Physician Training Modules for Certification in Radiation Safety Officer (RSO)

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Introduction

"Radiation safety officer" is a person who has the knowledge and responsibility to apply appropriate regulations for protection against ionizing radiation. All organizations that are registered to use ionizing radiation must have a Radiation Safety Officer (RSO). The RSO is the individual authorized by an organization (e.g., your clinic) to serve as the point of contact for all activities related to radiation protection. The RSO ensures that radiation safety activities are being performed in accordance with approved procedures and regulatory requirements. Some common RSO responsibilities include:

- Ensuring that all individuals using radiation equipment are appropriately trained and supervised.
- Ensuring that all individuals using the equipment have been formally authorized to use the equipment.
- Ensuring that all rules, regulations, and procedures for the safe use of radiation producing machines are observed.
- Ensuring that proper Operating, Emergency, and ALARA Procedures have been developed and are available to all system users.
- Ensuring that accurate records of radiation equipment maintenance and repairs are maintained.
- Ensuring that periodic QC and QA testing of the radiation producing equipment are completed.
- Ensuring that required radiation surveys are performed and documented.
- Ensure personnel radiation monitoring devices are properly used and processed, and the results are reviewed to verify personnel radiation exposures are kept to a minimum. Ensuring that the radiation machines secure from unauthorized access.

Sources of Radiation

We live in a world filled with radiation. There are many natural sources of radiation, which have been present since the earth was formed. These are primarily in the form of radioactive elements in the earth and cosmic rays from our sun and distant stars. In the last century, we have added somewhat to this natural background radiation with some artificial sources, most of which are from diagnostic medical procedures. It may surprise you to know that for an average person, the naturally occurring sources contribute about four to five times as much to your exposure as the human-made sources.

Natural Radiation

The three major sources of naturally occurring radiation are:

- Cosmic radiation.
- Sources in the earth's crust, also referred to as terrestrial radiation.
- Sources in the human body, also referred to as internal sources.

Cosmic Radiation

Cosmic radiation comes from the sun and outer space and consists primarily of positively charged particles (mainly high energy protons), as well as gamma radiation. At sea level, the average cosmic radiation exposure is about 26 mrem per year. At higher elevations the amount of atmosphere shielding these cosmic rays decreases and thus the radiation exposure increases. The average dose in the United States is approximately 43 mrem/year.

Natural Sources

There are natural sources of radiation in the ground, rocks, building materials and drinking water supplies. This is called terrestrial radiation. The main contributors of terrestrial sources are natural uranium and thorium and their radioactive ‘daughter’ products. Radon gas is a current health concern. This gas is from the decay of natural uranium in soil. Radon is one of the noble gases found on the right column of the periodic chart. These gases are chemically inert and do not readily bind to other elements or molecules. Thus radon rises from the soil under and around house basements and foundations, and can build up in homes, particularly well-insulated homes that don’t ‘breathe’. In the USA, the average effective whole body dose from radon is about 200 mrem per year.

Internal Sources

Our bodies also contain natural radionuclides. Potassium 40 is one example. The total average dose is approximately 45 mrem/year.

Human Sources

The difference between man-made sources of radiation and naturally occurring sources is the place from which the radiation originates. The following information briefly describes some examples of human-made radiation sources.

Medical Radiation Sources

X rays are produced from machines and gamma rays are produced from radioactive elements. X-rays and gamma rays are identical to each other: the difference is mainly a naming convention and is based on the history of their discovery. X-rays are from machines using special electrical circuits and components: X-rays are often called electrically produced radiation. Gamma rays on the other hand originate from radioactive elements as they decay. Both are medically useful, but both also present a potential ionizing radiation hazard. A typical radiation dose from a chest x ray is about 10 mrem while a typical CAT scan, which uses X-rays gives around 1,500 mrem. The total average dose from medical x-rays is 45 mrem per person in the US in a year. In addition to x-rays, radioactive isotopes are used in medicine for diagnosis and therapy. The total average dose from medical radioactive isotopes is 15 mrem per person in the US in a year.

Consumer Products

Examples include TV's, older luminous dial watches, some smoke detectors, and lantern mantles. This dose is relatively small as compared to other naturally occurring sources of ionizing radiation and averages 10 mrem in a year. It is noted that the microwave energy in a microwave oven is not ionizing radiation: It is below the ionizing energy threshold. Microwave energy produces heat not ions. More on this later.

Atmospheric Testing of Nuclear Weapons

Another man-made source of radiation includes residual fallout from atmospheric nuclear weapons testing in the 1950's and early 1960's. Atmospheric testing is now banned by most nations. The average dose from residual fallout is about 2 mrem in a year.

Industrial Uses

Industrial uses of radiation include x-ray machines and radioactive sources used for radiography to test pipe welds, bore-holes, etc. Most people receive little if any dose from these sources. Nuclear power plants also release very little radioactivity.

Summary
As a whole, these sources of natural and human-made radiation are referred to as background. The average annual radiation dose to a member of the general population from ALL background sources is about 360 millirem.

Radiation: Particle vs Electromagnetic

Particle radiation is energy radiated by means of fast-moving atomic and subatomic particles. Particle radiation is referred to as a ‘particle beam’ if the particles are all moving in the same direction, similar to a light beam. Due to the wave-particle duality of quantum physics, all moving particles also have wave character. Higher energy particles more readily exhibit particle characteristics, while lower energy particles exhibit some wave characteristics. Particles can be electrically charged or uncharged.

Particle radiation is generally emitted by an unstable atomic nucleus (via radioactive decay) by nuclear fission, or nuclear fusion. Particle radiation can also be generated via very high energy x-rays. The following is a list of common types of particle radiation, listed from lightest to heaviest. This information is being provided to help complete your understanding of various forms of ionizing radiation. It is noted that these are not used or created with Superficial Radiation:

- Neutrinos
- Mesons
- Muons
- Positively or negatively charged beta particles (β+ or β-) (the latter being more common)
- High speed electrons from Internal Conversion or the Auger Electrons.
- Protons (positive charge)
- Neutrons, (no charge)
- Positively charged alpha particles (α) from radioactive decay of heavy isotopes
- Helium ions at high energy levels (also considered α particles)
- Heavier element nuclei (atoms stripped of their electrons)
- HZE ions: high energy nuclei heavier than helium. HZE stands for high (H) atomic number (Z) and energy (E) [cosmic rays from distant supernovas

Mechanisms that produce particle radiation include:

Electrons (β+, β-, energetic electrons)

- Auger Effect
- Internal Conversion
- Beta decay (from nucleus)
- Ionization (Photoelectric, Compton, Pair Production)

Protons

- Proton emission
- Particle colliders in which streams of high energy particles are smashed
- Solar flares

Neutrons

- Neutron emission
- Nuclear fusion

Alpha Particles

- Alpha decay
- Cluster decay
- Nuclear fission and spontaneous fission

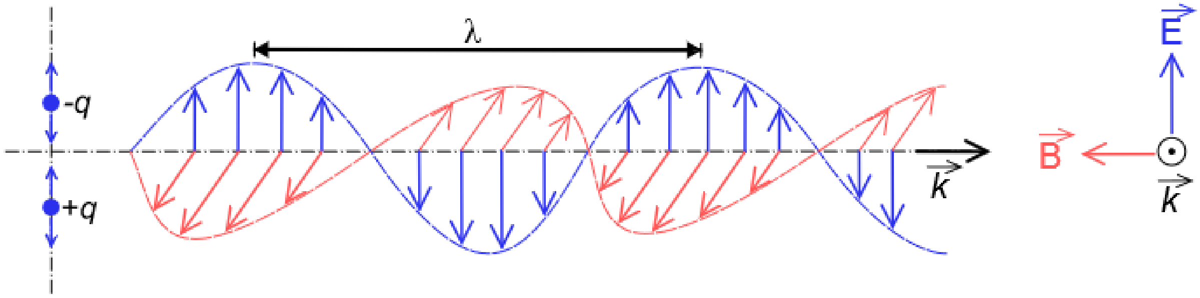
HZE

- Supernova explosions and other galactic sources

Charged particles (electrons, mesons, protons, alpha particles, heavy HZE ions, etc.) can be produced by particle accelerators. Ion irradiation is widely used in the semiconductor industry to introduce dopants into materials, a method known as ion implantation.

Electromagnetic Radiation

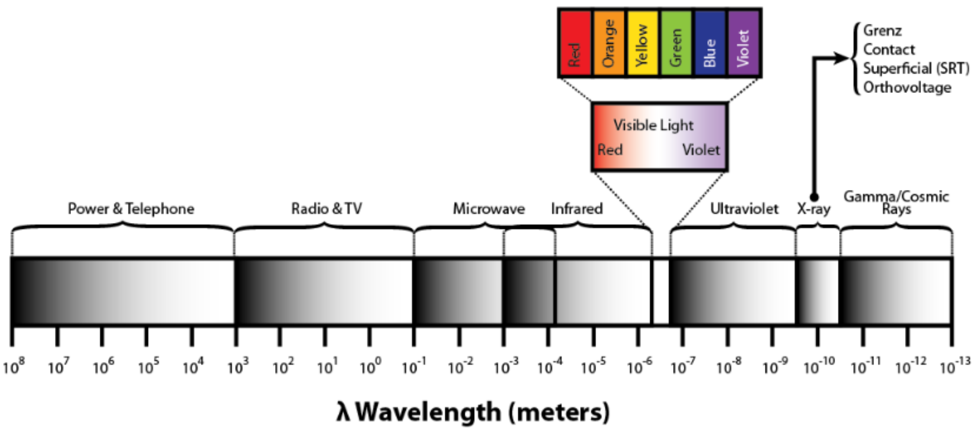
Electromagnetic radiation (EM radiation or EMR) is a form of radiant energy, propagating through space via electromagnetic waves called photons. In a vacuum, it propagates at its characteristic speed, the speed of light; and normally travels in straight lines. It has both electric and magnetic field components, which oscillate in a fixed relationship to one another, perpendicular to each other and perpendicular to the direction of energy and wave propagation.



The electromagnetic waves that compose electromagnetic radiation can be imagined as a self-propagating transverse oscillating wave of electric and magnetic fields. This diagram shows a plane linearly polarized EMR wave propagating from left to right. The electric field is in a vertical plane and the magnetic field in a horizontal plane. The two types of fields in EMR waves are always in phase with each other with a fixed ratio of electric to magnetic field intensity.

Such a component wave is said to be monochromatic. A monochromatic electromagnetic wave can be characterized by its frequency or wavelength, its peak amplitude, its phase relative to some reference phase, its direction of propagation, and its polarization.

The electromagnetic spectrum, in order of increasing frequency and decreasing wavelength, can be divided, for practical engineering purposes, into radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays. The eyes of various organisms sense a relatively small range of frequencies of EMR called the visible spectrum or light; what is visible depends somewhat on which species of organism is under consideration. Higher frequencies (shorter wavelengths) correspond to proportionately more energy carried by each photon, according to the well-known law E=hv, where E is the energy per photon, v is the frequency carried by the photon, and h is Planck's constant. For instance, a single gamma ray photon carries far more energy than a single photon of visible light.



Electromagnetic Spectrum

Electromagnetic radiation is associated with EM fields that are free to propagate themselves without the continuing influence of the moving charges that produced them, because they have achieved sufficient distance from those charges. Thus, EMR is sometimes referred to as the far field. In this language, the near field refers to EM fields near the charges and current that directly produced them, as for example with simple magnets and static electricity phenomena. In EMR, the magnetic and electric fields are each induced by changes in the other type of field, thus propagating itself as a wave. This close relationship assures that both types of fields in EMR stand in phase and in a fixed ratio of intensity to each other, with maxima and nodes in each found at the same places in space.

EMR carries energy—sometimes called radiant energy—through space continuously away from the source (this is not true of the near-field part of the EM field). EMR also carries both momentum and angular momentum. These properties may all be imparted to matter with which it interacts. EMR is produced from other types of energy when created, and it is converted to other types of energy when it is destroyed. The photon is the quantum of the electromagnetic interaction, and is the basic "unit" or constituent of all forms of EMR. The quantum nature of light becomes more apparent at high frequencies (thus high photon energy). Such photons behave more like particles than lower-frequency photons do.

In classical physics, EMR is considered to be produced when charged particles are accelerated by forces acting on them. Electrons are responsible for emission of most EMR because they have low mass, and therefore are easily accelerated by a variety of mechanisms. Rapidly moving electrons are most sharply accelerated when they encounter a region of force, so they are responsible for producing much of the highest frequency electromagnetic radiation observed in nature. Quantum processes can also produce EMR, such as when atomic nuclei undergo gamma decay, and processes such as neutral pion decay.

The effects of EMR upon biological systems (and also too many other chemical systems, under standard conditions) depend both upon the radiation's power and frequency. For lower frequencies of EMR up to those of visible light (i.e., radio, microwave, infrared), the damage done to cells and also too many ordinary materials under such conditions is determined mainly by heating effects, and thus by the radiation power. By contrast, for higher frequency radiations at ultraviolet frequencies and above (i.e., X-rays and gamma rays) the damage to chemical materials and living cells by EMR is far larger than that done by simple heating, due to the ability of single photons in such high frequency EMR to damage individual molecules chemically.

Ionizing and non- ionizing radiation

Radiation that has enough energy to move atoms in a molecule around or cause them to vibrate, but not enough to remove electrons, is referred to as "non-ionizing radiation." Examples of this kind of radiation are sound waves, visible light, and microwaves.

Radiation that falls within the ionizing radiation" range has enough energy to remove tightly bound electrons from atoms, thus creating ions. This is the type of radiation that people usually think of as 'radiation.' We take advantage of its properties to generate electric power, to kill cancer cells, and in many manufacturing processes. The energy of the radiation shown on the spectrum below increases from left to right as the frequency rises.

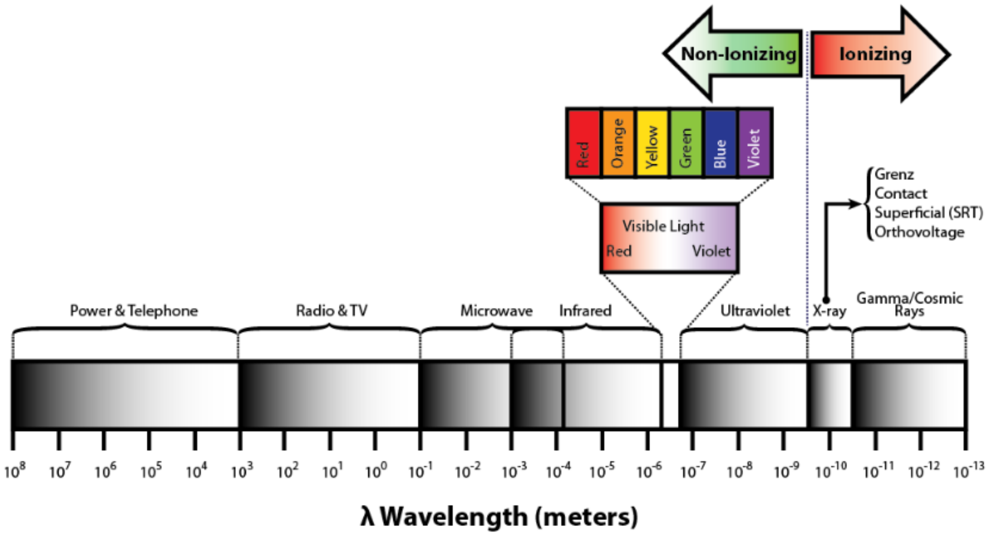
Non-ionizing Radiation

We take advantage of the properties of non-ionizing radiation for common tasks:

- Microwave radiation telecommunications and heating food.
- Infrared radiation infrared lamps to keep food warm in restaurants.
- Radio waves broadcasting.

Non-ionizing radiation ranges from extremely low frequency radiation, shown on the far left through the audible, microwave, and visible portions of the spectrum into the ultraviolet range.

Extremely low-frequency radiation has very long wave lengths (on the order of a million meters or more) and frequencies in the range of 100 Hertz or cycles per second or less. Radio frequencies have wave lengths of between 1 and 100 meters and frequencies in the range of 1 million to 100 million Hertz. Microwaves that we use to heat food have wavelengths that are about 1 hundredth of a meter long and have frequencies of about 2.5 billion Hertz.



Ionizing vs. Non-Ionizing Radiation

Ionizing Radiation

Higher frequency ultraviolet radiation begins to have enough energy to break chemical bonds. X-ray and gamma ray radiation, which are at the upper end of magnetic radiation have very high frequency in the range of 100 billion Hertz and very short wavelengths 1 million millionth of a meter. Radiation in this range has extremely high energy. It has enough energy to strip off electrons or, in the case of very high-energy radiation, break up the nucleus of atoms. Ionization is the process in which a charged portion of a molecule (usually an electron) is given enough energy to break away from the atom. This process results in the formation of two charged particles or ions: the molecule with a net positive charge, and the free electron with a negative charge.

Each ionization releases approximately 33 electron volts (eV) of energy. Material surrounding the atom absorbs the energy. Compared to other types of radiation that may be absorbed, ionizing radiation deposits a large amount of energy into a small area. In fact, the 33 eV from one ionization is more than enough energy to disrupt the chemical bond between two carbon atoms. All ionizing radiation is capable, directly or indirectly, of removing electrons from most molecules.

There are three main kinds of ionizing radiation:

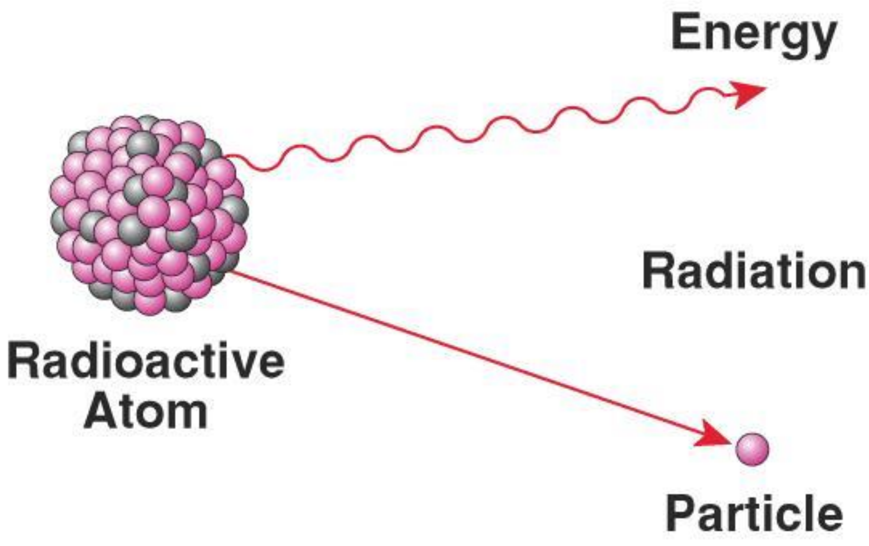
- Alpha Particles, which include two protons and two neutrons.
- Beta Particles, which are essentially electrons.
- Gamma Rays and x-rays, which are pure energy (photons).

Radioactive Decay

Radioactivity is the spontaneous disintegration of atomic nuclei. This phenomenon was first reported in 1896 by the French physicist Henri Becquerel. Marie Curie and her husband Pierre Curie contributed further to the understanding of radioactivity. Their research led to the discovery of two new radioactive elements, polonium and radium, and forced scientists to change their ideas about the structure of the atom.

Radioactivity is the result of an atom trying to reach a more stable nuclear configuration. The process of radioactive decay, can be achieved via three primary methods; a nucleus can change one of its neutrons into a proton with the simultaneous emission of an electron (beta decay), by emitting a helium nucleus (alpha decay), or by spontaneous fission (splitting) into two fragments. Often associated with these events is the release of high energy photons or gamma rays. There are some other method of radioactive decay, but they are more exotic in nature.

Each individual radioactive substance has a characteristic decay period or half-life. A half-life is the interval of time required for one-half of the atomic nuclei of a radioactive sample to decay. The radioactive isotope cobalt 60, which is used in radiation cancer therapy, has, for example, a half-life of 5.26 years. Thus after that interval, a sample originally containing 16 grams of cobalt 60 would contain only 8 grams of cobalt 60 and would emit only half as much radiation. After another interval of 5.26 years, the sample would contain only 4 grams of cobalt 60. Half-lives can range from thousands of years to milliseconds. Sometimes after undergoing radioactive decay, the new atom is still left in a radioactive form. This means that the atom will decay again as it attempts to reach a stable nuclear state



Alpha Decay

In alpha decay, a positively charged particle, identical to the nucleus of helium 4, is emitted spontaneously. This particle, also known as an alpha particle, consists of two protons and two neutrons. It was discovered and named by Sir Ernest Rutherford in 1899.

Alpha decay usually occurs in heavy nuclei such as uranium or plutonium, and therefore is a major part of the radioactive fallout from a nuclear explosion. Since an alpha particle is relatively more massive than other forms of radioactive decay, it can be stopped by a sheet of paper and cannot penetrate human skin. A 4 MeV alpha particle can only travel about 1 inch through the air. Although the range of an alpha particle is short, if an alpha decaying element is ingested, the alpha particle can do considerable damage to the surrounding tissue. This is why plutonium, with a long half-life, is extremely hazardous if ingested.

Beta Decay

Atoms emit beta particles through a process known as beta decay. Beta decay occurs when an atom has either too many protons or too many neutrons in its nucleus. Two types of beta decay can occur. One type (positive beta decay) releases a positively charged beta particle called a positron, and a neutrino; the other type (negative beta decay) releases a negatively charged beta particle called an electron, and an antineutrino. The neutrino and the antineutrino are high energy elementary particles with little or no mass and are released in order to conserve energy during the decay process. Negative beta decay is far more common than positive beta decay.

This form of radioactive decay was discovered by Sir Ernest Rutherford in 1899, although the neutrino was not observed until the 1960s. Beta particles have all the characteristics of electrons. At the time of their emission, they travel at nearly the speed of light. A typical .5 MeV particle will travel about 10 feet through the air, and can be stopped by 1-2 inches of wood.

Gamma Rays

Gamma rays are a type of electromagnetic radiation that results from a redistribution of electric charge within a nucleus. Gamma rays are essentially very energetic x-rays; the distinction between the two is not based on their intrinsic nature but rather on their origins. X rays are emitted during atomic processes involving energetic electrons. Gamma radiation is emitted by excited nuclei or other processes involving subatomic particles; it often accompanies alpha or beta radiation, as a nucleus emitting those particles may be left in an excited (higher-energy) state.

Gamma rays are more penetrating than either alpha or beta radiation, but less ionizing. Gamma rays from nuclear fallout would probably cause the largest number of casualties in the event of the use of nuclear weapons in a nuclear war. They produce damage similar to that caused by X-rays such as burns, cancer, and genetic mutations.

Neutron

Neutrons have no electrical charge. They have nearly the same mass as a proton (a hydrogen atom nucleus). A neutron has hundreds of times more mass than an electron, but 1/4 the mass of an alpha particle. The source of neutrons is primarily nuclear reactions, such as fission, but they may also be produced from the decay of radioactive nuclides. Because of its lack of charge, the neutron is difficult to stop and has a high penetrating power.

Neutrons are attenuated (reduced in energy and numbers) by three major interactions, elastic scatter, inelastic scatter, and absorption. In elastic scatter, a neutron collides with a nucleus and bounces off. This reaction transmits some of the kinetic energy of the neutron to the nucleus of the atom, resulting in the neutron being slowed, and the atom receives some kinetic energy (motion). This process is sometimes referred to as "the billiard ball effect." As the mass of the nucleus approaches the mass of the neutron, this reaction becomes more effective in slowing the neutron. Hydrogenous material attenuates neutrons most effectively.

In the inelastic scatter reaction, the same neutron/nucleus collision occurs as in elastic scatter. However, in this reaction, the nucleus receives some internal energy as well as kinetic energy. This slows the neutron, but leaves the nucleus in an excited state. When the nucleus decays to its original energy level, it normally emits a gamma ray.

In the absorption reaction, the neutron is actually absorbed into the nucleus of an atom. The neutron is captured, but the atom is left in an excited state. If the nucleus emits one or more gamma rays to reach a stable level, the process is called radiative capture. This reaction occurs at most neutron energy levels, but is more probable at lower energy levels.

X-ray Tube

An X-ray tube is a vacuum tube that produces X-rays. They are used in X-ray machines. X-rays are part of the electromagnetic spectrum, an ionizing radiation with wavelengths shorter than ultraviolet light. X-ray tubes evolved from experimental Crookes tubes with which X-rays were first discovered in the late 19th century, by Wilhelm Roentgen and the availability of this controllable source of X-rays created the field of radiography, the imaging of opaque objects with penetrating radiation. X-ray tubes are also used in CAT scanners, airport luggage scanners, X-ray crystallography, and for industrial inspection.
The x-ray tube is composed of parts that are better understood if consideration is given to what is needed for the production of x-rays. This includes:

- A source of electrons.
- A method of accelerating the electrons to a high speed.
- An evacuated path for the accelerated electrons.
- A target at which the energy of the electrons can be changed into energy in the form of X-rays.
- An envelope to provide a vacuum.

There are three major components that we will be discussing:

- The cathode.
- The Anode.
- The tube housing.

Cathode

The cathode is the negative side of the x-ray tube that consists of filament(s), focusing cup and loops of wires.

The cathode has three major functions:

- Produce thermionic cloud.
- Conduct the high voltage to the gap between cathode and anode.
- Focus the electron stream as it heads for the anode.

The filament within the focusing cup of the cathode assembly is a small coil of thin tungsten wire. Why tungsten? Because it has high melting point (3,370oC) and very difficult to vaporize or turn into gas.

The high melting point available in the tungsten wire permits the filament to operate at the high temperatures required of an x-ray tube. Tungsten wires make the filament which provides sufficient resistance to the flow of electrons so that heat produced will cause thermionic emission to occur. And since a tungsten filament do not exhibit significant thermionic emission below 2,200oC then this will cause electrons to leave the surface of the filament wire and form the necessary thermionic cloud that will be driven towards the anode target where x-ray photons will be produced. Continuous production of thermionic clouds by the filament will eventually cause vaporization of the tungsten wires that contribute to the reduction of vacuum capability of an x-ray tube. Vaporization of tungsten wires is also gradually deposited on the inner surface of the glass envelope, causing old tubes to have mirrored appearance and high-voltage arcing that eventually will destroy the x-ray tube. Vaporization will cause the filament to break over time similar to a light bulb with continuous usage.

The filament is housed in a shallow depression in the cathode assembly known as focusing cup. Focusing cup is made of nickel and its main purpose is to narrow the thermionic cloud as it is driven toward the anode. Focusing cup helps the negative electrons to travel into straight line toward the anode instead of diverging into different lines because of their similar charges.

Anode

The construction of the anode may vary greatly and represents one of the major differences that exists between types of x-ray tubes and the equipment in which they are placed. Basic construction of the anode consists of a target material placed on the surface of a larger cylinder or disc. It is estimated that more than 99% of the energy in the electron beam is converted to heat energy at the time of its interaction with the target. The ability of the target material to withstand high temperatures and the speed with which heat can be dissipated by the anode are therefore of great importance. If the atomic number of the target material is sufficiently high, it will favorably influence the efficiency of production of x-rays. Because tungsten satisfies these requirements, it has long served as a target material of choice.

Tungsten has:

- A high melting point (3370° C)
- A high atomic number (74)
- A low tendency to vaporize
- Good heat conductivity

The rhenium-tungsten target has replaced the solid tungsten target because of improved ability to dissipate heat. The physical form of the tungsten target and the manner in which heat is dissipated differ greatly in the two types of anode construction. Molybdenum is also used as a target material. Since it is a low atomic number, Bremsstrahlung production is less efficient and therefore characteristic radiation becomes more important.

There are two basic types of x-ray tubes dependent on the character of the anode. The difference in construction determines the maximum level of production of X-rays. Tubes with stationary anodes are found in dental units or small portable units. Tubes with rotating anodes are used in equipment of larger capacity.

Stationary Anode

The anode consists of a small plate of tungsten embedded in the end of a copper cylinder. Despite the high melting point of tungsten, a copper cylinder is still needed to dissipate the great amount of heat generated during an exposure. Copper is a better conductor of heat and has a relatively high melting point (1070° C). The tungsten block sits on the end of the copper cylinder with the surface of the tungsten plate at a predetermined angle. This is usually from 15 to 22.5 degrees. The size of the tungsten plate exceeds the size of the electron beam. This is necessary to avoid the electron beam striking the surface of the cylinder and causing melting of the copper, since it has a relatively lower melting point. One of the major technical achievements that made production of high heat load x-ray tubes was the discovery of a type of bonding that would hold the tungsten plate to the copper cylinder during the production of temperatures in excess of 1000°C, recognizing the different coefficient of expansion between the two metals.

Tube Housing

The tube housing serves several technical purposes. The housing is part of the electrical isolation between the high-voltage circuits and the environment. It also provides radiation protection for the patient. Tube housings are lead lined to keep the amount of leakage radiation below legal limits (this requirement assures that the major source of irradiation outside of the beam comes from scatter and the useful beam in the patient). The tube housing commonly has a low atomic number (usually Beryllium) exit window for the X rays is located in the center of the tube between the two poles (cathode and anode) of the power supply from the generator. The tubes are usually liquid cooled. The tube housing is a key portion in the waste heat handling system. Housings for tubes used at low mean power levels (<100 W or so) can be adequately air cooled, with or without a fan. Additional cooling may be obtained by circulating liquid through a heat exchanger contained in the tube housing or by circulating insulating oil through an external radiator.

Filtration

When the x-ray beam is produced, many energies of photons exist. Many are of such low energies that they will raise the skin dose, thus yielding a quick response to an acute reaction. Metals such as aluminum will absorb the soft low energy rays. This reduces the patient skin dose. The leaded glass window of the x-ray tube acts as Inherent Filtration. Aluminum is attached to the filter wheel. This is called Added Filtration. This filtration hardens the beam.

X-ray Beam Characteristics

X-ray quantity: it is the number of x-ray photons in the useful beam. It is also known as x-ray output, intensity or exposure. Unit of measurement is roentgen (R). It is affected by mA, kVp, distance and filtration.

X-ray Quality: it is a measurement of the penetrating ability of x-ray beam. Penetrability describes the distance an x-ray beam travels in matter. High penetrating (hard x-rays) and low penetrating (soft x-rays). X-ray quality is numerically represented by half-value layer (HVL). HVL is the thickness of absorbing material needed to reduce the x-ray intensity (quantity) to half its original value. X-ray quality is affected by kVp and filtration.

Interaction of Radiation with Matter

Radiation can be classified into two general groups, charged and uncharged; therefore, it may be expected that interactions with matter fall into two general types. Charged particles directly ionize the media through which they pass, while uncharged particles and photons can cause ionization only indirectly or by secondary radiation.

A moving charged particle has an electrical field surrounding it, which interacts with the atomic structure of the medium through which it is passing. This interaction decelerates the particle and accelerates electrons in the atoms of the medium. The accelerated electrons may acquire enough energy to escape from the parent atom. This process, whereby radiation "strips" off orbital electrons, is called ionization. Uncharged moving particles have no electrical field, so they can only lose energy and cause ionization by such means as collisions or scattering. A photon can lose energy by the photoelectric effect, Compton Effect, or pair production.

Modes of interaction: All radiation is detected through its interaction with matter. This section will focus on what happens to a particle and its environment when radiation passes through matter, schematically. Radiation has a profound effect on matter. Particularly in forms where it has high energy. There are basically two kinds of radiation, and they are electromagnetic energy and particulate radiation. Low energy electromagnetic radiation isn't generally hazardous, as long as the field strengths are low. You wouldn't want to stand in front of a radar antenna when it's radiating, but we are swept by low power electromagnet energy all the time. Those so-called radio waves are everywhere. Light is this kind of energy, too, and it's not too bad. But at higher energies, electromagnetic radiation is a hazard. Particulate radiation is straight up a problem. We often refer to particulate and high energy electromagnetic radiation as ionizing radiation, and both kinds have the ability to do some damage.

Heavy charged particle interactions: Energetic charged particles interact with matter by electrical forces and lose kinetic energy via:

- Excitation
- Ionization
- Radiative losses (Bremsstrahlung Production) ~ 70% of charged particle energy deposition leads to non-ionizing excitation

X-ray Interaction

The intensity of an x-ray beam is reduced by interaction with the matter it encounters. This attenuation results from interactions of individual photons in the beam with atoms in the absorber (patient). The x-ray photons are either absorbed or scattered out of the beam. In scattering, photons are ejected out of the primary beam as a result of interactions with the orbital electrons of absorber atoms. In the case of a dental x-ray beam, three mechanisms exist where these interactions take place: Coherent scattering, Compton scattering, and photoelectric absorption.

Coherent Scattering

Coherent Scattering (also known as classical scattering and Thompson Scattering) may occur when a low-energy incident photon passes near an outer electron of an atom (which has a low binding energy). The incident photon interacts with the electron in the outer-shell by causing it to vibrate momentarily at the same frequency as the incoming photon. The incident photon then ceases to exist. The vibration causes the electron to radiate energy in the form of another x-ray photon with the same frequency and energy as in the incident photon. In effect, the direction of the incident x-ray photon is altered.

Compton scattering

Compton scattering occurs when a photon interacts with an outer orbital electron, which receives kinetic energy and recoils from the point of impact. The incident photon is then deflected by its interaction and is scattered from the site of the collision. The energy of the scattered photon equals the energy of the incident photon minus the kinetic energy gained by the recoil electron plus its bonding energy. As with photoelectric absorption, Compton scattering results in the loss of an electron and ionization of the absorbing atom. Scattered photons travel in all directions. The higher the energy of the incident photon, however, the greater the probability that the angle of scatter of the secondary photon will be small and its direction will be forward.

The probability of Compton scattering is directly proportional to the electron density. The number of electrons in bone is greater than in water, therefore the probability of Compton scattering is correspondingly greater in bone than in tissue. In an x-ray beam, approximately 62% of the photons undergo Compton scattering.

Photoelectric Absorption

Photoelectric absorption occurs when an incident photon collides with an inner-shell electron in an atom of the absorbing medium resulting in total absorption and the incident photon ceases to exist. The electron is ejected from its shell, resulting in ionization and becomes a recoil electron (photoelectron). The kinetic energy imparted to the recoil electron is equal to the energy of the incident photon minus that used to overcome the binding energy of the electron. In the case of atoms with low atomic numbers (e.g. those in most biologic energy of the incident photon. Most Photoelectric interactions occur in the K shell because the density of the electron cloud is greater in this region and a higher probability of interaction exists. An atom that has participated in photoelectric interaction is ionized. This electron deficiency (usually in the K shell) is instantly filled, usually by an L- or M- shell electron, with the release of characteristic radiation. Whatever the orbit of the replacement electron, the characteristic photons generated are of such low-energy that they are absorbed superficially within the patient.

The recoil electrons ejected during photoelectric absorptions travel only a short distance in the absorber before they give up their energy. As a consequence, all the energy of incident photons that undergo photoelectric interaction is deposited in the patient. The frequency of photoelectric interaction varies directly with the third power of the atomic number of the absorber. For example, because the effective atomic number of compact bone ($Z = 7,4$), the probability that a photon will be absorbed by a photoelectric interaction in bone is approximately 6.5 times greater than in an equal distance of water.

Secondary Electrons

In both Photoelectric absorption and Compton scattering, electrons are ejected from their orbits in the absorbing material after interaction with x-ray photons. These secondary electrons give up their energy in the absorber by either of two processes: (1) collisional interaction with other electrons, resulting in ionization or excitation of the affected atom, and (2) radiative interactions, which produce bremsstrahlung radiation resulting in the emission of low-energy x-ray photons. Secondary electrons eventually dissipate all their energy, mostly as heat by collisional interaction, and come to rest.

Radiation Detection and Measurement

Radiation detection can be accomplished by stretching a wire inside a gas-filled cylinder and raising the wire to a high positive voltage. The total charge produced by the passage of an ionizing particle through the active volume can be collected and measured. Different names are used for the devices based on the amount of voltage applied to the center electrode and the consequent nature of the ionizing events. If the voltage is high enough for the primary electron-ion pair to reach the electrodes but not high enough for secondary ionization, the device is called and ionization chamber. The collected charge is proportional to the number of ionizing events, and such devices are typically used as radiation dosimeters. At a higher voltage, the number of ionizations associated with a particle detection rises steeply because of secondary ionizations, and the device is often called a proportional counter. A single event can cause a voltage pulse proportional to the energy loss of the primary particle. Some detection devices:

- Gas-filled chambers
- Scintillation detectors
- Semi-conductors
- Photographic emulsions

Gas-filled chambers

The operation of a gas-filled detector is based on the ionization of gas molecules by radiation, followed by collection of the ion pairs as charge or current with the application of a voltage between two electrodes. The measured charge or current is proportional to the applied voltage and the amount and energy of radiation, and depends on the type and pressure of the gas.

Scintillation detectors

A scintillation counter is an instrument for detecting and measuring ionizing radiation. It consists of a scintillator which generates photons of light in response to incident radiation, a sensitive photomultiplier tube which converts the light to an electrical signal, and the necessary electronics to process the photomultiplier tube output. Scintillation counters are widely used because they can be made inexpensively yet with good quantum efficiency and can measure both the intensity and the energy of incident radiation.

Semi-conductors

A semiconductor detector is a device that uses a semiconductor (usually silicon or germanium) to detect traversing charged particles or the absorption of photons. In the field of particle physics, these detectors are usually known as silicon detectors. When their sensitive structures are based on a single diode, they are called semiconductor diode detectors. When they contain many diodes with different functions, the more general term semiconductor detector is used. Semiconductor detectors have found broad application during recent decades, in particular for gamma and X-ray spectrometry and as particle detectors.

Photographic emulsions

Radiation detector generally in the form of a glass plate thinly coated with a transparent medium containing a silver halide compound. Passage of charged subatomic particles is recorded in the emulsion in the same way that ordinary black and white photographic film records a picture. After photographic developing, a permanent record of the paths of the charged particles remains and may be observed through a microscope. Radioactivity was discovered in 1896 by its effect on a photographic plate, and nuclear emulsions later played a pivotal role in cosmic-ray research-for example, in the discovery of the pion in 1947. Emulsions continue to be useful in the study of the production and decay of short-lived particles produced in high-energy particle physics experiments.

Biological Effects of Radiation

The fact that ionizing radiation produces biological damage has been known for many years. The first case of human injury was reported in the literature just a few months following Roentgen's original paper in 1895 announcing the discovery of x-rays. As early as 1902, the first case of x-ray induced cancer was reported in the literature. Early human evidence of harmful effects as a result of exposure to radiation in large amounts existed in the 1920s and 1930s, based upon the experience of early radiologists, miners exposed to airborne radioactivity underground, persons working in the radium industry, and other special occupational groups. The long-term biological significance of smaller, repeated doses of radiation, however, was not widely appreciated until relatively recently, and most of our knowledge of the biological effects of radiation has been accumulated since World War II. The following topics will be covered:

- Radiation quantities and units
- Quality factors
- Biological effects
- Mechanisms of biological damage
- Acute and latent reaction to x-ray radiation
- Risk of stochastic effects
- Radiation dose from natural and man-made sources

Radiation quantities and units

There are five measures of radiation that will commonly be encounter when addressing the biological effects of working with X-rays or Gamma rays. These measures are: Exposure, Dose, Dose Equivalent, and Dose Rate.

Exposure

Exposure is a measure of the strength of a radiation field at some point. It is a measure of the ionization of the molecules in a mass of air. It is usually defined as the amount of charge (i.e. the sum of all ions of the same sign) produced in a unit mass of air when the interacting photons are completely absorbed in that mass. The most commonly used unit of exposure is the Roentgen (R). Specifically, a Roentgen is the amount of photon energy required to produce 1.610×10^{12} ion pairs in one cubic centimeter of dry air at 0°C. A radiation field of one Roentgen will deposit 2.58×10^{-4} coulombs of charge in one kilogram of dry air. The main advantage of this unit is that it is easy to directly measure with a survey meter. The main limitation is that it is only valid for deposition in air.

Dose or Absorbed Dose

Whereas exposure is defined for air, the absorbed dose is the amount of energy that ionizing radiation imparts to a given mass of matter. The absorbed dose is used to relate the amount of ionization that x-rays or gamma rays cause in air to the level of biological damage that would be caused in living tissue placed in the radiation field. The most commonly used unit for absorbed dose is the "rad" (Radiation Absorbed Dose). A rad is defined as a dose of 100 ergs of energy per gram of the given material. The SI unit for absorbed dose is the gray (Gy), which is defined as a dose of one joule per kilogram. Since one joule equals 107 ergs, and since one kilogram equals 1000 grams, 1 Gray equals 100 rads.

The size of the absorbed dose is dependent upon the intensity (or activity) of the radiation source, the distance from the source to the irradiated material, and the time over which the material is irradiated. The activity of the source will determine the dose rate which can be expressed in rad/hr, mr/hr, mGy/sec, etc.

Dose Equivalent

When considering radiation interacting with living tissue, it is important to also consider the type of radiation. Although the biological effects of radiation are dependent upon the absorbed dose, some types of radiation produce greater effects than others for the same amount of energy imparted. For example, for equal absorbed doses, alpha particles may be 20 times as damaging as beta particles. In order to account for these variations when describing human health risks from radiation exposure, the quantity called "dose equivalent" is used. This is the absorbed dose multiplied by certain "quality" or "adjustment" factors indicative of the relative biological-damage potential of the particular type of radiation.

Type of Radiation	Rad	Q Factor	Rem
X-Ray	1	1	1
Gamma Ray	1	1	1
Beta Particles	1	1	1
Thermal Neutrons	1	5	5
Fast Neutrons	1	10	10
Alpha Particles	1	20	20

Dose Rate

The dose rate is a measure of how fast a radiation dose is being received. Knowing the dose rate, allows the dose to be calculated for a period of time. For example, if the dose rate is found to be 0.8rem/hour, then a person working in this field for two hours would receive a 1.6rem dose.

Quality Factor

The quality factor (Q) is a factor used in radiation protection to weigh the absorbed dose with regard to its presumed biological effectiveness. Radiation with higher Q factors will cause greater damage to tissue. The rem is a term used to describe a special unit of dose equivalent. Rem is an abbreviation for roentgen equivalent in man. The SI unit is the sievert (SV); one rem is equivalent to 0.01 SV. Doses of radiation received by workers are recorded in rems, however, sieverts are being required as the industry transitions to the SI unit system.

Biological effects

As matter absorbs radiation (alpha, beta or gamma) several process can occur. Radiation is usually classified into non-ionizing or ionizing radiation.

Non-ionizing Radiation Generally of lower energy, such as visible light electromagnetic radiation or slow moving neutrons. Causes heating of matter when absorbed. No bonding or nonbonding electrons are ionized in the interaction. Can cause thermal burns.

Ionizing Radiation Higher energy radiation that ionizes an electron from an atom or a molecule. Includes alpha, beta, gamma, X-rays and higher- energy UV radiation. Far more harmful to biological systems than non-ionizing radiation.

The occurrence of particular health effects from exposure to ionizing radiation is a complicated function of numerous factors including:

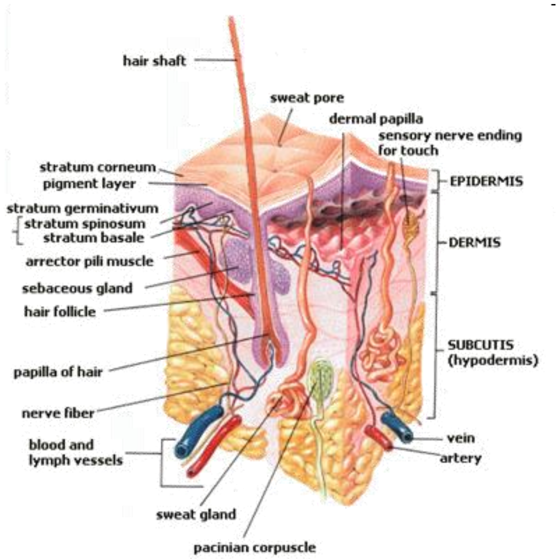
- **Type of radiation involved.** All kinds of ionizing radiation can produce health effects. The main difference in the ability of alpha and beta particles and Gamma and X-rays to cause health effects is the amount of energy they have. Their energy determines how far they can penetrate into tissue and how much energy they are able to transmit directly or indirectly to tissues.
- **Size of dose received.** The higher the dose of radiation received, the higher the likelihood of health effects.
- **Rate the dose is received.** Tissue can receive larger dosages over a period of time. If the dosage occurs over a number of days or weeks, the results are often not as serious if a similar dose was received in a matter of minutes.
- **Part of the body exposed.** Extremities such as the hands or feet are able to receive a greater amount of radiation with less resulting damage than blood forming organs housed in the torso.
- **The age of the individual.** As a person ages, cell division slows and the body is less sensitive to the effects of ionizing radiation. Once cell division has slowed, the effects of radiation are somewhat less damaging than when cells were rapidly dividing.
- **Biological differences.** Some individuals are more sensitive to the effects of radiation than others. Studies have not been able to conclusively determine the differences.

Effects of Radiation by Biological Organization

- Molecular: Damage to enzymes, DNA etc. and interference with biological pathways.
- Subcellular: Damage to cell membranes, nucleus, chromosomes etc.
- Cellular Inhibition of cell division, cell death, transformation to a malignant state.

Organ / Tissue Radiation Effects: Skin

- First tissue to exhibit noticeable radiation injury.
- High radiosensitivity due to the high rate of cell division and degree of exposure.
- 3rd or 4th fraction: Erythema (reddening).
- Monitor biological response in order to abstain from: blistering and ulceration.
- Long term complications if therapeutic index is exceeded: scarring and skin cancer.



Mechanisms of biological 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

Acute and latent reaction to x-ray radiation

Early (acute) normal tissue damage: Acute radiation side effects are caused by damage to rapidly dividing normal cells in the area being treated. Early radiation effects are predominantly seen in turnover tissues, where permanent cell loss is precisely counterbalanced by cell production in the germinal tissue compartments. Radiation-induced impairment of cell production results in progressive tissue hypoplasia and eventually in a loss of functional cells. These effects include skin irritation or damage at regions exposed to the radiation beams. Latent times for the clinical manifestation of early radiation effects are over a wide range of doses independent of radiation dose, and are related to normal tissue turnover times. In contrast, the time to tissue restoration increases with increasing dose. The radiation response in these turnover tissues is likely to be affected by parallel responses in other tissue compartments, i.e. the vascular response or radiation effects in associated connective tissue, transmitted by paracrine mediators. Most acute effects disappear after treatment ends.

Pathogenesis in critical normal tissues (skin), kinetics/latency cell turnover and stem cell function, role of inflammation, cytokines, reactive oxygen species

Early side effects:

- Skin that has been exposed to the radiation can become red and warm, like sunburn.
- It can sometimes peel and become moist and oozy.
- The affected skin may ulcerate, especially when mucous surfaces are affected.

Late (chronic) tissue damage: Latent times to chronic clinical effects can be as long as 20 years or even longer. They are the shorter the higher the dose was. This relationship, however, is non-linear. Late radiation effects are usually irreversible and progressive in nature, with a dose-dependent progression rate. Therefore, the tolerance doses for late effects clearly decrease with an increase in follow-up time. The clinical manifestation of late deterministic radiation effects is based on continuous processes progressing at a dose-dependent rate from the time of radiation exposure. Therefore, definition of a "latent time" is highly dependent on the endpoint studied, i.e. the quality and/or severity of changes analyzed, as well as on radiation dose and further factors.

Pathogenesis in critical tissues (skin) kinetics/latency cell turnover:

- Role of inflammation, cytokines, reactive oxygen species
- Microvascular damage, fibrosis, ischemia and atrophy
- Functional vs. structural damage
- Growth factors and stimulated regeneration (including stem cells)
- Concept of normal tissue tolerance

Late side effects:

- Skin atrophy (causing the skin to appear thin and pale)
- Telangiectasia (which are visible, small spidery blood vessels)
- Increased pigmentation (color change)
- Non-healing ulcer (rare)
- A different type of skin cancer can develop in the treated area (very rare)

Risk of stochastic effects

Stochastic effects are those that occur by chance and consist primarily of cancer and genetic effects. Stochastic effects often show up years after exposure. As the dose to an individual increases, the probability that cancer or a genetic effect will occur also increases. However, at no time, even for high doses, is it certain that cancer or genetic damage will result. Similarly, for stochastic effects, there is no threshold dose below which it is relatively certain that an adverse effect cannot occur. In addition, because stochastic effects can occur in individuals that have not been exposed to radiation above background levels, it can never be determined for certain that an occurrence of cancer or genetic damage was due to a specific exposure.

While it cannot be determined conclusively, it often possible to estimate the probability that radiation exposure will cause a stochastic effect. As mentioned previously, it is estimated that the probability of having a cancer in the US rises from 20% for non-radiation workers to 21% for persons who work regularly with radiation. The probability for genetic defects is even less likely to increase for workers exposed to radiation. Studies conducted on Japanese atomic bomb survivors who were exposed to large doses of radiation found no more genetic defects than what would normally occur.

Radiation-induced hereditary effects have not been observed in human populations, yet they have been demonstrated in animals. If the germ cells that are present in the ovaries and testes and are responsible for reproduction were modified by radiation, hereditary effects could occur in the progeny of the individual. Exposure of the embryo or fetus to ionizing radiation could increase the risk of leukemia in infants and, during certain periods in early pregnancy, may lead to mental retardation and congenital malformations if the amount of radiation is sufficiently high.

Radiation dose from natural and man-made sources

Natural

The earth, and all living things on it, are constantly bombarded by radiation from space, similar to a steady drizzle of rain. Charged particles from the sun and stars interact with the earth's atmosphere and magnetic field to produce a shower of radiation, typically beta and gamma radiation. The dose from cosmic radiation varies in different parts of the world due to differences in elevation and to the effects of the earth's magnetic field.

Radioactive material is also found throughout nature. It is in the soil, water, and vegetation. Low levels of uranium, thorium, and their decay products are found everywhere. Some of these materials are ingested with food and water, while others, such as radon, are inhaled. The dose from terrestrial sources also varies in different parts of the world. Locations with higher concentrations of uranium and thorium in their soil have higher dose levels.

The major isotopes of concern for terrestrial radiation are uranium and the decay products of uranium, such as thorium, radium, and radon.

In addition to the cosmic and terrestrial sources, all people also have radioactive potassium-40, carbon- 14, lead-210, and other isotopes inside their bodies from birth. The variation in dose from one person to another is not as great as the variation in dose from cosmic and terrestrial sources. The average annual dose to a person from internal radioactive material is about 40 millirems/year.

Man-Made

Although all people are exposed to natural sources of radiation, there are two distinct groups exposed to man-made radiation sources. These two groups are:

- Members of the public
- Occupationally exposed individuals

A member of the public is defined in 10 CFR Part 20 as any individual except when that individual is receiving an occupational dose.

Occupational dose is the dose received by an individual in the course of employment in which the individual's assigned duties involve exposure to radiation or to radioactive material. This does not include the dose received from background radiation, from any medical administration the individual has received, from exposure to individuals administered radioactive materials from voluntary participation in medical research programs, or as a member of the public.

By far, the most significant source of man-made radiation exposure to the public is from medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy. Some of the major isotopes would be I-131, Tc-99m, Co-60, Ir-192, Cs-137, and others.

In addition, members of the public are exposed to radiation from consumer products, such as tobacco (thorium), building materials, combustible fuels (gas, coal, etc.), ophthalmic glass, televisions, luminous watches and dials (tritium), airport X-ray systems, smoke detectors (americium), road construction materials, electron tubes, fluorescent lamp starters, lantern mantles (thorium), etc.

Of lesser magnitude, members of the public are exposed to radiation from the nuclear fuel cycle, which includes the entire sequence from mining and milling of uranium to the actual production of power at a nuclear plant. This would be uranium and its daughter products.

The final sources of exposure to the public would be shipment of radioactive materials and residual fallout from nuclear weapons testing and accidents, such as Chernobyl.

Occupationally Exposed Individuals

Occupationally exposed individuals, on the other hand, are exposed according to their occupations and to the sources with which they work. Occupationally exposed individuals, however, are monitored for radiation exposure with dosimeters so that their exposures are well documented in comparison to the doses received by members of the public.

Some of the isotopes of concern would be uranium and its daughter products, cobalt-60, cesium-137, americium-241, and others.

Shielding

Physical barriers designed to provide protection from the effects of ionizing radiation; also, the technology of providing such protection. Major sources of radiation are nuclear reactors and associated facilities, medical and industrial x-ray and radioisotope facilities, charged-particle accelerators, and cosmic rays. Types of radiation are directly ionizing (charged particles) and indirectly ionizing (neutrons, gamma rays, and x-rays). In most instances, protection of human life is the goal of radiation shielding. In other instances, protection may be required for structural materials which would otherwise be exposed to high-intensity radiation, or for radiation-sensitive materials such as photographic film and certain electronic components.

- Charged particle shielding: Charged particles lose energy and are thus attenuated and stopped primarily as a result of coulombic interactions with electrons of the stopping medium. Gamma-ray and x-ray photons lose energy principally by three types of interactions: photoemission, Compton scattering, and pair production. Neutrons lose energy in shields by elastic or inelastic scattering. Elastic scattering is more effective with shield materials of low atomic mass, notably hydrogenous materials, but both processes are important, and an efficient neutron shield is made of materials of both high and low atomic mass. See also Compton Effect; Electron-positron pair production; Photoemission.

- Photon shielding: Shielding from gamma rays requires large amounts of mass, in contrast to alpha particles which can be blocked by paper or skin, and beta particles which can be shielded by foil. Gamma rays are better absorbed by materials with high atomic numbers and high density, although neither effect is important compared to the total mass per area in the path of the gamma ray. For this reason, a lead shield is only modestly better (20–30% better) as a gamma shield, than an equal mass of another shielding material such as aluminum, concrete, water or soil; lead's major advantage is not in lower weight, but rather its compactness due to its higher density. Protective clothing, goggles and respirators can protect from internal contact with or ingestion of alpha or beta emitting particles, but provide no protection from gamma radiation from external sources. The higher the energy of the gamma rays, the thicker the shielding made from the same shielding material is required. Materials for shielding gamma rays are typically measured by the thickness required to reduce the intensity of the gamma rays by one half (the half value layer or HVL). For example gamma rays that require 1 cm (0.4″) of lead to reduce their intensity by 50% will also have their intensity reduced in half by 4.1 cm of granite rock, 6 cm (2½″) of concrete, or 9 cm (3½″) of packed soil. However, the mass of this much concrete or soil is only 20–30% greater than that of lead with the same absorption capability. Depleted uranium is used for shielding in portable gamma ray sources, but here the savings in weight over lead are larger, as portable sources' shape resembles a sphere to some extent, and the volume of a sphere is dependent on the cube of the radius; so a source with its radius cut in half will have its volume reduced eight times, which will more than compensate uranium's greater density (as well as reducing bulk). In a nuclear power plant, shielding can be provided by steel and concrete in the pressure and particle containment vessel, while water provides a radiation shielding of fuel rods during storage or transport into the reactor core. The loss of water or removal of a "hot" fuel assembly into the air would result in much higher radiation levels than when kept under water.

- Facility Shielding: Physical barriers designed to provide protection from the effects of ionizing radiation; also, the technology of providing such protection. Major sources of radiation are nuclear reactors and associated facilities, medical and industrial x-ray and radioisotope facilities, charged-particle accelerators, and cosmic rays. Types of radiation are directly ionizing (charged particles) and indirectly ionizing (neutrons, gamma rays, and x-rays). In most instances, protection of human life is the goal of radiation shielding. In other instances, protection may be required for structural materials which would otherwise be exposed to high-intensity radiation, or for radiation-sensitive materials such as photographic film and certain electronic components. Metals are resistant to radiation damage, although there is some change in their mechanical properties. Concretes, frequently used because of their relatively low cost, hold up well; however, if heated they lose water of crystallization, becoming somewhat weaker and less effective in neutron attenuation. Radiation shields vary with application. The overall thickness of material is chosen to reduce radiation intensities outside the shield to levels well within prescribed limits for occupational exposure or for exposure of the general public. The reactor shield is usually considered to consist of two regions, the biological shield and the thermal shield. The thermal shield, located next to the reactor core, is designed to absorb most of the energy of the escaping radiation and thus to protect the steel reactor vessel from radiation damage. It is often made of steel and is cooled by the primary coolant. The biological shield is added outside to reduce the external dose rate to a tolerable level.

Personnel Radiation Dosimetry Devices and Methods

The recording of radiation dose received by persons working with radioactive material and radiation- producing equipment is essential to minimizing exposure as well as maintaining compliance with state and federal regulations.

Monitoring Requirements:

Dosimeter badges must be worn by personnel meeting any of the following requirements:

1. Personnel likely to receive an annual radiation dose in excess of 10 percent of any of the following annual dose limits:
    a. Total effective dose equivalent of 5 rems b. Sum of the deep dose equivalent and the committed dose equivalent to an individual organ or tissue (other than the lens of the eye) being equal to 50 rems c. Eye dose equivalent of 15 rems d. Shallow dose equivalent of 50 rems to the skin or to an extremity.
2. Radiation and imaging employees with a declared or planned pregnancy.
3. Personnel who enter a High Radiation Area (exposure to greater than 100 millirem in any one hour).
4. Personnel who operate analytical X-ray devices.
5. Personnel who meet special criteria as assessed by the Radiation Safety Officer or his/her delegated representative.

External Monitoring:

1. The personal monitoring device (film badge) must be worn properly, stored properly and exchanged quarterly at the due date.
2. Badges are to be worn at collar level and outside of radiation protection garments. Pregnant employees will wear a second badge at waist level and underneath radiation protection garments
3. All issued badges must be opened by the user regardless of whether the user will be working in a radiation area or not.
4. Each department/unit with staff required to wear a dosimeter badge must designate a badge coordinator.
5. The Safety Office is responsible for delivery of the badges at the end of each month to each department. The designated badge coordinator is responsible for distribution and collection of the badges. The badge coordinator is also responsible for the return of the badges to the Radiation Safety Office. Any change in staff, such as transfer, resignation, pregnancy, etc., must be forwarded to the Safety Office. A delivery date and deadline date for return is emailed by the Safety Office prior to end of month.
6. Badges are not to be worn away from the hospital, not taken home and not worn as a badge for another job. In the event that you work weekends or are unavailable due to leave, your badge should be here to exchange and meet the deadline. Racks are provided for placing your badge when you leave from work.
7. The coordinator has the responsibility of collection and return of the badges. They are not responsible for tracking down the badges. They should be on the rack and ready for pickup.
8. Dosimeter badge reports are prepared on a set schedule. Failure to turn in a badge will affect the accuracy of exposure data on the report.

9. The badge coordinator and department head will be notified when badges are being turned in late. A missing or invalid dosimeter reading creates a gap in your radiation dose record.

External Dose Evaluation:

The Safety Office and Radiation Safety Officer (RSO) review occupational dose reports upon receipt. The Safety Office maintains occupational radiation exposure records. Investigations of exposures exceeding ALARA levels are conducted in accordance with hospital and state regulations. Records are also reviewed to determine the necessity of dosimeter badges.

Federal and State Regulations

There are laws at the federal and state levels, which vary by state, regulating radiation. Ionizing radiation generally refers to gamma rays and x rays; alpha and beta particles, high-speed electrons, neutrons, protons and other nuclear particles; but not sound or radio waves or visible, infrared or ultraviolet light. Byproducts include any radioactive material, except special nuclear material, yielded in, or made radioactive by, exposure to the radiation incident to the process of producing or utilizing special nuclear material.

Because of health and safety concerns, laws regulate the licensing and practices of those involved in the manufacture, storage, or transportation of radioactive materials. The United States Nuclear Regulatory Commission has primary authority over defining the materials subject to regulation. Some of the duties of agencies responsible for radiation exposure and radioactive materials include to:

1. Develop and conduct programs for evaluation of hazards associated with use of sources of ionizing radiation;
2. Develop programs with due regard for compatibility with federal programs for regulation of by-product, source and special nuclear materials;
3. Formulate, adopt, promulgate and repeal codes, rules and regulations relating to control of sources of ionizing radiation with due regard for compatibility with the regulatory programs of the federal government;
4. Advise, consult and cooperate with other agencies of the state, the federal government, other states and interstate agencies, political subdivisions and with groups concerned with control of sources of ionizing radiation;
5. Have the authority to accept and administer loans, grants or other funds or gifts, conditional or otherwise, in furtherance of its functions, from the federal government and from other sources, public or private;
6. Encourage, participate in or conduct studies, investigations, training, research and demonstrations relating to control of sources of ionizing radiation; and
7. Collect and disseminate information relating to control of sources of ionizing radiation.

Chronology of Standards

1. GENERAL PROVISIONS
2. REGISTRATION, INSTALLATION, AND SERVICE OF IONIZING RADIATION-PRODUCING MACHINES; AND CERTIFICATION OF MAMMOGRAPHY FACILITIES
3. RADIOACTIVE MATERIAL LICENSING
4. STANDARDS FOR PROTECTION AGAINST IONIZING RADIATION
5. SEALED SOURCE INDUSTRIAL RADIOGRAPHY

6. USE OF X-RAYS IN THE HEALING ARTS
7. MEDICAL USES OF RADIOACTIVE MATERIAL
8. RADIATION SAFETY REQUIREMENTS FOR ANALYTICAL X-RAY OPERATIONS
9. PARTICLE ACCELERATORS
10. NOTICES, INSTRUCTIONS, AND REPORTS TO RADIATION WORKERS; INSPECTIONS
11. INDUSTRIAL USES OF X-RAYS, NOT INCLUDING ANALYTICAL X-RAY SYSTEMS
12. ADMINISTRATIVE PROVISIONS
13. LICENSE AND REGISTRATION FEES
14. REGISTRATION OF NONIONIZING RADIATION SOURCES AND STANDARDS FOR PROTECTION AGAINST NONIONIZING RADIATION
15. TRANSPORTATION
16. RESERVED
17. . WIRELINE SERVICE OPERATIONS AND SUBSURFACE TRACER STUDIES

Sources of Standards, Recommendations and Requirements

The Nuclear Regulatory Commission (NRC), from which most of this information comes from strictly regulates academic, commercial and industrial uses of radioactive material.

Basis of Standards

In 1925, at the First International Congress of Radiology, the International Commission on Radiological Units and Measurements (ICRU) was formed, mainly because of the lack of a suitable dosage unit of international acceptance. In 1928, this group adopted the definition of an international unit, the Roentgen. For the first time measurements throughout the world could be made in terms of the same unit. Over the years the ICRU has been the main force in defining and adopting units for use on an international basis.

At the Second International Congress of Radiology in 1928, the first international body concerned with protection standards was formed. At first known as the International X-| ray and Radium Protection Commission, this group is now called the International Commission on Radiological Protection (ICRP). This group discusses and reviews basic protection principles, and these recommendations then serve as a guide from which regulations can be drawn up by each country to suit its needs. Although this group acts only as an advisory board, it has had a tremendous impact on the field of radiation protection.

In 1934, the ICRP made its first recommendation of a tolerance level of exposure: 0.2 R/day. This limit remained in force until 1950. However, because of World War II, the| ICRP did not meet between 1937 and 1950. This left much of the study of protection standards during this time to the national committees.

In this regard, one cannot help but mention the work done by the National Committee on Radiation Protection and Measurements (NCRP). This group was formed in the United States in 1929. The work of this body was coordinated by the National Bureau of Standards. The early recommendations of the Committee appeared in the National Bureau of Standards Handbooks. The NCRP recommendations as outlined in Handbooks 20 and 23, which have been superseded by later reports, served as the basis for protection practices during the days of the Manhattan project. This was the name given to the project developing the atomic bomb. Many members of the NCRP were engaged in this program and were helpful in seeing that protection standards prevailed.

From the standpoint of protection problems, it is hard to believe the dramatic impact that the war years produced. Of course, most of this effect can be traced to the development of the atomic bomb. Before the war, most of the problems concerned rather low energy x-rays. Now, not only were there these to treat, but also other types of radiation with a| wide range of energies. Added to this was the large increase of workers in the radiation field. Also, many new techniques and operations became a topic of real concern. New units would be needed to define the dose contributed by radiation other than x-rays. | Large amounts of waste were now produced and methods of disposal would have to be worked out. With reactors in use, not only the workers, but also others not connected with the work, would have to be considered. The scope of the radiation field had enlarged to an undreamed of extent.

The NCRP met in 1946 to reorganize. At this time a number of subcommittees were formed to deal with the new problems more effectively. This resulted in the publication of a number of handbooks after the war which represented changes and additions to the old recommendations. The Committee was replaced by a non-profit corporation chartered by Congress in 1964 and is now known as the National Council on Radiation Protection and Measurements. The Council is the successor to the Committee and was formed to carry on the work begun by the Committee.

The Council is made up of the members and the participants who serve on a number of committees. These committees develop proposed recommendations on various aspects of radiation protection and radiation measurements, which when approved by the Council, are published as NCRP Reports. The initial report issued by the Council was NCRP Report No. 32.

The three organizations, ICRU, ICRP and NCRP, have figured prominently in the development of present day radiation protection practices. Although these bodies act as advisory boards only, much of the radiation protection philosophy which has evolved and which has been adopted by various regulatory agencies throughout the world, had its origins in the recommendations of these organizations.

Current regulations

The Federal Radiation Council (FRC) was established in 1959 by Executive Order 10831. The Council arose as a result of new information that became available in the 1950s on the effects of radiation. Before that time, only nongovernmental radiation advisory bodies (i.e., ICRP and NCRP) existed, and their recommendations were not binding on users of radiation or radioactive materials. The FRC was established as an official Government entity and included representatives from all Federal agencies concerned with radiation protection. The Council served as the primary coordinating body for all radiation activities conducted by the Federal Government (FRC60a) and was responsible for:

Advising the President with respect to radiation matters, directly or indirectly affecting health, including providing guidance to all Federal agencies in the formulation of radiation standards and in the establishment and execution of programs of cooperation with States.

The Council's first recommendations concerning radiation protection guidance for Federal agencies were approved by President Eisenhower in 1960 (FRC60b). The guidance established exposure limits for members of the general public. These included the yearly radiation exposure of 0.5 rem per year for the whole body of individuals in the general population and an average gonadal dose of 5 rem in 30 years for the general population (exclusive of natural background and the purposeful medical exposure of patients).

The guidance also established occupational exposure limits, which differed only slightly from those recommended by the NCRP and ICRP at the time (NCR54, NCR59). The guidance included:

Whole body, head and trunk, active blood-forming organs, gonads or lens of the eyes are not to exceed 3 rem in 13 consecutive weeks, and the total accumulated dose is limited to 5 rems multiplied by the number of years beyond age 18, expressed as 5(N-18), where N is the current age.

Skin of the whole body and thyroid are not to exceed 10 rem in 13 consecutive weeks or 30 rem per year.

Hands, forearms, feet, and ankles are not to exceed 25 rem in 13 consecutive weeks or 75 rem per year.

Bone is not to exceed 0.1 microgram of radium-226 or its biological equivalent.

Any other organs are not to exceed 5 rem in 13 consecutive weeks or 15 rem per year.

In addition to the formal exposure limits, the guidance also established as Federal policy that any radiation exposure should be justified and that "...every effort should be made to encourage the maintenance of radiation doses as far below this guide as practicable...." Both of these concepts had previously been proposed by the ICRP. The inclusion of the requirements to consider benefits and keep all exposures to a minimum was based on the possibility that there is no threshold for radiation. The linear, no threshold, dose-response relationship was assumed to place an upper limit on the estimate of radiation risk.

Licensing procedures

A license application shall be approved if the Director determines that the requirements of this section have been satisfied.

The applicant shall qualify by reason of training and experience to use the material in question for the purpose requested in accordance with these regulations in a manner that minimizes danger to public health, safety, and property.

The applicant's proposed equipment, facilities, and procedures shall be adequate to minimize danger to public health, safety, and property.

The issuance of the license shall not be inimical to the health and safety of the public.

Radiological Safety Surveys, Records and Documentation

Surveys and inspections

Radiological surveys are performed at many types of facilities for a variety of purposes. Survey objectives range from ensuring operational radiological control to demonstrating that a remediated facility may be safely released for unrestricted use. Radiological surveys comprise a set of discrete survey tasks, such as, ambient dose rate measurements, air monitoring, evaluating radiation levels from radiation producing equipment, assessing radioactive material concentrations in environmental media, and determining surface contamination levels. It is essential that these fundamental radiological survey tasks be properly performed and documented so that survey results are sufficient for their intended purposes. The data life cycle, which includes survey planning, implementation, and assessment, can be used to ensure that these survey data satisfy their stated objectives.

Radiological Controls and ALARA

Radiological Control Personnel (RSO) is responsible for:

- Implementing radiological requirements, limits, guidelines, and procedures.
- Monitoring radiological work in progress to ensure radiologically safe practices are used.
- Measuring, documenting, and tracking personnel exposures and environmental impact of radiological work.
- Evaluating radiological performance and advising TJNAF management in implementing improvements.

Radiological workers is responsible for:

- Knowing and minimizing his/her exposure.
- Complying with all radiological rules and written and oral instructions from Radiological Control Personnel.
- Being familiar with emergency procedures.
- Being alert for and responding to unusual radiological situations.
- Knowing where/how to contact Radiological Control Personnel in your work area.

Dose Reduction Practices

The main goal of the ALARA program is to reduce both the external and internal radiation doses to a level that is As Low As Reasonably Achievable.

The three basic protective measures used to reduce external exposure are:

- Minimizing time in a field of radiation.
- Maximizing the distance from a source of radiation.
- Using shielding whenever possible.

Radiological Emergencies

A radiation emergency is defined as any unplanned event with a radiation producing device that may result in an increased exposure of individuals to ionizing radiation. The Radiation Safety Office should be promptly notified of any radiation incident to assure the proper response is taken to minimize personnel exposure and address any injury from possible overexposure to sources of radiation.

Notifications and assistance

The most likely scenario for a serious overexposure to radiation involves exposure to the primary beam of an analytical X-Ray device, linear accelerator, cyclotron, or a high activity sealed source. In any case, immediately notify the Radiation Safety Office, who will provide additional instructions, based on the exposure conditions.

Response: Radiation and Medical Evaluations

- The SRT-100™ produces radiation only when energized (i.e., beam is turned on).
- Radiation ceases to be emitted when the beam is turned off, power switch is turned off, or power plug is pulled.
- Emergency procedures, which contain as a minimum the phone numbers of persons to call in an emergency, should be located near the control console and known by all workers in the area.
- Follow this procedure in case of an emergency:

1. **Turn OFF equipment at Control Console.**
    - **Press the Stop Button or the Emergency Stop Button**
2. **Turn OFF SRT-100™'s main power switch in back of Base Unit.**
3. **Remove patient from treatment room, if present.**
4. **Post a sign on the equipment to prevent its use during incident investigation.**
5. **Call one of the individuals listed below immediately.**
6. **Call Sensus Healthcare if unit needs repair: 1-800-324-9890.**
7. **Safeguard radiation badges to prevent loss.**

Misadministration

For purposes of this rule "misadministration" means:

1. A therapeutic radiation dose from a machine:
    A. Delivered to the wrong patient.
    B. Delivered using the wrong mode of treatment.
    C. Delivered to the wrong treatment site.
    D. Delivered in one week to the correct patient, using the correct mode, to the correct therapy site, but greater than 130 percent of the prescribed weekly dose.
2.
    A. Radiation dose from a machine with errors in the calibration, time of exposure, or treatment geometry that result in a calculated total treatment dose differing from the final, prescribed total treatment dose by more than 20 percent, except for treatments given in 1 to 3 fractions, in which case a difference of more than 10 percent constitutes a misadministration.
    B. Reports of therapy misadministration 1. Within 24 hours after discovery of a misadministration, a registrant shall notify the Agency by telephone.

The registrant shall also notify the referring physician of the affected patient and the patient or a responsible relative or guardian, unless the referring physician personally informs the registrant either that he or she will inform the patient, or that in his or her medical judgment, telling the patient or the patient's responsible relative or guardian would be harmful to one or the other, respectively. If the referring physician or the patient's responsible relative or guardian cannot be reached within 24 hours, the registrant shall notify them as soon as practicable.

The registrant shall not delay medical care for the patient because of notification problems. Within 15 days following the verbal notification to the Agency, the registrant shall report, in writing, to the Agency and individuals notified under subsection (B) (1).

The written report shall include the registrant's name, the referring physician's name, a brief description of the event, the effect on the patient, the action taken to prevent recurrence, whether the registrant informed the patient or the patient's responsible relative or guardian, and if not, why not. The report shall not include the patient's name or other information that could lead to identification of the patient. 3. Each registrant shall maintain records of all misadministration for Agency inspection. The records shall:

A. Contain the names of all individuals involved in the event, including: i. the physician, ii. The allied health personnel, iii. The patient, IV. The patient's referring physician, v. The patient's identification number if one has been assigned, VI. A brief description of the event, vii. The effect on the patient, and viii. The action taken to prevent recurrence.
B. Be maintained for three years beyond the termination date of the affected registration.