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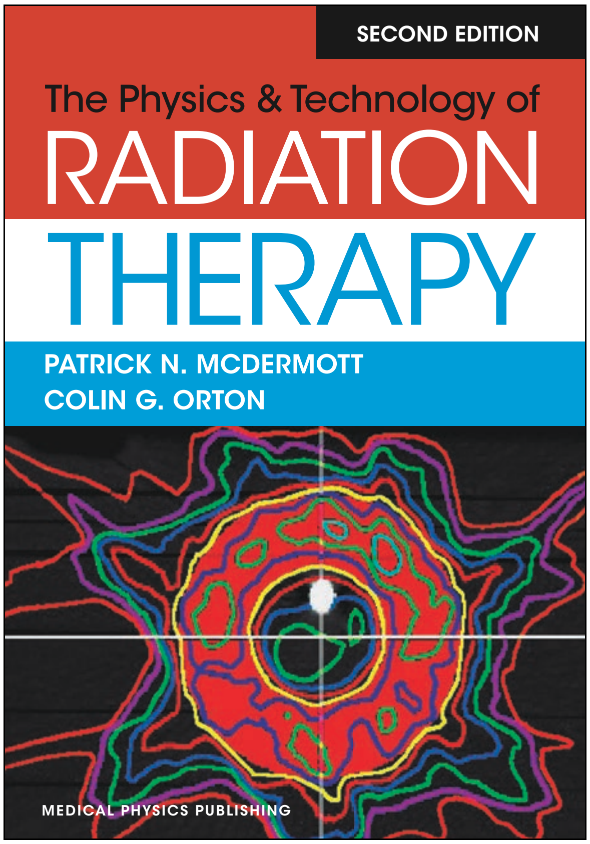

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SAMPLE CHAPTER (PARTIAL)—NOT FOR DISTRIBUTION

9 Medical Linear Accelerators

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9.1 Introduction

Throughout the history of radiation therapy, a variety of machines have been used to produce beams of radiation. Radiation therapy delivered with an external beam is sometimes referred to as *teletherapy*. There are two major classes of external beam treatment units: those that use radioactive isotopes and those machines called accelerators, which employ electric fields to accelerate charged particles. We will confine our discussion here to megavoltage (MV) beams and, therefore, we will not discuss superficial or orthovoltage x-ray units in this chapter (see chapter 4). Isotope machines have used cesium-137 (Cs-137) and cobalt-60 (Co-60). Cesium is not used any more. Co-60 units have almost completely disappeared, at least in the United States. Co-60 radiation has a relatively low penetrating power, a large penumbra, and a low dose rate. Specialized external beam units—such as robotic linacs and gamma stereotactic units—are discussed in chapter 20. Quality assurance tests for linear accelerators are discussed in chapter 21. Imaging devices attached to linacs are covered in chapter 19.

To obtain the benefits of deeply penetrating radiation and skin sparing, megavoltage photons are required. Such photons can be produced by accelerating electrons to high energy and directing them against a metallic target. As the electrons lose energy in the target, they produce x-rays (as well as heat) via the bremsstrahlung mechanism. For some types of therapeutic treatment it is desirable to use the high-energy electron beam directly. In this case, the metal target is removed, and the electron beam is allowed to enter the patient.

There are two main types of accelerators: those that accelerate charged particles in a straight line—called *linear accelerators* or *linacs* (see Figure 9.1)—and those that accelerate them in a circular or approximately circular fashion. There are a variety of circular machines: microtrons, cyclotrons, synchrotrons, and betatrons. Circular accelerators for radiation therapy are relatively rare and are found in only a handful of centers. Cyclotrons and synchrotrons are discussed in chapter 22 in the context of proton therapy.

Linear accelerators were developed after World War II for research in high-energy elementary particle physics and later adapted to medical use. Medical electron linear accelerators were first introduced in Britain in the 1950s. They first appeared in the United States in the 1960s, and their widespread use began in the 1970s. They have almost completely replaced every other type of external beam treatment machine. It is estimated that there are about 4500 medical linacs in the United States. There are now only two manufacturers of medical electron linear accelerators: Varian and Elekta (formerly Philips) (see Figure 9.2). Siemens no longer manufactures medical linacs, although there are still some of these units in clinical use.

An electron linear accelerator accelerates electrons along the length of an evacuated tube (called a *waveguide*) to almost the speed of light. As an example of this, if electrons are accelerated through the equivalent of 20 million volts (20 MV), they will travel at a speed that is within 0.03% of the speed of light! The electrons are accelerated by microwaves that travel down the waveguide. Microwaves are electromagnetic waves, and it is the electric field associated with these waves that accelerates the electrons (see section 2.4).

The electron beam can be used directly to treat patients, or it can be aimed at a metallic "target" (see Figures 9.1 and 9.3). The target absorbs the energy of the electrons and converts some of it to very energetic, highly penetrating x-rays via the bremsstrahlung process discussed in chapter 5. The radiation passes through the "collimator," whose field-defining jaws determine the cross-sectional size of the beam (see Figure 9.3). Modern linacs allow selection between two or three photon beam energies and five or six electron beam energies.

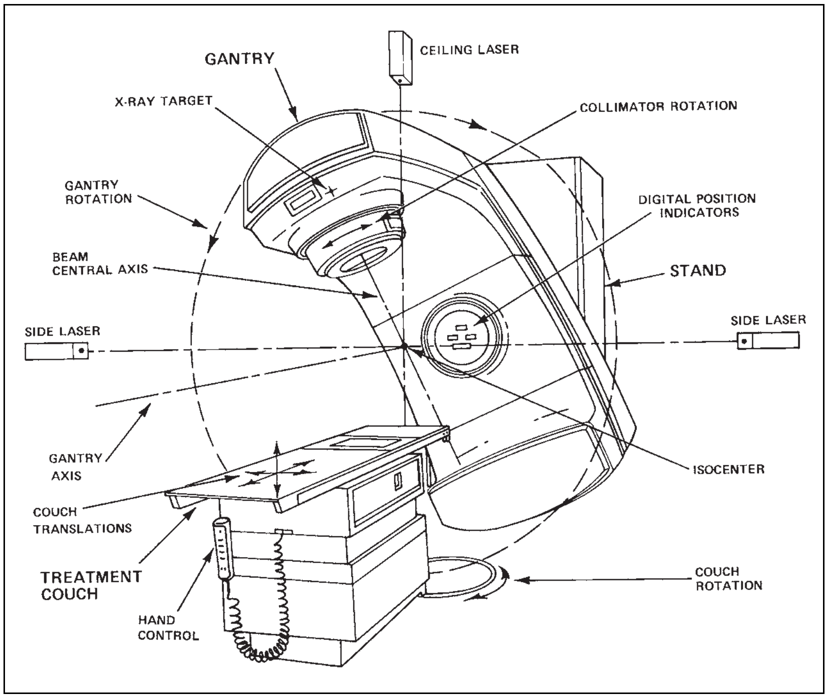

Figure 9.1 The major parts of a medical linear accelerator are the gantry, the gantry stand, and the couch. This diagram illustrates the large variety of mechanical motions possible. Motion is controlled by use of the hand control, which is sometimes called a pendant. The radiation beam is directed along the beam central axis. The gantry can rotate around an axis (labeled gantry axis) that extends out of the page, thus allowing rotation around the patient on the couch. The collimator can rotate around the beam central axis. The treatment couch or table can move up or down, in or out toward the gantry (longitudinal motion), or from side to side (lateral motion). The couch can also rotate around a vertical axis. The axes of rotation of the couch, the gantry, and the beam central axis meet at a point in space called the isocenter. Lasers are used for patient positioning. Modern linacs also have MV and kV imaging panels not shown here. (Reprinted from Karzmark, C. J., and R. Morton, *A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy*, 3rd Edition, Fig. 2. © 2017, with permission from Medical Physics Publishing.)

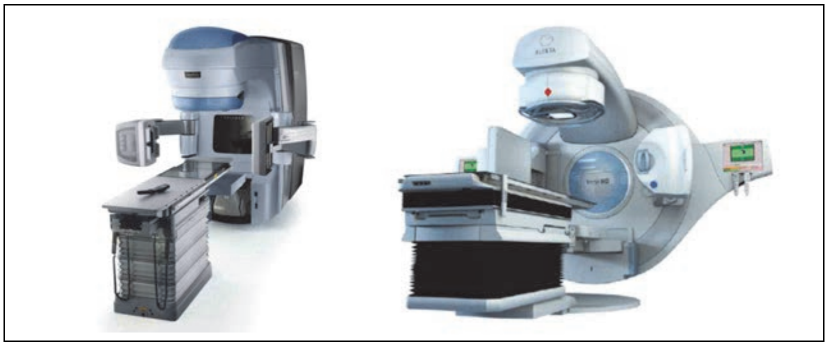

Figure 9.2 Varian (left) and Elekta (right) linear accelerators. Notice that the Elekta machine does not have a gantry stand. (Courtesy of Varian Medical Systems and Elekta AB.)

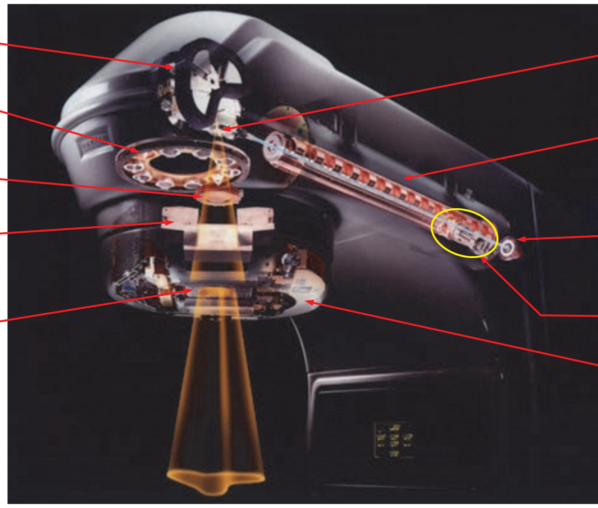

Figure 9.3 The waveguide and the treatment head of a modern dual photon energy linear accelerator. Electrons injected by the electron gun are accelerated down the waveguide. An electromagnet at the end of the waveguide deflects the electron beam downward so that it strikes the x-ray target. The collimator jaws and the MLC define the cross-sectional shape of the beam. Not shown are lead plates, positioned in the treatment head, that are used to shield against stray "leakage" radiation. (Image courtesy of Varian Medical Systems.)

The major components of the treatment machine are the gantry, the gantry stand, the treatment couch, and the treatment console. The console is outside the treatment room and is used to control the machine during the time that the beam is on. The gantry and the couch can move in numerous directions, allowing radiation beams to enter a patient from almost any angle (see Figure 9.1). The gantry can rotate around the patient. The rotation axes of the gantry, the collimator (same as beam central axis), and the couch meet at a common point in space called the *isocenter*.

Digital position indicators (Figure 9.1) show the gantry and collimator angle, as well as the collimator jaw settings. The round board on which these numbers are displayed is sometimes called the "pizza" board.

The source-to-axis distance, or SAD, is the distance from the source of radiation to the isocenter. In all modern linacs this distance is 100 cm. In some older linear accelerators—notably the Clinac 4 (Varian Medical Systems, Palo Alto, CA) and in many Co-60 units—the SAD is 80 cm. The SAD of a particular linac always remains the same; it is not adjustable.

The couch top has a portion that has thin Mylar® (a type of plastic) covering a web of nylon or a carbon fiber mesh for patient support. This mesh is sometimes referred to as the "tennis racket" because of its resemblance to the

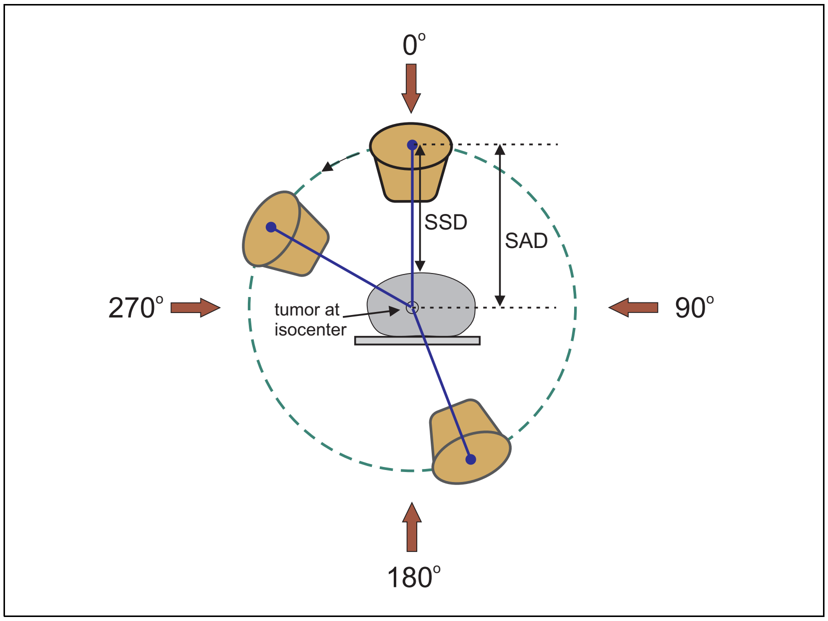

Figure 9.4 Gantry rotation around the patient. Patients are often positioned so that the isocenter is at or near the center of the volume to be treated. This is called an SAD treatment. As the gantry rotates, the beam always points at the isocenter. It is possible to treat through the table. The SSD is the distance from the source to the patient surface. The SSD changes with changing gantry angle. The IEC (International Electrotechnical Commission) scale is shown for gantry angles (IEC 61217 & IEC 60601-2-1) as seen facing the gantry. The arrows show the beam direction at each of the cardinal angles.

same. When the gantry head is underneath the table, it is possible to treat through the Mylar portion of the table.

There is extensive safety circuitry to ensure that a linac is not run in a dangerous configuration. If the status of the linac is not safe for the machine settings, then an “interlock” will prevent the beam from turning on.

Figure 9.4 shows a so-called SAD patient treatment. The isocenter is positioned at or near the center of the patient’s tumor. With this arrangement, the beam is always pointed directly at the tumor for all gantry angles. For a given gantry angle, the distance from the radiation source to the patient skin surface is called the source-to-surface distance, or SSD. The SSD will change when the gantry is rotated to a new angle. Figure 9.4 also shows the IEC angulation scale (IEC 61217 and IEC 60601-2-1) for gantry angle.

9.2 Accelerating Waveguides

When electrons (charge Q) are accelerated through a potential difference V, they acquire a kinetic energy $T = Q\ V$ (this was discussed in chapter 2). If electrons are accelerated through a potential difference of 1 million volts, they will acquire a kinetic energy of 1 MeV. As an electron penetrates the x-ray target, it undergoes bremsstrahlung interactions in which photons are radiated. The electrons lose an amount of energy equal to the energy of the photon produced. Generally, an electron will only lose a fraction of its kinetic energy in any single interaction. The photons that emerge from the target will, therefore, have a range of energies from close to zero up to a maximum value that is equal to the initial kinetic energy of the electron. As an example, if the electrons are accelerated to an energy of 6 MeV, the *maximum* photon energy produced in the target will be 6 MeV. The photons will have a broad range of energies from 0 to 6 MeV. It is, therefore, not correct to refer to the emerging x-ray beam as a 6 MeV beam. In fact, the average energy of the photons in such a beam is approximately 6/3 MeV = 2 MeV. The nomenclature that is used to refer to such a beam is based on the fact that the electrons were effectively accelerated through a potential difference of 6 million volts or 6 MV. The proper way to refer to the "quality" or energy of this x-ray beam is to describe it as a 6 MV beam. The average energy of the photons in a linear accelerator beam in MeV is approximately numerically equal to MV/3. The electron beam itself is nearly monoenergetic, with an energy of 6 MeV. It is, therefore, correct to refer to the electron beam as a 6 MeV beam.

Common x-ray beam energies for medical linear accelerators range from 4 MV to 18 MV. Most linacs have dual photon energies; 6 MV and 15 MV or 6 MV and 18 MV are common. Three photon energies are possible. Linacs also have multiple electron energies, ranging from as low as 4 MeV up to 22 MeV. A modern, dual-energy linac costs about $3.0 million, depending on options.

Let us think about how we might build an accelerator that would accelerate electrons to an energy of 10 MeV. Our first naive thought might be to take a pair of copper plates or disks and place a potential difference across them of 10 million volts (see Figure 9.5a). We will place a small hole in the positive electrode so that the electrons may exit through it. When an electron is placed between the plates it will be accelerated through a potential difference of 10 million volts and, thus, gain kinetic energy of 10 MeV. This would work in principle, but unfortunately it is not practical. Such large potential differences are very difficult to create. Let us imagine that we have a dial that will allow us to turn up the voltage. As we turn up the voltage and reach potential differences of thousands or tens of thousands of volts, the charge on the plates will begin to leak off into the surrounding air, frustrating our effort to increase the voltage. Eventually, when the potential difference becomes sufficiently large, there will be a spark that will reduce the potential difference to zero.

We might now be a little more clever. If we cannot produce a potential difference that is large enough between two plates, how about using a series of plates, each with a relatively small potential difference between them? Instead of accelerating the electron once through a large potential difference, let us accelerate it many times through a small potential difference. This is the "trick" that is used in all high-energy accelerators.

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Instead of a single set of plates, let us use a series of plates, each with a more modest potential difference between them. This is illustrated in Figure 9.5b. We now need an oscillating potential difference between the plates to ensure that whenever an electron is between a specific set of two plates, the plate on the left is negative and the one on the right is positive. The sign of the potential difference must switch completely during the time that the electron travels from the center of the gap between one set of plates and the next adjacent set of plates.

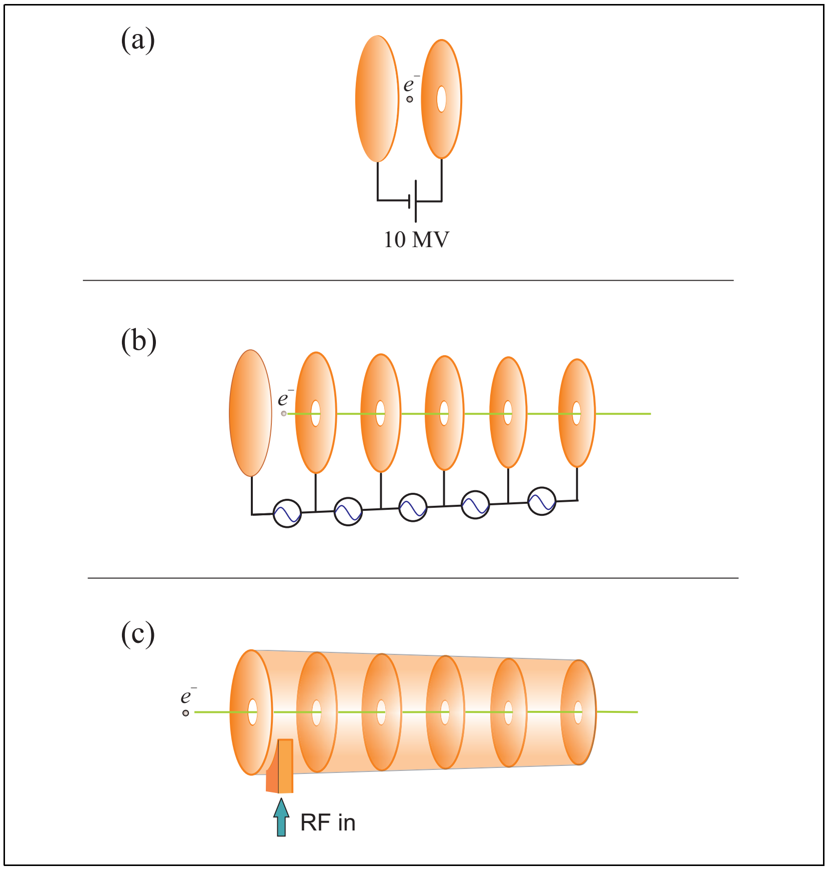

Figure 9.5 Progression of ideas for accelerating electrons. (a) Two copper plates with a potential difference of 10 million volts between the anode and the cathode. This method of accelerating electrons to high energy is not practical for reasons explained in the text. (b) A more sophisticated approach using a series of plates with a smaller potential difference between adjacent plates. The applied voltage must be oscillatory so that when an electron is in the gap between any two adjacent plates, the plate on the left always has negative polarity—ensuring that the electron is always accelerated toward the right. (c) Place the arrangement in (b) inside a cylindrical pipe, remove all the air, and replace the oscillators with microwave RF input; thus we have an accelerating waveguide. See the text for elaboration.

We want to accelerate the electron to 10 MeV. We know that by the time the electron gains about 0.5 MeV (rest mass of the electron) it will be highly relativistic (see section 2.5). This will happen quickly in the so-called buncher section of the linac, perhaps after traversing a few plates. Let us ignore the problem of initial acceleration for now and assume that the electrons are already relativistic. This means that they are traveling at close to the speed of light. Under these circumstances, the speed of an electron hardly increases as the energy increases. Let us estimate how rapidly the polarity of the potential difference between adjacent plates must switch back and forth. Assume that the distance between plates is 5.0 cm. If the electrons are traveling at close to the speed of light, they will travel from the center of the gap between one set of plates to the center between the adjacent set of plates in a time equal to $(0.05 \text{ m})/(3 \times 10^8 \text{ m/s}) = 1.66 \times 10^{-10}$ s. The voltage between the plates must return to its original polarity every 3.33×10^{-10} s. Let us compute the frequency that corresponds to this: $\nu = 1/(3.33 \times 10^{-10} \text{ s}) = 3 \times 10^9$ Hz or 3000 MHz. This frequency is in the "S-band" microwave portion of the electromagnetic spectrum (see section 2.4). The microwave power is sometimes referred to as RF (radio frequency).

In Figure 9.5b we show wires carrying the oscillatory potential difference to the plates. The frequency of the oscillatory voltage is very high, and this will cause the wires to act like a broadcast antenna and radiate microwaves. Instead of using wires, we shall use a rectangular copper pipe called a *transmission waveguide* to bring the microwave power to the accelerating structure. In addition, we need to accelerate the electrons in a vacuum, otherwise they will collide with molecules of oxygen and nitrogen in the air, thus interfering with acceleration. We can place the disks shown in Figure 9.5b in a pipe (see Figure 9.5c) and use a vacuum pump to evacuate all the air. This pipe with the disks in it is called an *accelerating waveguide*. Do not confuse the rectangular transmission waveguide that carries microwave power with the cylindrical accelerating waveguide in which the electrons are accelerated.

The accelerator waveguide is a highly evacuated copper "pipe" in which electrons are accelerated. This is one of the most expensive components of a linear accelerator. Its replacement cost is on the order of $200,000. There are two major types of accelerating waveguides: (1) traveling wave and (2) standing wave. Both of these designs use electromagnetic waves to accelerate electrons. As we have seen, these waves are in the microwave region of the spectrum: $\nu \approx 3000$ MHz (s-band radar) for conventional medical linacs (wavelength $\lambda = 10$ cm in free space). In both designs, electrons are accelerated in bunches and, therefore, the radiation output is pulsed. The pipe must be under high vacuum so that the electrons do not collide with air molecules and lose energy.

Electrons travel in bunches down the waveguide. In a traveling wave linac, the electrons "surf" on a traveling electromagnetic wave (see Figure 9.6). The electrons must travel at the same speed as the electromagnetic wave to "surf" along. In a vacuum with no conductors nearby, electromagnetic waves travel at speed c; electrons are prohibited from traveling at this speed by the special theory of relativity. Unless the waves are slowed down, they will roll over the electrons. The waves are slowed down by the disks in the waveguide. Such a waveguide is called a "disk loaded" waveguide (see Figure 9.7).

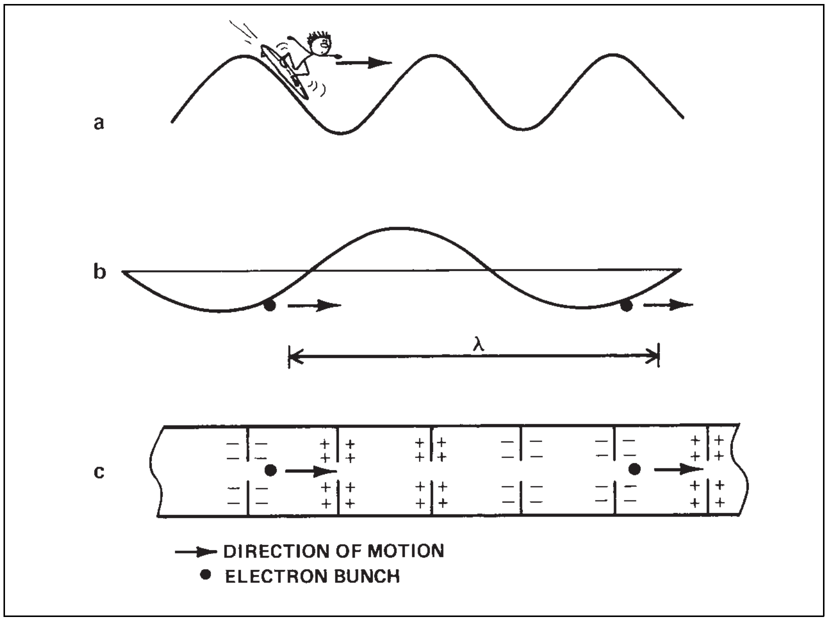

Figure 9.6 Traveling wave acceleration. In (a) a surfer is pushed along by a wave. In a similar way, electron bunches (b) are pushed along by an electromagnetic wave in a traveling wave accelerator waveguide. A snapshot of a waveguide is shown in (c) illustrating the charge distribution inside the waveguide at that instant which accelerates the electron bunches shown toward the right. (Reprinted from Karzmark, C. J., and R. Morton, *A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy*, 3rd Edition, Fig. 28. © 2017, with permission from Medical Physics Publishing.)

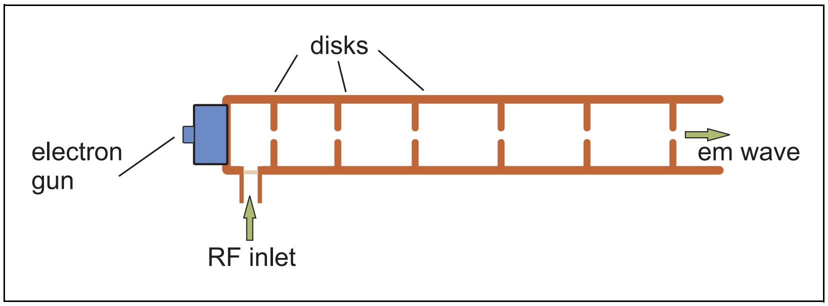

Figure 9.7 A cross section of an accelerating waveguide for a traveling wave linear accelerator. The waveguide is disk loaded to slow down the microwave electromagnetic waves so that bunches of electrons may "surf" on these waves down the guide from left to right. The electron gun injects electrons into the waveguide.

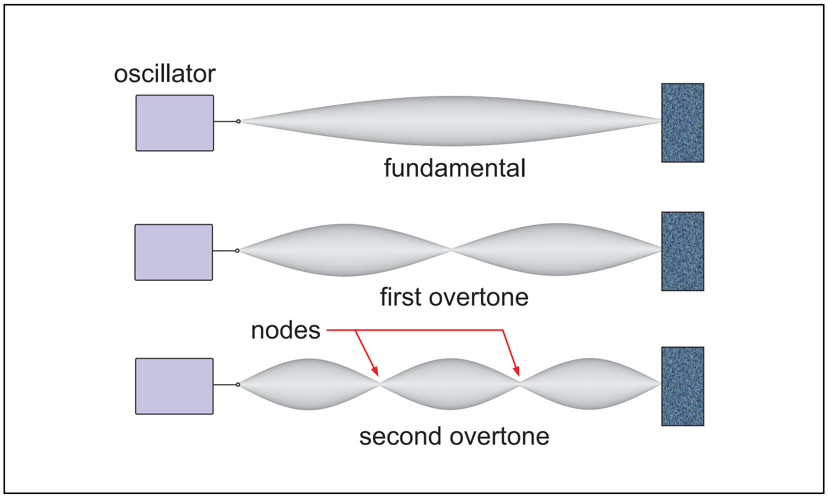

Figure 9.8 Time-lapse image of standing waves on a string. The string is tied to the wall on the right. The "fundamental" vibration is shown at the top. Increasing the frequency of the oscillator produces successive overtones.

Toward the beginning of the waveguide, the disks are spaced closer together. The disks are spaced equally apart once the electrons reach (nearly) the speed of light. The effect of this is to increase the speed of the electromagnetic traveling wave. If this is done in just the right way, the electron bunches will be able to continue to surf on the wave as they speed up and, in this manner, they will gain energy.

The other major type of waveguide is found in a standing wave linac. You can produce standing waves on a string by tying it to a nail on a wall, pulling the string taut, and then plucking it. Such waves are produced in the strings of musical instruments. Standing waves are illustrated in Figure 9.8. A standing wave is formed when a traveling wave moving down the string arrives at the wall and is then reflected back. This leads to two traveling waves moving in opposite directions. The two traveling waves add to produce a standing wave.

How can a standing wave accelerate electrons? The electrons cannot surf along the wave. The acceleration process is illustrated in Figure 9.9, which shows snapshots of a standing wave. This figure shows a graph of the electric field as a function of position at three instants in time. The electric field is proportional to the height of the graph above the horizontal axis. If the force on electron bunches due to this electric field always acts in the same direction, then the electrons will gain kinetic energy as they move down the waveguide. In the first instant shown, the force on the electron bunch is toward the right. In the middle instant, the electric field has momentarily become zero. There is no force on the electron bunch, but it will continue to move toward the right owing to its velocity in that direction. In the third frame, the electric field has

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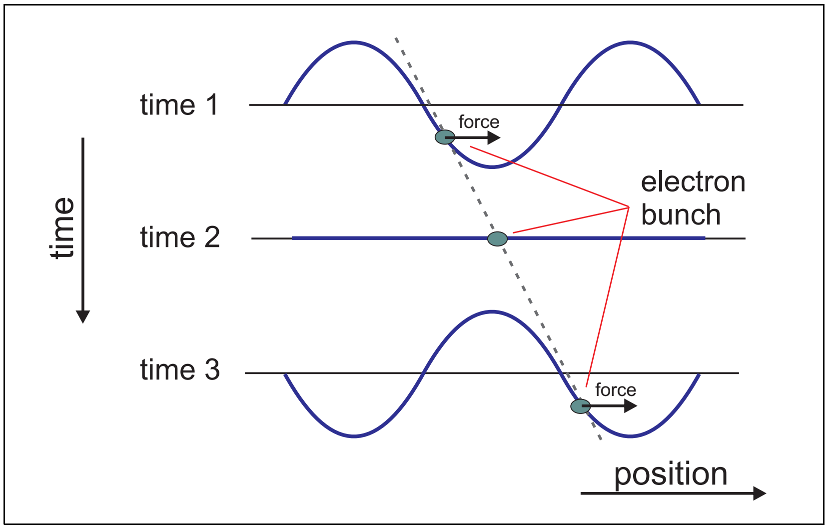

Figure 9.9 An electron bunch undergoing acceleration by a standing wave in a waveguide. The height of the wave represents the strength of the electric field. This shows three different instants in time starting at the top. At "time 1" the electric field seen by the negatively charged electron bunch is negative and, therefore, there is a force toward the right. At "time 2" the electric field is momentarily zero; it then reverses at the bottom. As the electric field oscillates in strength, the electron bunch will experience a force that is constantly toward the right.

returned, and in the meantime the electrons have moved to a new position; however, the electrons are in the same relative position with respect to the wave as they were in the first instant and, therefore, they again experience a force toward the right. If the electron bunch can maintain its relative position with respect to the standing wave, it will always be accelerated forward.

Among the two major linac manufacturers, Varian machines use a standing wave linacs and Elekta uses a traveling wave. The microwave power is introduced through the side of the waveguide (see Figure 9.10). Standing wave linacs require a device called a circulator, which prevents microwaves from reflecting back into the klystron (discussed later in this chapter). Traveling wave linacs require a "terminating" or "dummy" load to absorb the residual microwave energy. It is necessary to prevent a backward-reflected wave to avoid a standing wave from forming. For some Elekta linacs, the residual microwave power is fed back (called RF feedback) to the input to increase efficiency In a standing wave linac, every other waveguide cavity can be moved off to the side, as shown in Figure 9.10. This is called *side cavity coupling*. It reduces the length of the waveguide by almost a factor of two, a big advantage. The electrons gain roughly 2 MeV energy per cavity.

The orientation of the accelerating waveguide of a conventional linac depends on the design energy. This is illustrated in Figure 9.11. For low sin-

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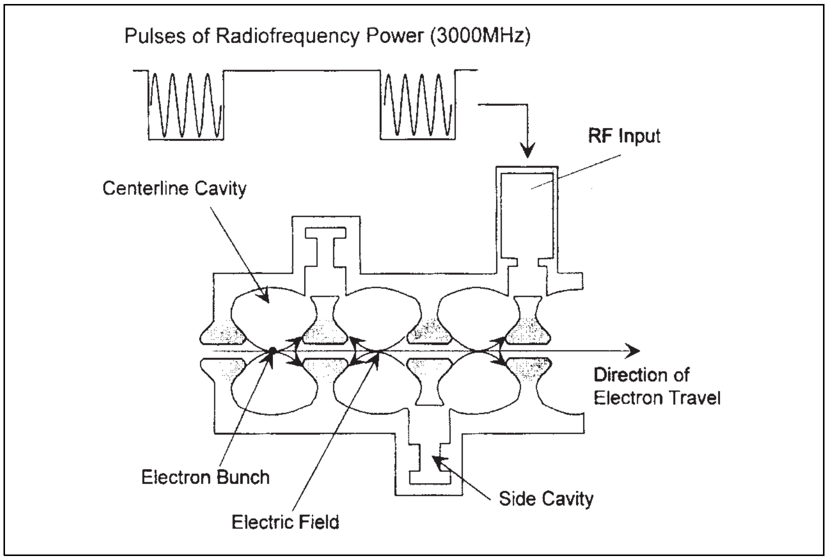

Figure 9.10 A cross-sectional view of a side-coupled standing wave accelerating waveguide. The length of the waveguide is reduced by a factor of two by introducing side cavities. The microwave radiofrequency (RF) power is fed into the waveguide through the RF input. Is the electric field in the correct direction? (Courtesy of Siemens Medical Solutions USA, Inc.)

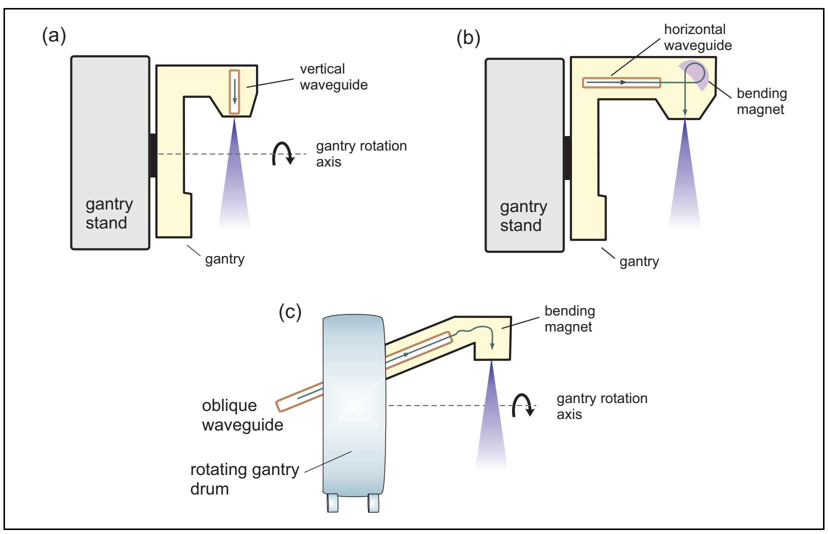

Figure 9.11 Orientation of the accelerating waveguide in linacs of different types. In standing wave low single-energy machines (4 to 6 MV), the waveguide is short enough that it can be mounted vertically as in (a). In higher-energy machines, the waveguide is too long to be mounted vertically and instead is mounted horizontally. This requires a bending magnet to redirect the beam down toward the patient. The addition of the bending magnet makes the linac considerably more complex. Most modern, dual-energy standing wave linacs are oriented as in (b). Traveling wave linacs and the highest-energy standing wave linacs require an oblique waveguide as in (c).

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gle-energy standing wave linacs, in the range 4 to 6 MV, the waveguide is short enough (perhaps 30 cm) so that it can be oriented vertically. For intermediate-energy standing wave linacs, in the range 6 to 25 MV, the waveguide is too long to orient vertically. Instead, the waveguide is oriented horizontally and a "bending magnet" is employed to "bend" or deflect the electron beam in a downward direction toward the patient. In the highest-energy standing wave waveguides (25 to 35 MeV) or in traveling wave waveguides, the guide may need to be oblique. A dual-energy traveling wave waveguide is about 2.5 m in length. Dual-energy standing wave waveguides are approximately 1.3 m in length. A long waveguide could be oriented vertically, but this would require both a tall ceiling and a pit in the floor so that the gantry could rotate underneath the patient couch.

9.3 Bending Magnets

The bending electromagnet in a linac must change the direction of the electron beam from horizontal or oblique to vertical (see Figure 9.11 and 9.12). The bending magnet is made from coils of wire that must be supplied with a high current to produce the magnetic field necessary to deflect the electron beam. Standing wave linacs use an "achromatic" bending magnet that deflects the electron beam through 270° rather than 90° (see Figure 9.12). When the electrons enter the region between the bending magnet poles, they have a

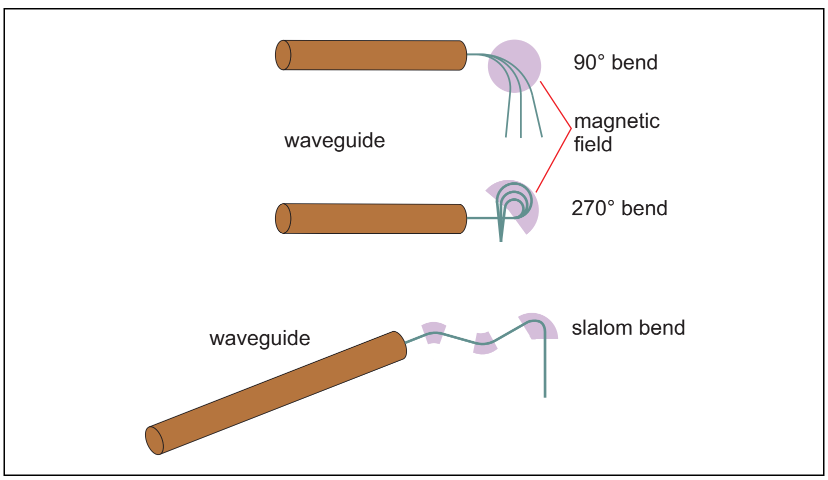

Figure 9.12 Bending magnet arrangements. The magnetic field is confined to the purple-shaded areas. Electrons emerge from the accelerating waveguide with a slight distribution in energy. If a 90° bending magnet is used, the electrons will be spread out by the magnetic field. The path of more energetic electrons will bend less than those with lower energy. By using a 270° bending magnet, all the electrons can be made to come together at the target. An actual achromatic bending magnet system is somewhat more complicated than this. Elekta linacs use a slalom bending magnet system like the one shown at the bottom of the diagram.

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small spread in energy. If a 90° bending magnet were used, the paths of electrons with slightly different energies would diverge. A 270° bending magnet causes all the electrons with various energies to converge at the focal spot. This is the arrangement employed in Varian and Siemens linacs; Elekta machines use a more elaborate "slalom" design. When the selection of the beam energy is changed, the bending magnet current must change—this takes a short while.

9.4 Sources of Microwave Power

Linear accelerators require high-power microwaves to accelerate electrons. There are two different devices that can supply the necessary power: magnetrons and klystrons.

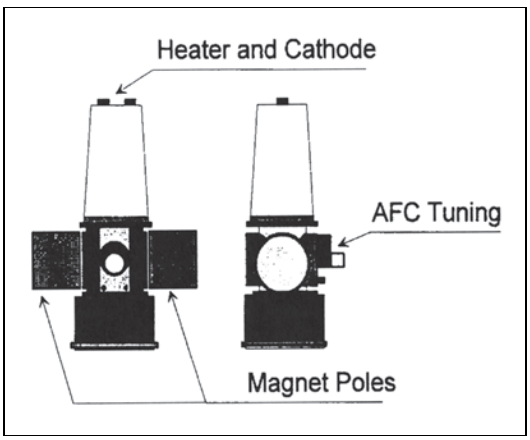

Figure 9.13 Two views of the external appearance of a magnetron. The magnets supply the magnetic field in which the electrons spiral. The AFC (automatic frequency control) plunger continually adjusts the frequency of the microwaves to maintain optimum accelerating conditions for the waveguide. The microwaves emerge from the bottom. (Courtesy of Siemens Medical Solutions USA, Inc.)

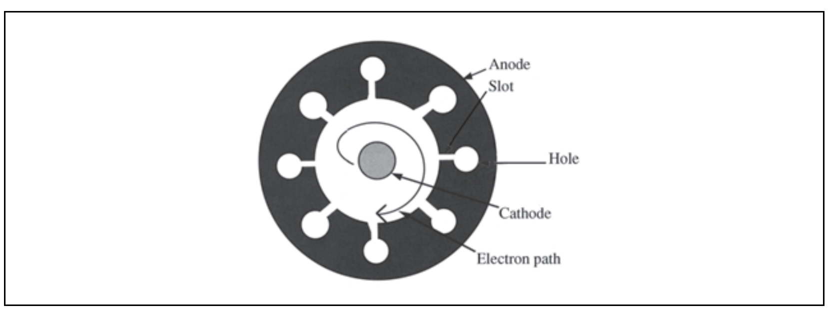

Figure 9.14 A cross section through a magnetron illustrating the principle of operation. Electrons emitted by the cathode spiral toward the anode in a magnetic field that is perpendicular to the page. As the electrons pass the cavities consisting of the holes and the slots, they induce oscillations at microwave frequencies. This is analogous to the sound waves that are produced by blowing air across the top of a soda bottle. (Adapted from Stanton, R., and D. Stinson, *Applied Physics for Radiation Oncology*, Fig. 9.6. © 1996, with permission from Medical Physics Publishing.)

A magnetron generates high-power microwaves (see Figure 9.13). You may even own one without realizing it. A magnetron supplies the microwaves for your microwave oven. Your home oven operates at a frequency of 2450 MHz and is capable of producing about 1 kW of power. By comparison, the magnetron in a linac produces pulses of microwaves with a frequency of approximately 3000 MHz and peak power of about 2.5 to 5.0 MW. This is why a magnetron for a linac costs about $30,000. The magnetron was invented during World War II, and it is widely used for radar applications (see the box at the end of this chapter entitled “The Invention of the Cavity Magnetron”). The lifetime of a magnetron is about 2000 hours of operation (perhaps two to four years).

In a magnetron, electrons move past cavities (see Figure 9.14) that have a resonant or natural frequency in the microwave part of the spectrum. The electrons induce electromagnetic oscillations in the cavities. This is somewhat like blowing air over the top of a soda bottle to produce a loud sound. If conditions are right, the airflow over the top of the bottle induces oscillations of the air inside the bottle, producing a loud sound.

While a magnetron generates high-power microwaves, a klystron amplifies them. Today, klystrons are capable of producing higher power levels than magnetrons: up to about 8 MW peak power. Magnetrons are used in low-energy standing wave linacs and in traveling wave linacs. Klystrons are used in standing wave linacs with energies above about 12 MV. Linear accelerators with klystrons (see Figures 9.15 and 9.16) require a low-energy source of

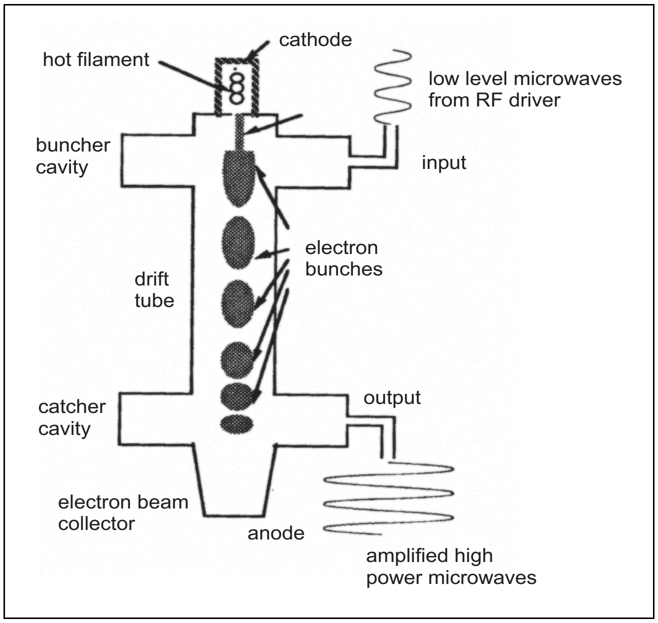

Figure 9.15
The operation of a klystron. Electrons are injected by the cathode at the top, and they are accelerated toward the anode at the bottom. Low-energy microwaves from the RF driver cause the electrons to break up into bunches. The electron bunches move past the catcher cavity and induce high-power microwave oscillations. (Reprinted from Stanton, R., and D. Stinson, *Applied Physics for Radiation Oncology*, Fig. 9.7. © 1996, with permission from Medical Physics Publishing.)

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microwaves called an “RF driver.” The output pulse power from the RF driver only needs to be about 100 W. Klystrons are bulkier than magnetrons, and they sit inside a tank of insulating oil (see Figure 9.16). This precludes gantry mounting and, therefore, the microwave power must be transmitted farther to reach the accelerating waveguide. Klystrons are sometimes mounted in separate cabinets. The microwaves are sent via a transmission waveguide to the gantry stand. A klystron costs about $70,000, considerably more than a magnetron. The operating lifetime of a klystron is about four to seven years.

Let us now consider the entire operation of a linear accelerator as a system. This is illustrated in the block diagram of Figure 9.17. Microwave power is supplied to the accelerating waveguide in short (5 μs) pulses. A power supply furnishes high-power DC to the modulator. The modulator contains the so-called “pulse forming network” (pfn). The high-power pulses are delivered simultaneously to the klystron (or magnetron) and the electron gun. The

Figure 9.16 A klystron inside the gantry stand of a high-energy standing wave linac. The tank of insulating oil can be seen at the bottom.

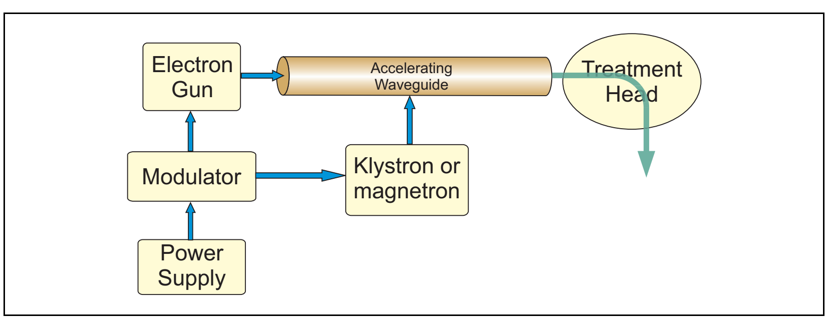

Figure 9.17 A block diagram showing the major components of a linear accelerator.

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pulses are triggered by a vacuum tube called a *thyratron* that acts as a switch and is capable of handling high current. The electron gun injects a pulse of electrons into the accelerating waveguide. The electrons are accelerated down the waveguide and emerge as a narrow beam about 3 mm in diameter.

In standing wave linacs, the photon beam energy can be changed with the use of an energy switch (see Figure 9.2). The switch has the effect of reducing the electric field in a portion of the waveguide, thus reducing the final energy of the electrons. For the high-energy photon beam, the electric field is at full strength over the entire length of the guide. In a traveling wave linac, the radiofrequency (RF) power delivered to the guide is adjusted to change the beam energy.

9.5 The Treatment Head

Inside the cover of the treatment head of a linear accelerator is a thick shell of shielding material (not shown in Figure 9.2) designed to reduce the amount of

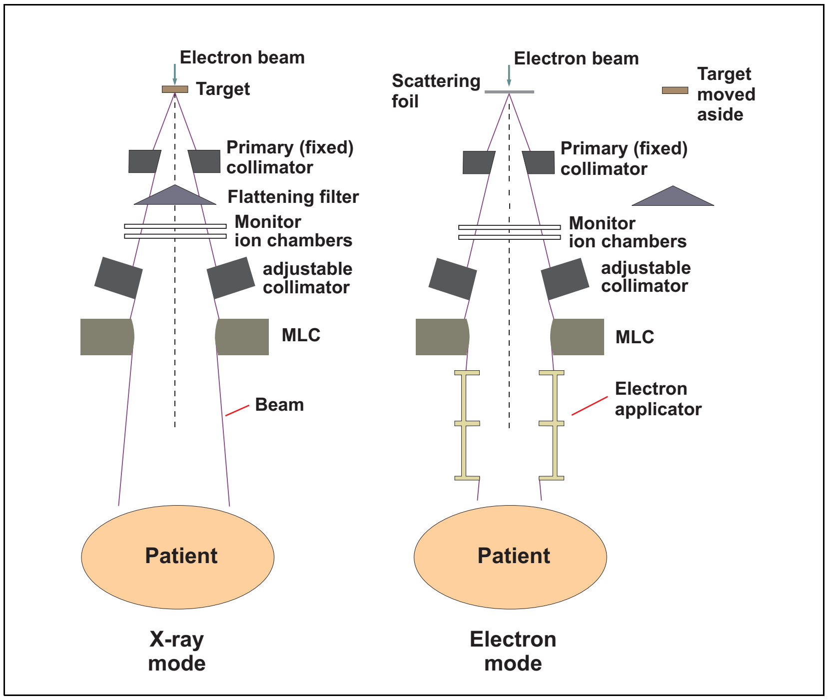

Figure 9.18 Schematic diagram of the components of a linear accelerator treatment head. The two major modes of operation are illustrated: x-ray mode on the left and electron mode on the right. In x-ray mode, a metallic target is placed in the electron beam. In electron mode, the target and flattening filter are moved aside, and a scattering foil is placed in the beam to spread out the narrow incident electron beam. In electron mode, an electron applicator is added to collimate the beam down close to the patient's skin surface.

The Invention of the Cavity Magnetron

Before the invention of the cavity magnetron, radar was unreliable and limited to short range. The shortcomings of early radar were due to the fact that it was not possible to generate microwaves of sufficiently high power and short wavelength to have the needed range and spatial resolution. The cavity magnetron was invented by physicists Randall and Boot at the University of Birmingham, England in early 1940. It was one of the single most important technical developments of World War II. Even early models produced hundreds of times more microwave power output than any other type of microwave-generating device. As the physicist Luis Alvarez commented in the 1980s, "If automobiles had been similarly improved, modern cars would cost about a dollar and go a thousand miles on a gallon of gas." Furthermore, the magnetron is a compact device that can be mounted inside airplanes.

The original Randall and Boot cavity magnetron (courtesy of Wikipedia).

The devotees of radar have made a compelling argument that it played a decisive role in WWII. It has been argued that it played a more important role than the atomic bomb, although certainly less dramatic. Admirers of radar like to say that radar ended the war and that the atomic bomb finished it. The invention of the cavity magnetron gave the Allies a distinct advantage, not only for detecting airplanes at long distance, but also for detecting German U-boats. Toward the end of the war, a U-boat could hardly surface without being pounced upon by Allied aircraft with on-board radar.

At first there was no clear or detailed theoretical understanding of the mechanism of operation of the magnetron. When the device arrived in the United States, a prominent group of theoretical physicists gathered around to look at it. "It's simple," the physicist I. I. Rabi declared. "It's just kind of a whistle." "Okay, Rabi," said E. U. Condon, "How does a whistle work?" The klystron was developed prior to the invention of the cavity magnetron by brothers Sigurd and Russell Varian at Stanford University. Initially, it was unable to produce the high power output that the cavity magnetron was capable of. Today klystrons are capable of higher power output than magnetrons. Magnetrons are now widely used in police radar and in microwave ovens.

Further Reading:

The Invention that Changed the World by Robert Buderi. New York: Simon and Schuster, 1996.

Winning the Radar War by Jack Nissen. New York: St. Martin's Press, 1987.

Chapter Summary

- There are two main types of external beam treatment units: isotope machines and accelerators.
- Accelerators use electric fields to accelerate charged particles; linear accelerators (linacs); circular accelerators: microtrons, cyclotrons, synchrotrons and betatrons, etc.
- Linacs accelerate electrons down an evacuated tube (waveguide) to almost the speed of light. The electrons can be used to treat directly, or they can be directed onto a metallic target and produce x-rays.
- **Isocenter** of a linac is the (ideal) point in space where the gantry rotation axis, collimator rotation axis, and couch rotation axis meet. The location of this point is fixed.
- **Source-to-axis distance (SAD)**: Distance from radiation source to isocenter (usually 100 cm).
- **Source-to-surface distance (SSD)**: Distance from the radiation source to the surface of the patient. This distance will generally vary with gantry angle.
- **Linear accelerators**: Photon beam energy stated in terms of MV not MeV; energies range from 4 MV to 25 MV; cannot set beam time on but rather monitor units (MU): MU1 primary setting, MU2 is backup.

  Accelerating waveguide: Essentially a copper pipe under high vacuum; electrons are accelerated down waveguide by 3000 MHz microwaves (S-band radar). Two major types: standing wave (Varian, Siemens) and traveling wave (Elekta). In low-energy machines (4 to 6 MV) waveguide can be mounted vertically. In higher-energy machines, waveguide is mounted either horizontally or obliquely; therefore, a bending magnet is required.
- **Source of microwave power**: (1) magnetron: generates high-power microwaves, which are fed into waveguide; (2) klystron amplifies low-energy microwaves supplied by "RF driver." Klystron can produce higher power than magnetron; generally used in high-energy standing wave linacs.
- **Electron gun**: Injects pulses of electrons into waveguide.
- **Modulator**: Supplies high-power pulses to the klystron (or magnetron) and to electron gun; pulses are triggered by a vacuum tube called a thyratron that acts like a switch.
- **Treatment head**:
  1. X-ray target: Used for photon beams only, electron beam strikes target, x-rays produced, transmission target.
  2. Scattering foils: Used for electron beams only, spreads beam out, makes beam "flat."

3. Flattening filter: Used in x-ray mode only, shaped like an inverted cone, flattens beam at depth of 10 cm. Must be carefully centered on beam central axis.
4. Ion chambers: Determine MU1 and MU2; beam symmetry and flatness monitored.
5. Fixed (primary) and movable (adjustable jaws) collimators: often independent (asymmetric) jaws, usually up to 40 cm × 40 cm field size. Most linacs have multileaf collimator (MLC) for field shaping.
6. MLC
7. Electron applicator (or cone) for electrons beams only
8. Light localizing system (or field defining light).
9. Optical distance indicator (ODI) or rangefinder.

- **MLC**: series of motorized tungsten leaves used to shape the beam.
  - Number of leaves ranges from 52–160, each leaf has a motor.
  - Leaf width at isocenter ranges from 2.5 mm to 10 mm (5 mm is common).
  - Intraleaf transmission is 2% or less, interleaf transmission is larger, reduced by stepped leaves or tongue-and-groove arrangement.
- **Field size**: Distance between 50% levels (central axis 100%).
- **Penumbra**: Region at edge of radiation beam over which dose drops sharply. No universal quantitative definition. One definition: Lateral distance between the 80% and 20% level measured at a depth of 10 cm with SSD = 100 cm and field size 10 × 10 cm^2. For this definition, penumbra 0.9 cm (Varian). Caused by: (1) non-point source (called geometric penumbra); (2) transmission through collimator jaws or blocks, and (3) scattering of photons and electrons in the medium.
- **Geometric penumbra** $P = s\frac{SSD - SDD + d}{SDD}$, where s is the source size, SSD is the source-to-surface distance, SDD is the source-to-diaphragm distance (distance to distal end of jaws or MLC), and d is the depth in the patient. Typical values of the source size are several millimeters for the x-ray source spot size of a linear accelerator.

  Systematic behavior: $P\uparrow$ when SSD $\uparrow$or $d\uparrow$
  $P\downarrow$ when SDD $\uparrow$.
- **Beam flatness**: Usually evaluated at 10 cm depth, must be flat to ±3% or less, measured over central 80% of the beam.
- **Beam symmetry**: Many ways to define, e.g., area under the beam profile on either side of central axis should be the same to within some tolerance.
- **Flattening Filter Free (FFF)**: remove flattening filter from beam
  - Advantages: dose rate goes up by factor of 2-4. Less head leakage, less neutron and electron beam contamination
  - Beam energy is reduced slightly

Problems

1. Define the term isocenter and source-to-axis distance (SAD).

2. An electromagnetic wave (S-band microwaves) has a frequency of 3000 MHz.
   a. Calculate the wavelength in free space. Express your answer in cm.
   b. If each cavity in an accelerator waveguide is 1/2 of a wavelength long, then how long is each cavity in cm?
   c. If the energy gain is 0.6 MeV per cavity and the maximum electron energy is 18 MeV, how long is this waveguide?

3. Explain the major differences between traveling wave and standing wave linacs.

4. a. How do the features of klystrons and magnetrons differ?
   b. Why are klystrons used in some accelerators and magnetrons in others?

5. What is the meaning of the stated x-ray beam energy in MV of a linac?

6. An 18 MeV electron beam strikes the target in a linear accelerator. What is the maximum energy, average energy, and minimum energy of the photons produced. What is the mechanism by which x-rays are produced in the target of a linac?

7. Why is a transmission target used for a linac and a reflection target for a low-energy diagnostic x-ray machine?

8. What is an achromatic bending magnet?

9. How much does the beam current for a linac change in going from x-ray mode to electron mode?

10. If the dose at the center of a patient's square treatment field is 2 Gy at a depth of 10 cm, what is the dose at the field edge?

11. A linac beam has cross-sectional dimensions of 40 cm by 40 cm at the isocenter (distance of 100 cm from the source). What is the field length at a distance of 3 m from the isocenter?

12. For a particular brand of linac, the source-to-diaphragm distance is 60 cm. Calculate the geometric penumbra at a distance of 100 cm from the source assuming the source size is 3 mm. Express the answer in units of mm.

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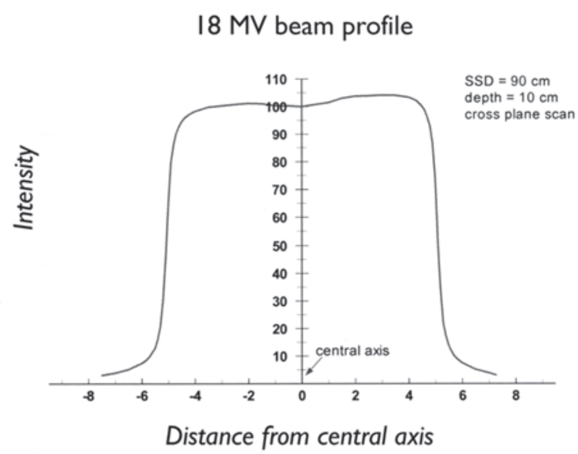
13. The bottom of the lower jaws on a linac (see Figure 9.2) is at a distance of 44 cm from the source, and the bottom of the upper jaws is at 36 cm. Assuming a source size of 3 mm, compute the geometric penumbra for both sets of jaws at the isocenter (100 cm). Express the answer in mm.

14. How does a flattening filter free (FFF) beam compare to a beam with a flattening filter in terms of the dose rate, depth dose, head leakage, and neutron production?

15. For the beam profile shown: measure (a) the field size and (b) the flatness (as defined in this text). Does the beam meet typical specifications for flatness? You will need to use a ruler and to make careful measurements.



16. What are the differences between X-band and S-band linacs?

17. If you have access to a linac, ask a medical physicist to give you a tour. You should look at the console, the information displayed on the console, and how to program the console for simple beam delivery. Note the backup MU counter and the door interlock. Inside the room, locate the emergency off switches. Observe gantry and collimator rotation and the pendant used to control these functions. Observe couch movements (lateral, longitudinal, vertical, and rotation). Observe operation of the light field and the ODI. Rotate the gantry to 180°. Use a flashlight to look into the head of the machine. Identify the upper and lower jaws and the MLC. Examine an electron applicator and see how it is attached to the collimator. Check the collision avoidance on the applicator. For a Varian or Siemens machine, examine a wedge, and see how wedges are mounted on the collimator. Examine the magnetron or the klystron (and the RF driver, if present) and the thyratron, if accessible. Look at the heat exchanger, water level indicator, water temperature gauge, demineralizing cartridge, and the SF_6 supply and gauge.

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On-line linac videos:

1. http://www.ionactive.co.uk/multi-media_video.html?m=8media_video.html
2. http://www.youtube.com/watch?v=jSgnWfbEx1A