Therapeutic radiological physics, commonly referred to as radiation oncology physics or radiation therapy physics, is a branch of medical physics that deals with the therapeutic applications of radiation in medicine. Therapeutic Medical Physics is a newly introduced term by the American Board of Radiology. The branch of medicine that uses radiant energy to treat diseases is called therapeutic radiology and radiation oncology is the treatment of tumors. Radiation therapy, still referred to as radiotherapy in European countries, is the therapeutic treatments with the use of radiant energy. Radiation therapy should not be confused with radiology (more appropriately referred to as diagnostic radiology), a specialty in the use of ionizing radiation for medical imaging and diagnosis. The other sub-fields of medical physics are Diagnostic Radiological Physics, Medical Nuclear Physics, and Medical Health Physics (www.aapm.org under qualified medical physicists). In the academic environment, therapeutic radiological physics is a branch of radiologic physics. A common link among these sub-fields is the expected understanding of (a) the fundamentals of radiation physics, (b) the interaction of radiation with matter, (c) health physics, and (d) radiobiology. These subject matter had been discussed in an earlier published textbook – Foundation of Radiological Physics (referred as pre-requisite textbook).¹ The objective of this particular textbook is to provide supplementary materials for a complete curriculum on therapeutic radiological physics.

This introductory chapter will examine the (a) basic principles, (b) clinical aspects, and (c) radiation protection in therapeutic radiological physics. With respect to the basic principles, the scope of therapeutic radiological physics, radiological quantities and units, radiation therapy beams, and methods of administering of radiation therapy will be discussed.

This is followed by the philosophy of cancer management, radiation therapy procedures, side effects of radiation treatments, and biological basis of radiation therapy. Treatment planning systems that have permitted the implementation of complex treatment techniques with precise dose delivery will be examined. The discussion on the emerging new role for medical physicists specializing in radiation therapy and radiation protection will be the last part of this chapter.

1.1 Scope of Therapeutic Radiological Physics

Therapeutic radiological physics concentrates on (a) the physical aspects of therapeutic applications of x-rays, gamma rays, electrons and charged particle beams, neutrons, and radiations from sealed sources, (b) the equipment associated with their production, use, measurements, and evaluation, (c) the quality of images resulting from their production and use, and (d) medical health physics associated with this sub-field of medical physics. The discipline of radiation oncology is rapidly changing in the (a) equipment development, (b) treatment techniques, and (c) management of cancer. As such, therapeutic radiological physics is inherently linked to the advancements of modern technology. Medical physicists specializing in this field must keep pace with these advances in order to assure (a) safe operation of the equipment, (b) efficient production of radiation beams, (c) precise and accurate radiation dose delivery, and (d) practical and reproducible patient positioning to support patient care in an efficient and convenient manner. In addition, medical physicists in this field should be very knowledgeable in the handling of radiation sources and exposures. This is crucial because the inadvertent high exposures from these radiation sources, either from radioactive materials or radiation producing machines, can cause detrimental effects to patients undergoing radiation therapy as well as personnel.

In the past, radiation therapy was practiced using simple blocked fields with manual treatment planning techniques. The blocking technique was later automated using the multileaf collimation (MLC) system. This MLC system attached to the head of a medical linear accelerator (see Figure 1.1) consists of two banks of leaves that move bidirectional to form various field shapes as shown in Figure 1.2. The
standard practice of radiation oncology was transformed in the early 1990s with the introduction of three-dimensional (3D) treatment planning systems. 3D treatment planning systems offer the ability to visualize the spatial location of the tumor relative to the patient anatomy in three dimensions. This ability has aided in radiation beam placements that precisely target the tumor while minimizing the irradiation of normal anatomical structures. Further advancements in treatment planning system software helps to better manipulate the MLC system on the radiation dose delivery systems. This has led to the development of conformal radiation therapy (CRT) and intensity-modulated radiation therapy (IMRT) treatment techniques. In the CRT treatment technique, the projection of the MLC shape from the radiation source must conform to the target cross-section. On the other hand, the MLC leaves modulate across each projection to yield a dose distribution that conforms to the targets in the IMRT treatment technique.

The implementation of CRT and IMRT led to the requirement for precise and repeated patient setups and management of target motions caused by inherent patient responses. Patient setup is verified using image-guided radiation therapy (IGRT) tools. Patient motion management has been investigated extensively. The mechanisms of motion management include free breathing, breath-hold, forced breathing, and beam-gated free breathing. Adaptive radiation therapy refers to the various methods to account for changes in dose distributions due to the variation of daily patient setup.

### 1.2 Radiation Quantities and Units

Various methods of quantifying the effects of radiation have been introduced including the qualitative observation of skin reaction. **Table 1.1** lists the commonly used radiological quantities: radiation exposure, absorbed dose, dose equivalent, and radioactivity. Their associated SI units are the C/kg, Gy, Sv, and Bq, respectively.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Values</th>
<th>SI Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation Exposure</td>
<td>R</td>
<td>2.58 x 10^{-4}</td>
<td>C/kg</td>
</tr>
<tr>
<td>Absorbed Dose</td>
<td>rad</td>
<td>1 x 10^{-2}</td>
<td>Gy</td>
</tr>
<tr>
<td>Dose Equivalent</td>
<td>rem</td>
<td>1 x 10^{-2}</td>
<td>Sv</td>
</tr>
<tr>
<td>Radioactivity</td>
<td>Ci</td>
<td>3.7 x 10^{-10}</td>
<td>Bq</td>
</tr>
</tbody>
</table>

The radiation exposure (X) at a point is defined as the quotient of dQ by dm,

\[ X = \frac{dQ}{dm} \quad (1.1) \]

where \( dQ \) is the total charge of the ions of one sign produced when photons ionize a small mass (dm) of air and are completely stopped in air.\(^2\) The unit of radiation exposure is the “roentgen”, named after Wilhelm Roentgen who

---

discovered x-rays in 1895. One roentgen (R) is defined as the exposure that will produce 1 electrostatic unit (esu) of charge within a cubic centimeter (cm$^3$) of dry air at standard temperature and pressure (STP) condition.

EXERCISE 1.1 One esu is defined as the amount of charge on two point objects that gives rise to a force of 1 dyne. Show that one esu is equivalent to $2.08 \times 10^9$ ion pairs.

In the United States, the standard temperature and pressure condition is referenced at 22 °C and 760 torr, respectively. Since the density of dry air at STP is 0.001293 gm per cc (1.293 kg/m$^3$), the early definition of the roentgen was given as the exposure of x-rays and gamma rays such that the associated corpuscular emission per 0.001293 gram of dry air produces ions carrying one electrostatic unit of charge (esu) of either sign. The SI unit for one roentgen is $2.58 \times 10^{-4}$ coulombs per kilogram (C/kg) of air.

EXERCISE 1.2 Show that 1 R is equal to the production of 1 esu of charge in 1 cm$^3$ of air.

As defined, the roentgen has a number of limitations as a unit of radiation measurement. First, the roentgen is valid only for exposure to x-rays and gamma rays. Other forms of radiations such as electron and neutron beams are not applicable. Second, the application of roentgen is limited to ionizations in air medium only. Third, the roentgen assumes that a dosimeter must be capable of collecting all ions released during a radiation exposure. This requirement is satisfied in the orthovoltage range where the energy of photon beams is low. As the photon energy increases, the electron range increases, requiring a larger collection volume. Up to a certain volume, it would become impractical to measure radiation exposure. As such, it is generally accepted that exposure is defined for photons with energies of less than 3 MeV. Fourth, the type of dosimeters available for exposure measurement in roentgen is limited. The devices must be made of materials similar to air in composition so that the secondary emissions are similar to those from air.

The absorbed dose, $D$ at a point is defined as the quotient of $dE$ by $dm$,

$$D = \frac{dE}{dm} \quad (1.2)$$

where $dE$ is the mean energy imparted by ionizing radiation to a small mass ($dm$) in a volume element. As defined, absorbed dose describes the energy deposition in a medium per unit mass and hence, absorbed dose can be

---

applied to any type of radiation in any medium. The unit of absorbed dose is the rad, an acronym for “radiation absorbed dose”. The rad is defined as 100 ergs of radiation energy absorbed in a gram of matter. The SI unit of absorbed dose is the gray (Gy), which is equivalent to one joule per kilogram. Since one joule is equal to \(10^7\) ergs, one rad is equal to 0.01 J/kg.

**EXAMPLE 1.1** If 200 rads are delivered to 10 grams of tissue, what is the total energy absorbed? Express your answer in gram-rad.

**SOLUTION:**

\[ E = 200 \text{ rad} \times 10 \text{ gm} = 2000 \text{ gram-rad} \]

**EXERCISE 1.3** Show that the gram-rad is equivalent to the unit of energy.

The absorbed dose can be related to the exposure. The average energy needed to produce an ion pair in dry air (\(\bar{W}\)) is 33.97 eV and is almost constant over a wide range of temperature and pressure conditions. Since the electronic charge per ion pair is \(1.6021 \times 10^{-19}\) C, the average energy required per unit charge is

\[ \frac{\bar{W}}{e} = 33.97 \text{ J/C} \quad (1.3) \]

**EXERCISE 1.4** Show that \(\frac{\bar{W}}{e}\) is equal to 33.97 J/C from 33.97 eV per ion pair.

**EXAMPLE 1.2** How much charge expressed in coulomb would be liberated in air by a 10 MeV electron?

**SOLUTION:**

\[ Q = (1 \times 10^7 \text{ eV}) \times \frac{1 \text{ ion}}{33.97 \text{ eV}} \times \frac{1.6 \times 10^{-19} \text{ C}}{1 \text{ ion}} = 4.71 \times 10^{-14} \text{ C} \]

The absorbed dose in air from one roentgen of exposure is 0.876 cGy. This equivalence is calculated in EXAMPLE 1.3.

**EXAMPLE 1.3** Show that 1 R of ionization in air is equivalent to 0.876 cGy of absorbed dose in air.

**SOLUTION:**

\[ 1 \text{ R} = 2.58 \times 10^{-4} \frac{\text{C}}{\text{kg}} \times 33.97 \frac{\text{J}}{\text{C}} = 8.76 \times 10^{-3} \frac{\text{J}}{\text{kg}} = 8.76 \times 10^{-3} \text{ Gy} = 0.876 \text{ cGy} \]

Another energy quantity is the kinetic energy released in a medium (kerma). The kerma (K) is defined as the quotient of dE, by dm as
Chapter 1: Therapeutic Radiological Physics

Table 1.2 Radiation weighting factors

<table>
<thead>
<tr>
<th>Radiation Types</th>
<th>Weighting Factor (w_R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-rays, gamma rays, electrons, positron, and muons</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons &lt; 10 keV</td>
<td>5</td>
</tr>
<tr>
<td>10 keV to 100 keV</td>
<td>10</td>
</tr>
<tr>
<td>&gt; 100 keV to 2 MeV</td>
<td>20</td>
</tr>
<tr>
<td>&gt; 2 MeV to 20 MeV</td>
<td>10</td>
</tr>
<tr>
<td>&gt; 20 MeV</td>
<td>5</td>
</tr>
<tr>
<td>Protons, other than recoil protons with energy &gt; 2 MeV</td>
<td>2</td>
</tr>
<tr>
<td>alpha particles, fission fragments</td>
<td>20</td>
</tr>
<tr>
<td>non-relativistic heavy nuclei</td>
<td>20</td>
</tr>
</tbody>
</table>

The w_R is a dimensionless quantity and accounts for the differences in relative biological effectiveness (RBE) per absorbed dose of various types of radiation. The radiation-weighting factors for various types of radiation listed in Table 1.2 are taken from NCRP Report No. 116.\(^5\) In an environment where different types and different energies of radiation are present, for example, in a power plant, the equivalent dose is the sum of the contributions from each type of radiation (R) as

\[
H_{T,R} = w_R \times D_{T,R}
\]

(1.5)

In the case where the exposure is not uniform, the concept of effective dose is used. The effective dose (E) for a whole body exposure is defined as the sum of the product of the equivalent dose and the tissue-weighting factor (w_T) for all irradiated tissues or organs. The mathematical equation for effective dose is

\[
E = \sum_T (w_T \times H_T)
\]

(1.7)


\(^5\) Data from NCRP Report No. 116 (1993). Compared to data from NCRP Report No. 91 (1987), the quality factor for neutrons (other than thermal neutrons), α-particles, and multiple-charged particles of unknown energy is 20.

\(\text{K} = \frac{dE_{tr}}{dm}\)

(1.4)

where \(dE_{tr}\) is the sum of the initial kinetic energies of all charged ionizing particles (electrons in the medium) liberated by uncharged ionizing particles (such as x-rays and gamma rays) in a small mass dm.\(^4\) As defined, the kerma describes the initial transfer of energy to the medium. The energy loss through bremsstrahlung radiation by the charged particles and Auger electrons is included in the kerma. The kerma has the same unit as the absorbed dose.

The equivalent dose (\(H_{T,R}\)), due to radiation type (R), is defined as the product of the radiation-weighting factor (\(w_R\)) and the average absorbed dose (\(D_{T,R}\)) in a tissue or organ (T). Mathematically, it is written as

\[
H_{T,R} = w_R \times D_{T,R}
\]

(1.5)
The tissue-weighting factor, which is also a dimensionless quantity, accounts for tissue sensitivity to radiation. A list of tissue-weighting factors for various organs (Table 1.3) is provided in the NCRP Report No. 116. Note that \( w_R \) is independent of tissue or organ while \( w_T \) is independent of radiation type and energy. Overall, the effective dose takes into account the relative detrimental effect to each tissue or organ including the mortality and morbidity risks from cancer, the risk of hereditary effects, and the length of life lost (shortening of life span). This effective dose is now used to set regulatory exposure limits.

The unit of equivalent dose is the rem, the acronym for “rad equivalent man”. The SI unit of equivalent dose is the sievert (Sv). One sievert is equal to 100 rem. Like absorbed dose, the SI unit of equivalent dose is the joule per kilogram (J/kg). For radiation protection considerations in the medical field where the types of radiation used (gamma rays, x-rays, electrons, and beta rays) have the same biological destructiveness, the radiological quantities are often used interchangeably, i.e., 1 rem \( \approx 1 \) rad \( \approx 1 \) R in spite of their known differences.

**EXAMPLE 1.4** Find the effective dose of 100 cGy of alpha particles and 100 cGy of photons.

**SOLUTION:**

\[
E = \sum (H_T) = \sum (w_R x D_T) \\
= (20 \times 1) \text{Sv} + (1 \times 1) \text{Sv} = 21 \text{Sv}
\]

The radioactivity of a radioactive material represents the number of disintegrations per second (dps). It is a spontaneous nuclear transformation process where the exact time of emission cannot be predicted. The unit of activity is the curie, named after Madame Marie Curie. One curie (Ci) represents the number of disintegration per second (dps) from one gram of radium-226. It carries a value of \( 3.7 \times 10^{10} \) dps. The SI unit of radioactivity is the becquerel (Bq), which represents one disintegration per second. However, a larger unit (MBq) is often used. One curie is equivalent to \( 3.7 \times 10^4 \) MBq. Radioactive materials decay exponentially as a function of time as explained in Chapter 8 of the *Foundation of Radiological Physics* textbook. The exponential function is given as

\[
A = A_0 e^{-0.693t/\tau}
\]  

(1.8)

where \( A \) is the activity at time \( t \), \( A_0 \) is the initial activity at time \( t=0 \) and \( \tau \) is the half-life of the radioactive material. The half-life of a radioactive material
represents the time for the activity of a sample to decays to one-half of its original value.

**EXAMPLE 1.5** Compute the shipment activity in mCi of a radioactive isotope (half-life=60 days) if the amount to be received is 15 mCi after 3 days?

**SOLUTION:**

\[
A_t = A_0 \left( \frac{1}{2} \right)^{t/\tau} = \frac{15 \text{ mCi}}{0.9659} = 15.5 \text{ mCi}
\]

### 1.3 Radiation Therapy Beams

Radiation therapy beams are characterized by their type and energy. The type of radiation provides information on the relative biological effectiveness (RBE) in cell-kills and the penetration by the radiation beam energy. Both photon beams (x-rays, bremsstrahlung, and gamma rays) and particle beams (electrons, beta rays, proton and heavy-ions) have been used in radiation therapy. The most widely used radiation therapy beams presently are the photon beam and electron beam from medical linear accelerators and gamma rays from high-dose rate (HDR) remote afterloading systems.

**Kilovoltage photon beam** (x-rays produced from kilovoltage x-ray machines) is characterized by (a) maximum doses at the skin surface, (b) rapid dose fall-off resulting in low exit doses, (c) better RBE than electron beam by 15% for a 200 kVp beam, and (d) sharper penumbra than electron beam. These characteristics are well-suited to treat superficial skin lesions but these machines are becoming obsolete in favor of electron beams because of the limited applications. Deep-seated tumors are treated using megavoltage photon beams (also called high-energy photon beams) produced from cobalt-60 units and medical linear accelerators. Megavoltage photon beams offer unique features of (a) skin sparing effect, which is the reduction of skin dose compared to the kilovoltage beam, (b) highly penetrating beam for treating deep-seated tumors, and (c) Compton effect interaction, which is independent of the atomic number of human composition, whether bone or tissue. This type of interaction avoids “bone shadowing” effects where the bone differentially absorbs more dose than tissue due to the photoelectric effect, thereby causing serious under dosage beyond the bone structure. Low energy megavoltage photon beams such as cobalt-60, 4 MV, and 6 MV photon beams are used to treat cancers of the head and neck. Higher energy megavoltage photon beams, in the range of 15–25 MV, are ideal for treating deep-seated tumors in particular, in the pelvic regions. Cobalt-60 units have been replaced with medical linear accelerators, which have better dosimetric characteristics. Electron beams and beta rays are usually used to treat superficial lesions.

Interests have continued to bring high linear energy transfer (LET) particle beams to clinical use because of their unique advantages of dose localization (ability to place dose at particular depths) and better RBE. However, the cost of the machines to produce these beams is still very
expensive and affordable to only a few centers. These particles include protons, neutrons, alpha particles, pions, and heavy ions such as helium, neon, and carbon. The mass and charge properties of these beams are listed in Table 1.4. The notation, $m_e$, refers to the electron mass, which is equal to 9.1095 x $10^{-31}$ kg (or 5.48 x $10^{-4}$ u = 0.511 MeV). The unit u is the atomic mass unit (amu) which is equal to 1.66054 x $10^{-27}$ kg. The other notations, $m_p = 1.6726 x 10^{-27}$ kg and $m_n = 1.6750 x 10^{-27}$ kg are the masses of the proton and neutron, respectively. Charged particles are produced in cyclotrons and accelerators while neutron beams are produced in a reactor or a D-T (deuteron-tritium) generator.

In a D-T generator, the tritium target is bombarded with a low-energy deuteron beam of around 100–300 keV. This reaction produces a neutron beam with energy of about 14.1 MeV. The nuclear reaction is given as

$$^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + n \quad (1.9)$$

where a disintegration energy of 17.6 MeV is released.

---

### Exercise 1.5

Using equation (1.9), show that the excess neutron energy is derived from the difference in binding energies between the helium and tritium.

---

### The neutron beam is monoenergetic and also isotropic.

Although a major advantage of the D-T generator is its small size, allowing for easy mounting on the isocentric structure, the neutron beam suffers from low output rate. The highest dose rate is 15 cGy per min at one meter.

Protons, discovered by E. Rutherford in 1919, in the range of 150–250 MeV have been used for therapeutic purposes. The major advantage of the heavy (or massive) charged particle beam is the presence of the Bragg peak. This is an enhancement where there is a maximum energy deposition near the end of the particle’s range. The range of heavy charged particles can be estimated based on the energy per nucleon. For example, 150 MeV protons, 300 MeV deuteron, and 600 MeV helium have approximately the same range of 16 cm in water since the energy per nucleon of each of these beams is the about the same, that is 150 MeV per nucleon. The range of ions heavier than helium is less predictable based on the energy per nucleon rule. This is because the range is proportional to the mass number and inversely proportional to the square of the nuclear charge. As the ions get heavier, the

---

range of these heavier ions decreases for the same energy per nucleon (MeV/\text{u}).\textsuperscript{7}

Another type of particle beam of interest is the pions. The existence of pi (\(\pi\)) mesons (simply called pions) was predicted by Yukawa’s theory in 1935 and later discovered in cosmic rays in 1947. According to the theory, protons and neutrons are held together in a nucleus through the exchange of pions. The pion is said to mediate between the strong nuclear forces. A pion is about 273 times more massive than an electron rest mass. It can carry a positive charge, a negative charge, or be neutral. The charged pion (mean life = \(2.54 \times 10^{-8}\) s) decays into mu meson and neutrinos. A neutral pion (mean life = \(1.8 \times 10^{-16}\) s) decays into two photons (98.8%) or an electron, a positron and a photon (1.2%).

Only negative pions had been found to be useful in radiotherapy. Negative pion beams are produced through the bombardment of beryllium or carbon targets with protons of energies from 400–800 MeV. Although the beam has all types of pions, each with a spectrum of energies, the negative pions can be extracted using bending and focusing magnets. Negative pions with energies close to 100 MeV have a range of 24 cm in water. The Bragg peak is more pronounced for negative pion beams because of the additional effect of nuclear disintegration by negative pion capture. During this negative pion capture by the media, several particles such as protons, neutrons and alpha particles are released. This process is commonly known as star formation.

The percent depth dose (relative dose as a function of depth) curves of a few radiation beams are shown in Figure 1.3. The electron beam has a finite range which is well-suited for treating superficial lesions. The range increases with depth as the energy of the electron beam increases. The range for megavoltage photon beams is deeper compared to the electron beams. Cobalt-60 and neutron beams have similar depth dose characteristics. The advantage of proton beam is the presence of the Bragg peak which allows for precise target localization. By careful modulation of the beam achieved through using a rangeshifter (also called energy attenuator), a broad uniform dose region across the tumor can be generated for treatment. Pion beams have depth dose characteristics similar to that of a proton beams.\textsuperscript{8}


For manual brachytherapy, the most widely used isotopes are iridium-192, iodine-125, palladium-103, cesium-131, phosphorous-32, and strontium-90. The iridium-192 source is used in both manual and remote afterloading high-dose-rate brachytherapy. Due to their short half-lives, iodine-125, cesium-131, and palladium-103 sources are principally used in permanent implants, in particular, the treatment of prostate cancer. Beta rays from strontium-90 are used to treat pterygium and endovascular brachytherapy. The percent depth dose of radioisotopes decreases as the inverse square of the distance from the clusters of sources. This unique characteristic is the advantage of brachytherapy over external beam radiation therapy.

**EXERCISE 1.6** Explain why cesium-137 source with a half-life of 30 years, cannot be used in permanent implant.

### 1.4 Methods of Administering Radiation Therapy

The aim of radiation therapy is to deliver the prescribed radiation doses to the lesions uniformly and to spare the surrounding normal tissues. The prefix "prescribed" is used to indicate that the doses have been selected by the radiation oncologist for treatments. These doses may not be curative doses, but may have the potential to maximize local control and minimize morbidity to the patients.

The methods of administering radiation therapy are dependent on the location of the lesion, the extent of the disease, and the surrounding critical structures or organs. The widely practiced method is the external beam radiation therapy (EBRT) using computer-controlled medical linear accelerators. Brachytherapy is usually performed in a limited number of centers while internally administered radionuclide therapy is often done in the nuclear medicine department because of the concerns of spillage and for their radionuclide precautionary expertise.

In external beam radiation therapy, the radiation source is external and far away from the patient. Since the source is distant, it was referred in the past as teletherapy. If the radiation source is a radioisotope such as cobalt-60 or cesium-137, the method of administration was referred as gamma ray beam therapy. If the radiation came from x-ray tubes, it was referred as x-ray beam therapy. X-ray beam therapy was further sub-divided in accordance to their potential voltage, for example kilovoltage therapy, orthovoltage therapy, deep therapy, and so on. These will be discussed in the next chapter. Since the make up of the radiation beam is principally bremsstrahlung radiation, the dose delivery technique is commonly called external photon beam therapy. Today EBRT is commonly performed using medical linear accelerators and hence the distinction as described above becomes insignificant. EBRT is
usually performed on a fractionated schedule for a therapy course of daily treatments lasting five days per week over several weeks. Some treatments may require two fractions per day, referred to as “b.i.d”, from the Latin “bis in die”, meaning twice a day. Since EBRT is not a surgical procedure, it is better tolerated and does not require hospitalization. However, it requires daily visits to the radiation oncology facility over the course of the treatment.

**Brachytherapy** where the radiation source is implanted near or inside the lesion is the next commonly used dose delivery method. It is an invasive treatment technique compared to the EBRT. The radiation sources are radioactive materials that are encapsulated and sealed into small pellets to minimize the risk of source contamination. If the radiation sources are left in the patient for a few days and then removed, it is called **temporary implants**. These implants are typically referred as **low dose rate (LDR) implants** using low activity radioactive sources. Another type of temporary implants is the **high-dose-rate (HDR) implants**, where the radiation sources are left in the patients for only a few minutes and immediately removed after treatment. If the radiation sources are left in the patient permanently, the treatment is called **permanent implants**.

The third method of dose delivery is **internally administered radionuclide therapy** which has also been referred as **systemic therapy**. In this dose delivery method, unsealed or liquid radioactive sources administered intravenously or taken orally circulate through the body, even to normal functioning organs. With sufficient specificity, these radionuclides seek and attach themselves to the lesions for treatment. The administration of radioactive sources in liquid form poses significant risk to environmental and personnel contamination. As such, the procedure is usually performed in a well-equipped setting to manage environmental and personnel contamination. Commonly used internally administered radionuclides are iodine-131 (I-131), strontium-89 (Sr-89), samarium-153 (Sm-153), and phosphorus-32 (P-32). I-131, taken orally is typically used for the treatment of thyroid cancers while both Sr-89 and Sm-153 are used for bone pain palliation. More recently, radium-223 (Ra-223), which is an alpha emitter has been shown to be effective in the management of bone metastases from castration-resistant prostate cancers. P-32 has been used in the treatment of brain cysts and diseases of the pleural cavity. Radiolabeled monoclonal antibodies labeled with yttrium-90 (Y-90) and I-131 have been used in the treatment of other cancers such as non-Hodgkin’s lymphoma.

### 1.5 Philosophy of Cancer Management

The management of cancer involves multidisciplinary care. The three principal modalities that have been used in the management of cancers are surgery, chemotherapy, and radiation therapy. They have been used alone or in combination to treat a particular type of cancer. Other types of treatment
such as hormonal therapy, immunotherapy, gene therapy, radiofrequency ablation, hyperthermia have also been used.

**Surgery** involves the removal of tumors and its surrounding normal tissues, and hence, is a localized treatment. It is the oldest form of cancer treatment. At one time, this was the only effective as well as the preferred means of treatment. Surgery also allows the study of the spread of the disease by accurately mapping the extent of the tumor. By having this information, the disease can be staged, which affects the course of treatment. Another advantage of surgery is that there is no carcinogenic effect. The disadvantage of surgery is that it offers no specificity between neoplastic tissues and normal tissues. Surgery has the potential threat to life, and it can cause significant morbidity and may result in deformity or loss of function. Limited surgical resection may be performed to avoid damage to vital structures. In cases where there is a spread beyond the regional sites, surgery alone is not a curable treatment.

**Chemotherapy** refers to treatments using drugs taken either orally, intramuscularly, or intravenously. It serves as a systemic management of cancer. Since the drug travels throughout the body, cancer cells in remote location can be eradicated using this mode of treatment. This systemic therapy distinguishes itself from radiation therapy or surgery where the treatments are localized. Most cytotoxic drugs are effective in the destruction of cancer cells by inhibiting the synthesis or function of the nucleic acids. However, the chemotherapeutic agents also produce undesirable damage to the normal tissues such as hematologic suppression, mucositis, and hair loss. The drugs also have the tendency to cause nausea and vomiting. Advancements are being made to reduce the cell toxicity and chemotherapy-induced nausea and vomiting. Other agents such as interferon and interleukins, radiosensitizers, and radioprotectors have been helpful in the management of cancers.

**Radiation therapy** requires the precise delivery of high radiation doses to the tumor or suspected diseased tissues. The effect of radiation therapy can be immediate, such as in the treatment of spinal cord compression. External beam radiation therapy is usually performed on a fractionated schedule over the course of treatment. Typically, a fraction (also called a treatment) is given once a day over five days per week. The actual number of fractions prescribed for a treatment course will depend on the total dose to be delivered for a particular type of malignancy. A course of radiation treatment ranges from 2 to 7 weeks for a patient undergoing external beam radiation therapy. Brachytherapy is an alternative but an invasive treatment option.

The goal of radiotherapy can be classified as either "curative" or "palliative". The goal of **curative radiotherapy** is to produce local tumor control without causing significant harm or complications to the normal tissues. With **palliative radiotherapy**, the aim is to relieve distressing symptoms. Cancer distressing symptoms can be pain due to bone invasion, headaches due to brain metastasis, paralysis due to spinal cord compression, or bleeding due to involvement of the skin, bladder, or bowels. Besides
curative and palliative intent, there are circumstances when the family demands that all possible efforts be done to the patient. The treatment following this aim is classified as "radiation psychotherapy".

The tumor radiocurability depends on the radiosensitivity of the tumor and normal tissue tolerance. The therapeutic ratio (TR), defined as the ratio of the normal tissue tolerance dose to the lethal tumor dose, is used as a measure of radiocurability. It is the ratio of the dose that leads to 50% of the patients with serious complications to the dose that yields a tumor control for the same percent of patients, e.g.,

\[
TR = \frac{\text{Normal Tissue Tolerance Dose}}{\text{Lethal Tumor Dose}}
\]

(1.10)

If TR is greater than one, the tumor cell is said to be radiosensitive compared to normal tissue. If the TR is less than one, the tumor cells are radioresistant. The therapeutic ratio is explained using the tumor control and normal tissue injury probabilities curves shown in Figure 1.4. The normal tissue responses are sharply dependent on dose, although the curve tends to be less steep than that of tumor control responses. As the dose increases, the tumor control and normal tissue injury increase. However, there exist some conditions, for example, like dose B, where the tumor control is very high compared to the complications. It is generally expected that a change of 7–10% in dose can significantly alter the tumor control probability.9

1.6 Radiation Therapy Procedures

Since radiation therapy used high doses, every precaution must be taken to avoid the risk of injuring the patients as well as personnel. Although the preparation of each method of administrating radiation therapy is different, we will discuss the external beam radiation therapy as an example to elucidate the processes or the steps in the preparation of the patients to undergo individualized radiation therapy. The radiation therapy procedures involve four steps: (a) patient workup, (b) patient simulation, (c) treatment planning, and (d) dose delivery.

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Patient workup refers to the process of determining the extent of the disease such as lymph nodes involvement and metastatic nature prior to the preparation for radiation therapy. Typically, it involves the review of available patient information including imaging scans and clinical reports in consultation with the referring physicians. Additional tests or examinations may be requested for the diagnosis. Ultimately, the primary radiation oncologist must reached an understanding on the general health of the patient, the extent of the disease or staging, and provide a confirmation that there is a need for radiation therapy.

Patient simulation involves both the immobilization and patient data acquisition procedure. Immobilization refers to the innovative process of selecting the appropriate fixation or immobilization device and treatment aids that would limit patient movement and provide support in a comfortable manner so that the physical position of the patient can be maintained (in a static position) and reproduced throughout the radiation treatment. Commonly used fixation devices include thermoplastics molded over the patient’s head and attached to the treatment couch, vacuum bags, and alpha cradle constructed by mixing two chemical to create foam that hardens and conform to the contour of the patient. Treatment aids such as pillows or Styrofoams can be used to support the patient posture. After immobilization, the patient anatomical information and lesions are obtained using a patient data acquisition system prior to releasing the patient. A patient data acquisition system is typically a modified imaging modality such as a CT or MRI scanner that can acquire images for the purpose of performing treatment planning. After the simulation, the images are downloaded into a 3D treatment planning system to generate a virtual patient for treatment planning. The advantage of the virtual patient is that the patient can be immediately released following the simulation process.

Treatment planning also called dose planning refers to the process of generating a plan of radiation dose delivery that can results in an appropriate dose distribution for the patient. This is a very important process because the clinical outcome is dependent on the quality of the individualized treatment plan. A poor treatment plan can result in unacceptable radiation toxicity or can cause morbidity and even mortality. Due to its importance, this subject matter will be further discussed in section 1.9. After an individualized treatment plan is generated, the machine parameters for the plan are downloaded into a database that can be retrieved by the medical linear accelerators for dose delivery.

Dose delivery refers to the process of directing the radiation beam to the target to deliver the dose in accordance to the patient treatment parameters retrieved from the treatment plan. Prior to dose delivery, the patient must be set up in the same position or orientation as defined at the time of simulation on the treatment machine. In order for the treatment machine to be able to deliver the radiation dose, the delivery instructions must conform to the constraints of the dose delivery system. The dose delivery is computer-controlled and hence leaf sequencing techniques are critical to
successfull implementation. Prior to the initial treatment and subsequent treatment, the patient set up must be verified using image-guided radiation therapy (IGRT) devices.

**EXERCISE 1.7** Compare the difference between the HDR brachytherapy and the external beam radiation therapy procedures.

### 1.7 Side Effects of Radiation Treatment

As radiation is a potent tool in the management of cancers, it can cause a variety of side effects. As such, patients undergoing radiotherapy should be monitored at regular intervals (usually once a week) to keep abreast of the well-being of the patient. The side effects are not present in all patients and their severity will depend on the type of cancer, the amount of radiation received, and the size and region of the body being treated. The side effects usually appear in the later stages of radiation treatments and are temporary. However, they should be reported to the radiation oncologist so that medication can be given for temporary relief. Most side effects may continue for a few weeks and some even longer after the completion of radiation treatment.

An obvious side effect is fatigue due to the need for energy to fight cancer cells and repair injured cells. Blood counts and body weight may decrease and periodic assessments are therefore required. The skin at the treatment area may be reddened, irritated, tanned, or sunburned. This effect is expected to clear up after completion of treatment. Upset stomach or diarrhea is expected in the radiation treatment of the lower abdominal region. For prostate treatment, there are risks of impotence and, to a lesser extent, incontinence. Other side effects include frequent and painful urination and rectal irritation or bleeding. Nausea or vomiting may also occur in the treatment of the upper abdominal region. For patients with treatment to the head and neck region, there is the possibility of sores in the mouth, decreased saliva excretion leading to dry mouth and difficulty in swallowing. It is also possible for the patient to lose or develop a change in taste called **taste blindness**. Temporary hair loss called **alopecia** can also occur in the treatment of the scalp or head. The hair will regenerate later after the completion of treatment.

### 1.8 Biological Basis of Radiation Therapy
The subject matter of radiobiology has been dealt with in Chapter 15 of the prerequisite textbook.\textsuperscript{10} That chapter explained the interaction of radiation with cellular structures at the atomic and molecular levels. The concepts of linear energy transfer (LET), relative biological effectiveness (RBE), and cell survival curve were also examined. Acute radiation effects, dose response relationship, late effects of radiation, hereditary effects, embryonic, and fetal effects were also discussed. Radiosensitivity of cells and also some tumor biology mechanism were noted. The reader is referred to the prerequisite textbook for radiobiology information.

Body cells normally grow, divide, and replace themselves. Sometimes, these cells may lose their ability to regulate its growth; they divide rapidly and grow into masses of tissue known as tumors without any order or regard for their function. Tumors can be benign or malignant. Benign tumors usually grow slowly, and generally do not spread to other part of the body and hence, are considered non-cancerous. Benign tumors can generally be removed surgically without any further problems. On the other hand, malignant tumors are cancerous. They are capable of compressing, invading, and destroying adjacent tissues. In addition, it can metastasize to other parts of the body. The most common mechanism for cancer to spread is through the lymphatic system to the regional nodes or through the blood circulation system to distant organs. As cancer can spread rapidly, early detection and thereafter, treatment can increase the chance of cure. Cancers are most curable if they are localized.

The ability to eradicate a tumor is highly dependent on the size, radiosensitivity, and the presence or absence of a radiation-resistant anoxic component in the tumor. Generally, lesser dose is required for small and radiosensitive tumors. As the size of the tumor increases, the number of viable cells increases and so do the importance of anoxia. It is well documented that the greater the volume of tissue irradiated, the lower the dose can be given without exceeding the tolerance limits. The overall experience has been the delivery of a wide range of radiation doses, depending on the nature and location of the tumor as well as on whether the radiation is used alone or in combination with other modalities of treatment. Radiosensitive tumors include leukemias, lymphomas, seminomas, and dysgerminomas while radiosistant tumors include melanomas and sarcomas. Reoxygenation is the only “4 R’s” (see below) that occurs in tumors but not in normal tissues. Tumor cells contain about 5–20\% of hypoxic cells due to the limited diffusion distance of oxygen from the inadequate tumor vascular supply. Normal tissue contains little or no hypoxic cells. The extent to which tumors reoxygenate during a course of radiation may determine whether it can be eradicated by radiation therapy.

In cancer management, radiation treatment is usually fractionated to improve the efficiency of killing cancerous cells and reduce normal tissue injury. The biological response of tumors and normal tissues to fractionated

treatment is governed by four factors, namely: (a) repair of sublethal damage, (b) repopulation of surviving cells in the irradiated tissues, (c) reassortment of cells throughout the division cycle, and (d) reoxygenation of hypoxic cells in tumors. These four factors are often referred to as the “four R’s” of radiobiology.

1.9 Treatment Planning Systems

Nowadays, 3D treatment planning systems are used for treatment planning which is the design of individualized treatment plan. The 3D treatment planning systems use dose calculation algorithms to compute radiation doses as the radiation beams enter a patient. The radiation beam used is typically derived from a set of measurements of the actual radiation beams from the treatment machines at the time of commissioning. In the past, correction-based dose calculation algorithms were used in treatment planning systems, but today, model-based dose calculation algorithms are commonly used. In model-based dose calculation algorithms, a kernel is initially derived from the set of measurements. During treatment planning the kernel is convolved to take advantage of tissue heterogeneity information in the patient provided by image data sets. The image data sets provided by the CT simulation scanners offer images of patient anatomy and their relative locations to the lesion in three dimensions. To differentiate from past treatment planning systems, modern treatment planning systems are called image-based treatment planning systems or commonly called 3D treatment planning systems. Besides 3D dose computations, the treatment planning systems also offer a mechanism for extracting the location and extent of the tumor spread relative to the patient anatomy through other imaging modalities such as PET or MRI. This is achieved by performing image fusion technique. Advances in 3D treatment planning have facilitated the implementation of CRT and IMRT treatment techniques which are now widely implemented. The inverse-planning techniques have allowed the ability to place dose constraints to critical structures and hence reducing radiation toxicity. The quality of treatment plans is very dependent on prior knowledge or experiences of the dose planner, either the medical physicist or the medical dosimetrist. A poor treatment plan can easily results in serious level of radiation toxicity. In addition to radiation toxicity, it may results in under treatments and even caused morbidity and mortality.

While the aim of treatment planning is to design optimal individualized treatment plans, the plans must also be deliverable or implementable. That means that the treatment plans must be broken down into machine parameters that are consistent with the operational rules of the radiation dose delivery machines. Due to this requirement, some treatment planning systems are

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design specifically for the different types of radiation dose delivery mechanisms.

While a 3D treatment planning system has been useful in generating accurate dose distributions for evaluation, it has its limitation. The beam entrance doses, exit doses, beam edge doses, and doses outside the treatment field are generally not accurate. This inadequacy is the result of (a) inappropriate input data, (b) insufficient or the lack of input data, (c) limitation in modeling the actual situation (in patient), or (d) calculation spatial resolution.

EXERCISE 1.8 Identify two AAPM Task Group Reports that support the inaccuracy of treatment planning systems. Discuss with the medical physicist at your facility and estimate the expected inaccuracies.

Figure 1.5 shows the clinical evaluation of a fabricated mold placed over the patient’s nostril to overcome these limitations. These limitations also affect treatments with oblique incident beams. The understanding of these limitations is critical if the intent is to design a treatment plan that involves the irradiation of areas near or at the skin. Inaccuracy of dose determination also arises for the presence of tissue inhomogeneity such as air cavity and metallic implants. Figure 1.6 shows an expander used to maintain the shape of the breast following lumpectomy causing artifacts on the image. The artifacts create air pockets and the streaking high metallic lines that alter the CT number and distorting the radiation dose distributions. A radiation oncology physicist should be consulted for clarification of the doses in these regions as well as the introduction of foreign materials. Furthermore, some of the radiation toxicities such as ulcerated teeth imprint, mucositis, and bone pain can be avoided by consulting a radiation oncology physicist, in particular, in the use of electron beam therapy to treat the lips or mouth areas.

1.10 Radiation Oncology Physics Practice

Physicists have played a major role in the development and advancing the field of radiation oncology. Following the discovery of x-rays by Wilhelm Rontgen in 1895 and then the discovery of radium by Madam Curie in 1898, radiation was used in the treatment of a variety of diseases in the late 1890s.
By the early 1900s, clinical evidence had been accumulated demonstrating the effects of ionizing radiation on a variety of malignant neoplasms and their injurious effects on many normal tissues. By 1934, Coutard had developed a protracted, fractionated scheme that remains the basis for current radiation therapy.\textsuperscript{12} These events highlighted the contributions in science by physicists and provided the clinicians the tools for radiation therapy. This relationship continued with the discovery of artificially produced radionuclides and the development of high-energy dose delivery machines. Physicists have also been active in the clinical applications of radiation, for example, Herbert M. Parker in the development of the Paterson-Parker dosage tables and Edith H. Quimby in the implant dosimetry system. Today physicists are directly involved in advancing modern radiation oncology with the introduction of 3D treatment planning systems and the implementation of CRT and IMRT treatment techniques. Further developments are on-going in the area of patient setup and patient motion as well as the use of particle beams.

Over the years, physicists have become integral members of the radiation oncology community. In the early days, physicists were exclusively pioneers and scientists. Their expertise is in research with innovative insights. Training programs generally involve a two-year post-doctoral fellowship to increase familiarity with medical physics research. With the increase need for medical physics, the area of \textbf{clinical medical physics services/practice} has emerged. This new area pose many challenges for medical physics training program because the skills needed are no longer all analytical and scientific but also practical in nature. The practical nature embodies different attributes such as common sense, intuition, and resourcefulness. To illustrate this point, Figure 1.7 shows the innovative use of a trash bin filled with water to generate a uniform dose distribution throughout the patient’s leg undergoing radiation therapy.\textsuperscript{13} Other areas that require innovations are in (a) fabricating immobilization devices, (b) positioning aids, (c) fabricating shielding blocks, and (d) treatment planning. These attributes cannot be learned through formal courses but by working or in training under experienced mentors. Currently, clinical medical physics residencies are being developed to provide the skills and manpower for this area.

The role of a \textbf{medical physicist specializing in radiation oncology} (\textbf{radiation oncology physicist}) has been described in the AAPM Report No.


The booklet states the first responsibility of the radiation oncology physicist is to assure the best possible treatment given the state of technology and the skills of the other members of the radiation oncology department. The radiation oncology physicist has the primary responsibility for (a) planning for resource allocation (budget, manpower, and additional equipment) with radiation oncologists, administrators, and radiation therapists, in particular for newly acquired equipment, (b) physical aspects of all radiation sources acquired in a radiation oncology program such as acceptance testing and commissioning, (c) the radiation safety program possibly shared with the radiation safety officer of the institution, (d) the physical aspects of patient’s treatments, (e) interaction with the medical physics community to receive and disseminate state-of-art information on physical aspects of the dose delivery systems and treatment techniques. Depending on each circumstance, the radiation oncology physicist may be asked to serve as the radiation safety officer (RSO) for the facility. The regulatory agency has also mandated the physical presence of authorized medical physicist during the Gamma Knife and HDR treatment procedures. The prefix “authorized” indicates that the radiation oncology physicist has the appropriate training and qualification to perform the task expected of him or her for that procedure in accordance to the regulatory requirements.

EXERCISE 1.9

At times, a patient may be left unattended in a radiation therapy treatment room or a Gamma Knife suite. Should a medical physicist offer (or if requested, accept) to watch the patient until a health care personnel (radiation therapist, nurse, or physician) returns?

The other members of the radiation oncology department are (a) radiation oncologist, (b) medical dosimetrist, (c) radiation therapist, (d) radiation oncology nurse, and (e) ancillary personnel such as dietician and social workers. The radiation oncologist is a physician who manages the well-being of the patients prior to, during, and after radiation therapy. The radiation therapists are the persons who actually perform patient positioning, patient setup, and thereafter dose delivery to patients in accordance to approved treatment plans. Individualized treatment plans are generally designed by the medical dosimetrist and implemented under the supervision of the radiation oncologists in consultation with radiation oncology physicists. However, in most countries outside the United States, the radiation oncology physicists themselves design individualized treatment plans. The radiation oncology nurse coordinates with the radiation oncology members in regard to the welfare of the patients including the hygienic aspects of equipment used for evaluation and treatment, the educational training about cancers, and the management of the effects of radiation treatments.

1.11 Radiation Protection

Radiation protection or radiological protection refers to the protection of the people and the environment from the harmful effects of ionizing radiation. This subject matter had been discussed in detail in the Heath Physics I & II chapters in the pre-requisite textbook. In radiation therapy, radiation protection is limited to exposures from radiation-producing equipment and radioactive materials. Here, we will briefly review the standard of radiation exposures or radiation exposure limits and the principles of radiation protection.

The radiation dose exposure limits follows the recommendation of NCRP Report No. 91, given in Table 1.5. While NCRP is not a regulatory body, its recommendations are usually adopted by the state (radiation protection section of the Department of Environmental Protection of each state) and federal (United States Nuclear Regulatory Commission) regulatory agencies. The radiation exposure limit is 10 times lower for the public compared to the occupational workers set at 50 mSv per year. The structural shielding design on the thickness of the primary and secondary barriers of any vault that will house a radiation producing equipment is based on these radiation exposure limits. Public exposure dose limits were divided into two classifications, continuous or frequent and infrequent. The infrequent dose limit is intended for those people who made unusual visit to a radiation environment such as visiting a related brachytherapy patient as compared to a cleaning person who is always present in a radiation oncology facility. Reducing radiation exposure to personnel is based on three factors: (a) time, (b) distance, and (c) shielding. Practical radiation protection tends to be a task in weighing among these three factors that will arrive at a cost effective solution. In addition, the evaluation of situation can lead to the practice of “As Low As Reasonably Achievable”, termed as the ALARA principle.

<table>
<thead>
<tr>
<th>Table 1.5 Dose limits recommendation</th>
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</thead>
<tbody>
<tr>
<td>SI Units</td>
</tr>
<tr>
<td>A. Occupational exposures</td>
</tr>
<tr>
<td>Effective dose limits</td>
</tr>
<tr>
<td>a) Annual</td>
</tr>
<tr>
<td>b) Cumulative</td>
</tr>
<tr>
<td>B. Public exposure limits (annual)</td>
</tr>
<tr>
<td>Effective dose limits</td>
</tr>
<tr>
<td>a) Continuous</td>
</tr>
<tr>
<td>b) Infrequent</td>
</tr>
<tr>
<td>C. Education, and training exposures (annual)</td>
</tr>
<tr>
<td>Exposure dose limit</td>
</tr>
<tr>
<td>D. Embryo-fetus exposures (monthly)</td>
</tr>
<tr>
<td>Exposure dose limit</td>
</tr>
</tbody>
</table>

Over exposures are rare in this era of medical linear accelerators as the main dose delivery systems compared to cobalt-60 teletherapy units. Radiation beams from the medical linear accelerators can be turned off at will and the repairs can be performed in a radiation free environment. Furthermore, the radiation safety features associated with radiation producing equipment are duplicated to give additional levels of radiation protection. As a general rule, radiation safety features such as door interlocks, inter-communication systems, and “radiation in use” indicator devices must be tested daily or prior to first use each day. Door interlocks inhibit energizing the treatment machine if the door to the treatment room is opened. In compliance with regulatory guidelines, the console of all radiation-producing machines should be locked when not in use. **It is good practice to always have a calibrated survey meter accessible when operating radiation-producing equipment.** The survey meter should be calibrated at least once a year. The survey meter should have a reading scale with $< 0.05 \text{ mR/h}$ to indicate radiation level below background. Prior to use, the functionality check for the survey meter should include (a) battery voltage, (b) high voltage value, and (c) meter response using a standard radioactive source (cesium-13). Over exposures can occur if safeguards are lacking and/or equipment malfunctions.

**Nowadays, manual brachytherapy performed using sealed sources for temporary implants are relatively rare** with the advent of HDR remote afterloading system. In the event the patient needs hospitalization for manual brachytherapy, a designated isolation room must be used. Radiation protection rules should be in effect. Radioactive materials and radiation precautionary warning signs must be posted in front of the patient’s room and in the patient’s chart. A radiation survey must be performed and stay time for visitor must be determined. Nurses and visitors must be advised of the exposures and exposure times. All soiled materials must be kept for radiation survey before disposal. After the completion of the treatment, the patient and the room must be surveyed, postings must be removed, and the room must be declared radiation safe. The radiation sources must be returned to the safe and inventoried. For those patients receiving permanent implant, the patients must be counseled on radiation protection and instruction sheets on radiation protection must be provided to the patients prior to their release.

The nursing staff caring for brachytherapy patients must be trained in the handling of radiation sources on an annual basis. Usually, the radiation safety officer of the hospital trains the nursing staff on the (a) type of brachytherapy sources used, (b) radiation safety signs, (c) handling of dislodged radioactive sources, and (d) handling of house staff and visitors during routine and emergency situations. In case a radioactive source is found, it should be properly handled and placed inside a pig. In addition, the attending radiation oncologist should be informed of the incident.

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**Summary**
1.1 Therapeutic radiological physics, also referred to as radiation oncology physics or radiation therapy physics, is a branch of medical physics that deals with the therapeutic application of radiation in medicine.

1.2 Radiation oncology is the use of radiant energy to treat tumors.

1.3 Radiation therapy is the therapeutic treatments using radiant energy.

1.4 The subfields of medical physics are (a) therapeutic radiological physics, (b) diagnostic radiological physics, (c) medical nuclear physics, and (d) medical health physics.

1.5 Therapeutic radiological physics concentrates on (a) the physical aspects of therapeutic applications of radiant energy, (b) the equipment used in their production of radiant energy, (c) the quality of images from their production and use, and (d) medical health physics associated with medical physics.

1.6 Modern radiation oncology practice uses 3D treatment planning systems to implement conformal radiation therapy (CRT) and intensity-modulated radiation therapy (IMRT) treatment techniques.

1.7 The SI units for (a) radiation exposure is C/kg, (b) absorbed dose is Gy, (c) effective dose is Sv, and (d) radioactivity is Bq.

1.8 The roentgen as defined has limitations as a unit of radiation measurement. First, it is defined only in reference to ionization of air by photon beams. Second, it assumes that the measuring instrument collects all ions released. Thirdly, the type of instruments available for this type of measurements is limited.

1.9 Photon and particle beams are used for radiation therapy. The most widely used beams are photon and electron beams from medical linear accelerators. Particle beams, in particular proton and carbon beams, are becoming more available because of the precise dose localization and higher relative biological effectiveness. For manual brachytherapy, palladium-103, iodine-125, cesium-131, and strontium-90 radioactive sources are used. Iridium-192 is also used in HDR brachytherapy.

1.10 The advantages of high-energy photon beams for therapeutic use include (a) skin sparing, (b) deeper penetration, (c) high output rate, and (d) dose absorption that is nearly independent of tissue type.

1.11 The three methods of administering radiation therapy are (a) external beam radiation therapy, (b) brachytherapy, and (c) internally administered radionuclide therapy. External beam radiation therapy refers to the treatments where the source is external to the patient and brachytherapy where the source(s) is placed close to or inside the lesions. In internally administered radionuclide therapy, the radionuclide, in liquid form, is taken orally or administered intravenously.

1.12 The goal of radiotherapy can be classified as either “curative” or “palliative”. For curative intent, the aim of treatment is to deliver sufficient radiation dose to eradicate the tumors while minimizing radiation toxicity. For palliative treatment, a lesser dose is given to relief symptoms.

1.13 The basic steps in external beam radiation therapy procedure are (a) patient workup, (b) patient simulation, (c) treatment planning, (d) patient QA in the case of IMRT, and (e) dose delivery.
1.14 The common side effects of radiation treatment are fatigue and skin response. Other side effects will depend on the treatment areas. For the abdominal region, nausea and vomiting may occur. For head and neck treatments, sore mouth, difficulty in swallowing and loss of taste sensation may occur. Generally, the side effects are temporary.

1.15 The biological response of tumors and normal tissues to fractionated treatment is governed by four factors: (a) repair of sublethal damage, (b) repopulation of surviving cells in the irradiated tissues, (c) reassortment of cells through the cell cycle, and (d) reoxygenation of hypoxic cells in tumors.

1.16 A 3D treatment planning system which is used to design individualized treatment plans is an integral component of modern radiation therapy. While the treatment planning system is a versatile tool, a poorly designed treatment plan can cause adverse effects to the patient.

1.17 Physicists have played major roles in the development and advancement in the field of radiation oncology. Early physicists were pioneers and scientists. With the increase reliance on physics support in radiation oncology, a new area of clinical radiation oncology physics service emerged. This new area pose many challenges for radiation oncology physics training program because the skills required are no longer all analytical and scientific, but practical in nature. These skills cannot be acquired through formal course work, but on-the-job experience under mentors.

1.18 Radiation protection deals with the protection of the people and the environment from ionizing radiation. In radiation therapy, the radiation sources are from radiation producing equipment and radioactive materials.

1.19 The basic radiation protection principles are (a) time, (b) shielding, and (c) distance.

1.20 A list of formulas:

\[
\text{Exposure: } X = \frac{dQ}{dm} \\
\text{Absorbed Dose: } D = \frac{dE}{dm} \\
\text{Kerma: } K = \frac{dE_{tr}}{dm} \\
\text{Equivalent Dose: } H_{TR} = w_k x D_{TR} \\
\text{Effective Dose: } E = \sum_{T} (w_T x H_T) = \sum_{T} w_T x (w_k x D_{TR}) \\
\text{Radioactivity: } A = A_0 e^{-0.693t/\tau}
\]

### Study Guide

1. Define in your own words the following terms:
   (a) therapeutic radiological physics  
   (b) radiation therapy  
   (c) MLC system  
   (d) CRT treatment technique  
   (e) IMRT treatment technique  
   (f) exposure  
   (g) absorbed dose  
   (h) KERMA  
   (i) equivalent dose  
   (j) effective dose  
   (k) radioactivity  
   (l) high energy radiation beam  
   (m) Bragg peak  
   (n) percent depth dose
(o) external beam radiation therapy  (p) internally administered radionuclide therapy
(q) brachytherapy  (r) patient simulation
(s) dose planning  (t) three dimensional treatment planning

1.2 Identify the four areas of concentration of therapeutic radiological physics.

1.3 What are the temperature and pressure values at STP condition?

1.4 Is there any difference between the absorbed dose of 100 cGy in bone from gamma rays and 100 cGy in tissue from beta rays?

1.5 Identify two differences between exposure and absorbed dose.

1.6 List three limitations of the roentgen.

1.7 List three properties of photons.

1.8 List three types of radiation beams used in radiotherapy.

1.9 List three advantages of megavoltage photon beams over kilovoltage beams.

1.10 Describe how neutrons are produced for neutron therapy?

1.11 List an advantage of electron beams over photon beams.

1.12 Identify two advantages of pions over photon beams for radiation therapy.

1.13 Identify the three methods of delivering radiation therapy.

1.14 Differentiate between temporary and permanent implants.

1.15 List the three primary modalities currently used to manage cancers.

1.16 What is the difference between curative and palliative intent of a treatment?

1.17 List the four steps that must be implemented before a patient can undergo external beam radiation therapy.

1.18 List three possible side effects of radiotherapy.

1.19 Identify the four Rs used in radiobiology.

1.20 Review Chapter 1 of the textbook, Foundation of Radiological Physics, and identify three additional applications of radiation therapy besides the treatment of malignancies.

1.21 Access the internet and explore the New York Times articles on radiation safety. Identify a few radiation mishaps.

**Problems**

1.1 Compute the amount of charge, expressed in coulombs, liberated in air by a 6 MeV electron.

1.2 The density of dry air at STP is 1.293 kg/m$^3$. Show that 1 cc of air weighs 0.001293 g.
1.3 A 100 g tissue receives 2 Gy of absorbed dose. Compute the amount of absorbed dose received by 1 g of tissue. Express your answer in rads.

1.4 A dose of 2 Gy is delivered to 5 grams of tissue. Compute the energy absorbed and express your answer in units of (a) gram-rad and (b) ergs.

1.5 The output of a kilovoltage unit is 3000 R/min in air. Convert this exposure rate to absorbed dose in air and express the result in Gy/min.

1.6 A radiation worker is exposed to 50 cGy of 50 keV neutrons and 80 cGy of photons. Compute its equivalent dose and express the result in Sv.

1.7 Compute the activity of a palladium-103 (half-life = 17 days) source 3 days after shipment, if the initial activity is 40 mCi.

1.8 A muon has a rest mass energy of 105.7 MeV. Approximately how many times more massive is the muon relative to an electron?

1.9 Table 1.6 presents two product lines (150 and 350 series) of digital survey meters from an instrument company. Concentrating only on the most sensitive scale, are the exposure rate and the exposure ranges the same for the two series?

1.10 Compute the rest mass expressed in kilograms of the pi-minus meson whose rest mass energy is 139.6 MeV. Refer to the prerequisite textbook.

1.11 An erg is defined as the amount of energy needed to move one gram of mass through a distance of 1 cm with a force of 1 dyne. Show that 1 Joule is equal to $1 \times 10^7$ ergs.

**Table 1.6 Range and resolution of digital survey meters**

<table>
<thead>
<tr>
<th>Model</th>
<th>Exposure Rate</th>
<th>Exposure</th>
<th>Full Scale</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Scale</td>
<td>Resolution</td>
<td>Full Scale</td>
<td>Resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3x150</td>
<td>200 mR/hr</td>
<td>0.1 mR/hr</td>
<td>200 µR</td>
<td>0.1 µR</td>
</tr>
<tr>
<td>series</td>
<td>2 R/hr</td>
<td>1 mR/hr</td>
<td>2 mR</td>
<td>1 µR</td>
</tr>
<tr>
<td></td>
<td>20 R/hr</td>
<td>10 mR/hr</td>
<td>20 mR</td>
<td>10 µR</td>
</tr>
<tr>
<td>3x350</td>
<td>2 mSv/hr</td>
<td>1 µSv/hr</td>
<td>200 µSv</td>
<td>0.1 µSv</td>
</tr>
<tr>
<td>series</td>
<td>20 mSv/hr</td>
<td>10 µSv/hr</td>
<td>20 µSv</td>
<td>0.01 µSv</td>
</tr>
<tr>
<td></td>
<td>200 mSv/hr</td>
<td>0.1 mSv/hr</td>
<td>2 µSv</td>
<td>0.001 µSv</td>
</tr>
</tbody>
</table>

**Multiple Choice Questions**

Choose one correct answer.

1.1 Which one of the following is NOT a subfield of medical physics?
   a) Monte carlo physics
   b) Therapeutic radiological physics
   c) Medical nuclear physics
   d) Diagnostic radiological physics
   e) Medical health physics

1.2 The collection of charges from all ions of one sign, produced by ionizing radiation in a small volume of air under electronic equilibrium, is a measure of
   a) exposure
   b) absorbed dose
   c) kerma
   d) equivalent dose
   e) effective dose
1.3 Which of the following statement is NOT TRUE of the roentgen?
a) It is not defined for other types of radiation except photons.
b) It is not defined for ionization of other medium except air.
c) It is not a unit of dose.
d) It represents the amount of either positive or negative charge collected.
e) All are true.

1.4 A centiGray (cGy) is actually
a) equal to 0.01 J/kg
b) determined in air
c) defined only for photons
d) the SI unit for exposure
e) all of the above

1.5 The difference between exposure and absorbed dose is
a) the difference between rad and gray.
b) the difference between ionization in air and absorption in medium.
c) the difference between ionizing and non-ionizing radiation.
d) the difference between roentgen and rem.
e) none of the above.

1.6 The average value of W/e has been determined experimentally to be 33.97 eV per ion pair. This value
a) is independent of the incident radiation energy.
b) is a constant for all materials.
c) has a specific value for a given mass of air.
d) has a specific path length of air.
e) is a constant for water.

1.7 If 2 Gy is delivered to 200 g of tissue, 1 g of tissue receives
I. 200 rads
II. 20,000 ergs
III. 200 g-rad
IV. 1 rad
a) I and II
b) II and IV
c) I, II, and III
d) II, III, and IV
e) IV only.

1.8 A patient underwent a course of radiation therapy consisting of 10 fractions in two weeks. The cumulative dose delivered is expressed in the unit of
a) R
b) Gy
c) Sv
d) Bq
e) rem

1.9 Under which circumstance would a patient be considered “hot” or radioactive?
a) After a single treatment using a linear accelerator
b) After a temporary implant
c) After a permanent implant
d) After a superficial treatment
e) After an electron beam treatment
1.10 Go to your clinic and find out the number of fractions commonly used for WHOLE BRAIN treatments.
   a) 1 fraction
   b) 5 fractions
   c) 10 fractions
   d) 20 fractions
   e) 30 fractions

1.11 Comparing curative and palliative radiotherapy, palliative intent prescribes
   a) same total dosage
   b) lesser total dosage
   c) more total dosage
   d) more fractions
   e) same number of fractions

1.12 Review the radiobiology chapter in the pre-requisite textbook, Foundation of Radiological Physics. The RBE for the following radiation beams are almost the same, EXCEPT
   a) photon beam
   b) electron beam
   c) cobalt-60 beam
   d) neutron beam
   e) proton beam

1.13 The biological response of tumors and normal tissues to fractionated treatments is governed by the following mechanisms, EXCEPT
   a) repair of sublethal damage
   b) repopulation by surviving cells
   c) reasortment of cells through the cell division cycle
   d) reoxygenation of hypoxic cells in tumors
   e) reimplantation of damaged cells

1.14 Which of the following is not the responsibility of a radiation oncology physicist?
   a) Reviews daily QA measurements taken by radiation therapist
   b) Performs monthly spot checks on medical linear accelerator
   c) Provides consultation to radiation oncologist on impact of radiation
   d) Preats patients if the radiation therapist or Radiation oncologist is not available
   e) Report medical events to the regulatory agency

1.15 Figure 1.8 shows the safety features and postings at the entrance of a machine room. Which of the following may BE TRUE?
   a) A medical linear accelerator
   b) A HDR unit
   c) A surgical suite
   d) An implant suite
   e) A simulator

1.16 If the door interlocks to a medical linear accelerator vault fail, which of the following will most likely fails to function?
   a) The “RADIATION IN USE” indicator
   b) The adiation monitoring system
   c) The medical linear accelerator cannot be energized
   d) The beam ON button
e) None of the above