed in the body. Imaging is performed with a gamma camera, which consists of a collimator and a position-sensing detector in which the high-energy photons or gamma rays interact. The collimator is a sheet of lead with holes that define the directions of the incoming gamma rays that can reach the detector to form the image (Figure 4-4A). Figure 4-4 also shows a typical gamma camera and the image it produces. A system may consist of two gamma camera heads, allowing two different views to be acquired at the same time. Clinical applications of scintigraphy include bone scans to evaluate whether cancer has spread to the skeleton, kidney and liver function tests and evaluation of thyroid conditions.



A B C

Figure 4-4: A: Concept of a gamma camera. The lead collimator only allows photons emitted parallel to the holes to reach the detector (red solid line), whereas those emitted obliquely are absorbed by the collimator (dashed line). This allows an image to be formed. B: Commercial system with two gamma cameras (courtesy Siemens Healthineers). C: Planar images of the radiotracer ^{99m}Tc-MDP which selectively concentrates in bone. Front and back views corresponding to images from each of the gamma cameras are shown (Cherry et al, *Physics in Nuclear Medicine*, Elsevier, 2013).

Single photon emission computed tomography (SPECT): SPECT is analogous to the CT scanner in that the gamma camera is rotated around the patient and images are acquired at different angles. These images can then be reconstructed into cross- sectional slices that together form an image volume. This allows the radioactivity distribution to be visualized in 3-D, greatly facilitating interpretation and quantification of where the radiotracer is localized in different organs. Figure 4-5 shows SPECT images of the heart of a patient with coronary artery disease, showing reduced blood flow in particular areas of the heart muscle. Sometimes, a SPECT scanner is integrated with a CT scanner, to provide combined functional (SPECT) and anatomical (CT) imaging capabilities. Clinical applications of SPECT imaging include measuring blood flow in the heart or brain.

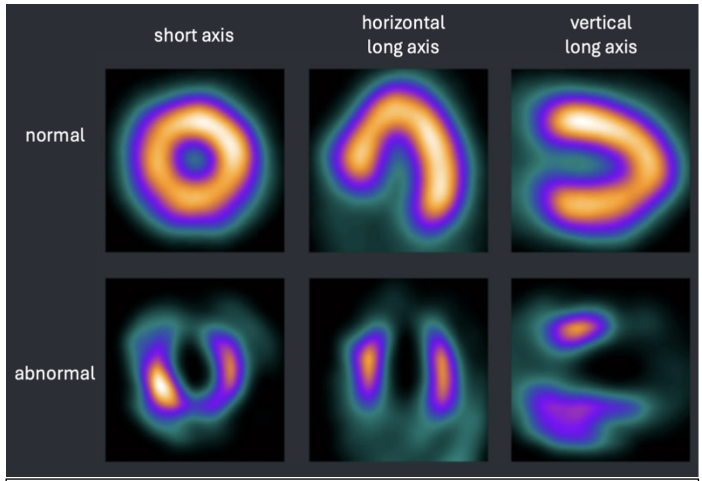


Figure 4-5: SPECT images of cardiac blood flow showing three different views of the left ventricle of the heart in a healthy subject with uniform blood flow (top row) and a patient with abnormal blood flow (bottom row) (Images courtesy of Digirad Inc.).

Positron emission tomography (PET): PET scanning exclusively uses radioisotopes that decay by the process of positron emission (known as β^+ decay). The resulting positron, which is the antiparticle to an electron, will quickly find an electron in the surrounding tissue and the two particles annihilate, converting their mass into two high-energy photons, emitted back-to-back. It is this pair of photons that are detected in a PET scanner. Because detection of both photons determines their direction through the body, no collimator is needed to form an image. Instead, coincident detection of photons by a pair of detectors 180° apart, determines the direction of travel. A PET scanner typically consists of multiple rings of radiation detectors (Figure 4-6A) that can capture photon pairs emitted in many different directions, and volumetric images are produced using an image reconstruction algorithm. PET scanners are typically combined with a CT scanner, or less commonly an MRI scanner for anatomic correlation. Major clinical indications include metabolic imaging to assist with staging of cancer or monitoring response to treatment in cancer patients, imaging blood flow in the myocardium, and imaging of the amount of amyloid in the brain of patients with Alzheimer's disease. Figure 4-6 shows a PET/CT scanner and example images.

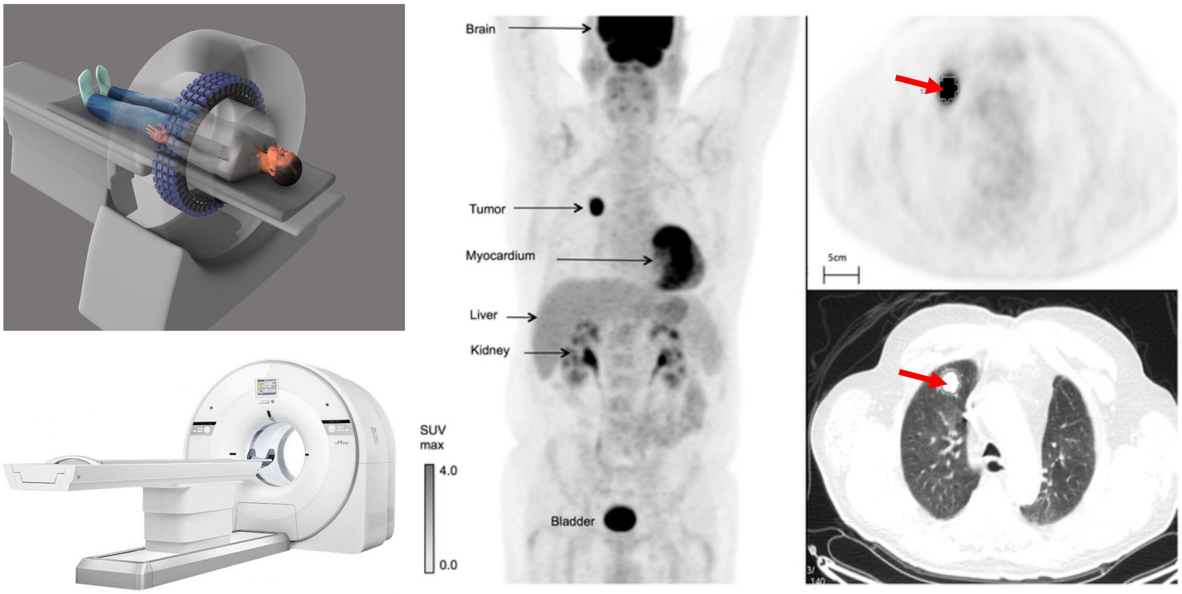


Figure 4-6: Left: Schematic view of a PET scanner (Cherry et al, *Sci Trans Med* 2017; 9: eaaf6169) and photograph of a clinical PET/CT scanner (courtesy United Imaging Healthcare). Right: Metabolic whole-body PET image of a patient with a lung tumor, and a single slice at the level of the tumor (arrow) with correlating anatomical CT image (Nair et al, *PLOS ONE* 2013; 8: e67733).

Therapeutic Uses

Radiation is one of the major approaches used to treat cancer, either using external beams of radiation that are aimed at the tumor, or by injecting compounds labeled with radioisotopes that can selectively localize to tumors, and by emitting energetic particles, destroy them. The key challenge in the therapeutic use of radiation is to maximize the dose to the tumor cells while keeping the dose to surrounding healthy tissues below the levels that can cause lasting damage. Thus, careful planning of the radiation dose distribution is an integral part of the therapeutic use of radiation. Radiation has been demonstrated to be a highly effective and essential tool in treating cancer.

External Beam Radiation Therapy

External beam radiation therapy uses beams of photons or particles that are directed onto the tumor being treated. The beam delivery is carefully planned to conform to the shape and location of the tumor. The beam can be shaped using a collimator and modulated in intensity and multiple beams entering the body from different directions are often used to maximize the dose to the tumor relative to surrounding tissues. The time over which the radiation is delivered is another important factor. The dose is commonly divided into fractions that may be delivered in separate visits over a period of weeks. Figure 4-7 shows a typical linear accelerator used in a hospital, and a multi-beam treatment plan for a patient with a prostate tumor.

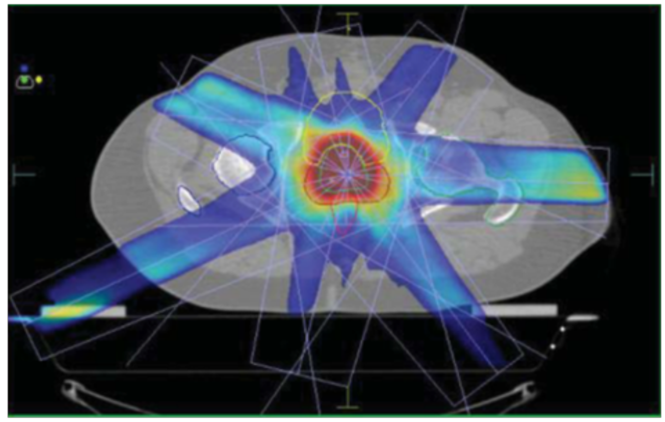


Figure 4-7: Left: Linear accelerator used for external beam radiation therapy (courtesy Varian Inc.). Right: Typical treatment plan showing dose distribution for multiple intersecting beams delivering high dose to the prostate region and much lower dose to surrounding tissues. (Sia et al, *Cancers* 2011, 3, 3419-3431).

The most widely used radiation for cancer treatment are high energy photons, produced by a linear accelerator (known as a LINAC) which accelerates electrons onto a target to produce the photons. For superficial tumors, the electrons produced by the LINAC, which only have a small range in tissue, can be used directly. Protons and heavy ions also can be used for cancer treatment, with the advantage that their range in tissue can be quite precisely controlled by tuning their energy. However, they require more complex and expensive accelerators for production.

Internal Radionuclide Therapy

Using radioisotopes that emit energetic particles such as electrons and alpha particles, radiolabeled compounds that are delivered to or targeted towards cancer cells can be an effective treatment for certain types of cancer. For example, ^{131}I is used to ablate the thyroid in the case of thyroid cancer and Grave's disease, ^{90}Y microspheres are directly injected into the blood vessels supplying liver tumors and ^{177}Lu labeled compounds can be used to target prostate cancer cells or neuroendocrine tumors. These internal radiopharmaceutical treatments represent a rapidly growing area in cancer treatment.

Radiation Risks, Safety in Medical Settings

Radiation doses received by patients undergoing diagnostic imaging with ionizing radiation are carefully controlled and minimized to levels where the risks from the radiation dose are generally far lower than the risks due to under- or mis-diagnosing a disease that would occur from not receiving the imaging examination. The doses are of a similar magnitude to those received annually from natural background radiation. The radiation doses from some typical diagnostic imaging tests are shown in Table 4-1. In therapeutic uses, the doses are far higher, as the goal is to give sufficient dose to a tumor to kill all the cancer cells, while minimizing, to the extent possible, dose to healthy surrounding tissues. This balance is chosen for each patient based on extensive dose planning, the particular patient and their condition, and the intent of the treatment (curative versus palliative).

Procedure		Approximate effective radiation dose (mSv)	Approximate comparable time of natural background radiation exposure
ABDOMINAL REGION	Computed Tomography (CT) — Abdomen and Pelvis	7.7 mSv	2.6 years
	Computed Tomography (CT) — Abdomen and Pelvis, repeated with and without contrast material	15.4 mSv	5.1 years
	Computed Tomography (CT) — Colonography	6 mSv	2 years
	Intravenous Urogram (IVU))	3 mSv	1 year
	Barium Enema (Lower GI X-ray)	6 mSv	2 years
	Upper GI Study With Barium	6 mSv	2 years
BONE	Lumbar Spine	1.4 mSv	6 months
	Extremity (hand, foot, etc.) X-ray	< 0.001 mSv	< 3 hours
CENTRAL NERVOUS SYSTEM	Computed Tomography (CT) — Brain	1.6 mSv	7 months
	Computed Tomography (CT) — Brain, repeated with and without contrast material	3.2 mSv	13 months
	Computed Tomography (CT) — Head and Neck	1.2 mSv	5 months
	Computed Tomography (CT) — Spine	8.8 mSv	3 years
CHEST	Computed Tomography (CT) — Chest	6.1 mSv	2 years
	Computed Tomography (CT) — Lung Cancer Screening	1.5 mSv	6 months
	Chest X-ray	0.1 mSv	10 days
DENTAL	Dental X-ray	0.005 mSv	1 day
	Panoramic X-Ray	0.025 mSv	3 days
	Cone Beam CT	0.18 mSv	22 days
HEART	Coronary Computed Tomography Angiography (CTA)	8.7 mSv	3 years
	Cardiac CT for Calcium Scoring	1.7 mSv	6 months
	Non-Cardiac Computed Tomography Angiography (CTA)	5.1 mSv	< 2 years
MEN'S IMAGING	Bone Densitometry (DEXA)	0.001 mSv	3 hours
NUCLEAR MEDICINE	Positron Emission Tomography — Computed Tomography (PET/CT) Whole body protocol	22.7 mSv	7.6 years
WOMEN'S IMAGING	Bone Densitometry (DEXA)	0.001 mSv	3 hours
	Screening Digital Mammography	0.21 mSv	26 days
	Screening Digital Breast Tomosynthesis (3D Mammogram)	0.27 mSv	33 days

Note: This chart simplifies a highly complex topic for patients' informational use. The effective doses are typical values for an average-sized adult. The actual dose can vary substantially, depending on a person's size as well as on differences in imaging practices. It is also important to note that doses given to pediatric patients will vary significantly from those given to adults, since children vary in size. Patients with radiation dose questions should consult with their medical physicists and/or radiologists as part of a larger discussion on the benefits and risks of radiologic care.

Table 4-1: Radiation dose to adults from common medical imaging procedures (*RadiologyInfo.org*).

5. Conclusion

We are exposed to radiation from atomic and nuclear sources every day from our environment, medical applications, and man-made sources. Understanding the sources, benefits and dangers of radiation exposure can help us to understand how this impacts our lives. We benefit from the exploitation of atomic and nuclear radiation through the generation of electricity in nuclear power plants and from a myriad of medical applications including imaging and the treatment of diseases. At the same time, we must keep in mind that radiation can be a dangerous if mismanaged or not controlled by appropriate engineering of the systems. Through responsible use and innovation, radiation can be managed to bring great benefits to our society.

References

There are hundreds of books and thousands of articles on atomic and nuclear radiation. Some references:

Radiation Detection and Measurement, Glenn F. Knoll, John Wiley and Sons, Inc., 5th Edition (2022)
What is Radiation, International Atomic Energy Agency
What Are the Different Types of Radiation?, US Nuclear Regulatory Commission