

## 2. Fundamentals of Electrosurgery

### Part I: Principles of Radiofrequency Energy for Surgery

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Electrosurgery is the use of radiofrequency (RF) alternating current (AC) to raise intracellular temperature in order to achieve vaporization or the combination of desiccation and protein coagulation. These effects can be translated into cutting or coagulation of tissue, the latter usually to attain hemostasis, but also to occlude lumen-containing structures, or to destroy large volumes of tissue such as soft tissue neoplasms. The concept of RF electrosurgery must be distinguished clearly from the process of cautery, derived from the Greek *kauterion* (hot iron), in which the destruction or denaturation of tissue is by the passive transfer of heat from a heated instrument. In short, RF electrosurgery is *not* cautery.

Electrical energy has been used in the performance of surgical procedures since the late nineteenth century. However, it wasn't until the introduction of the first electrosurgical generator (or electrosurgical unit) (ESU) by Bovie as reported in 1928 that the potential of RF electrosurgery was popularized [1]. Similar to any surgical procedure or instrument, RF electricity was found to have its own unique issues that resulted in unanticipated complications. Since that time, much has been learned about the biophysics involved in the use of RF electricity, and both devices and techniques have evolved to the point where the energy can be applied safely and effectively. However, to do so, it is necessary for the surgeon to possess an understanding of the fundamentals of RF alternating current, and the impacts of RF electricity on tissue, and the mechanisms whereby adverse outcomes can occur.

## History of Electrosurgery

The use of heat for the treatment of wounds can be traced to Neolithic times [2]. Ancient Egyptians (c. 3000 BC) have described the use of thermal cautery to treat ulcers and tumors of the breast, Hippocrates (469–370 BC) employed heat to destroy a neck tumor, and Albucasis (c. 980) was reported to have used a hot iron to control bleeding [3, 4]. Direct current (DC) was the first electrical energy used for medical therapeutics, first described in the mid-eighteenth century by contemporary scientists such as Benjamin Franklin and John Wesley. Indeed the techniques used relied on the use of DC to heat an instrument that was then applied to tissue causing a tissue effect secondary to *passive* heat transfer. The resulting coagulation and desiccation of the tissue was, and is, a form of cautery [5].

In the latter part of the nineteenth century, investigators in Europe and the United States began experimenting with the biological effects of AC on tissue. One of the pioneers was Arsené D’Arsonval, a French inventor and physiologist, who, in 1893, was the first to report these effects used in a clinical context [6]. He designed capacitors, later modified by Oudlin, which developed a high-voltage discharge in the form of sparks that could arc to, and superficially destroy nearby tissue, a process termed *fulguration* (from the Latin noun *fulgur* for lightening, and the verb *fulgurare*, to flash).

In 1907, Rivère, a student of D’Arsonval, demonstrated that if high-frequency AC was applied directly to tissue, without sparking, another electrosurgical process called “white coagulation” occurred [7]. Shortly thereafter, in 1909, Doyen described the use of bipolar RF instruments for the coagulation of tissue [8]. In the next 10–20 years, more powerful generators allowed these techniques to be employed in humans to treat nevi, granulation tissue, and bladder tumors.

An important step in the development of electrosurgery was de Forest’s invention, in 1907, of the “Audion” (US Patent 879,532) a triode-containing vacuum tube that amplified electrical signals and served as the lynchpin for radio broadcasting. Coincidentally, of course, the invention also facilitated production of the types of high-frequency continuous AC necessary to evenly coagulate, or, if properly focused, to vaporize tissue. Linear propagation of vaporization would result in tissue transection or cutting. In 1924 Wyeth became the first to report use of a vacuum tube-generated, continuous alternating RF current to cut tissue in humans [9].

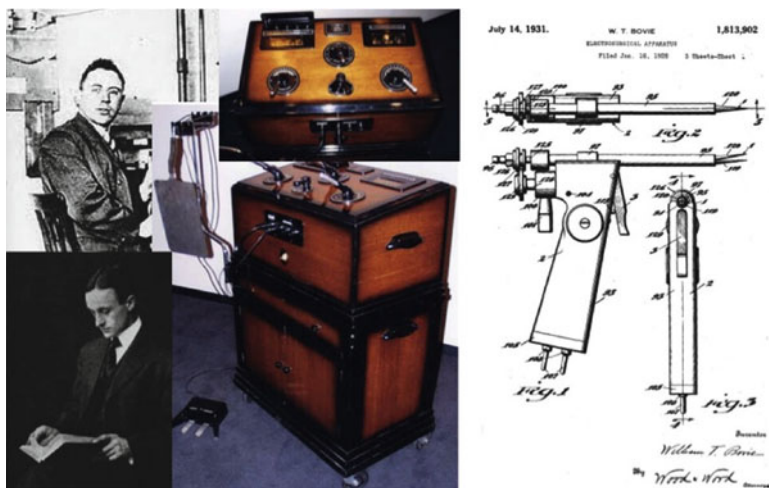


Fig. 2.1. Historical collage. William T. Bovie (*upper left*) was the inventor of the electrosurgical generator. The machine coupled a spark gap generator (for high-voltage modulated outputs) and a generator producing a continuous low-voltage waveform (*upper and lower middle panels*). The patent and a diagram of the pistol gripped monopolar instrument are shown on the *right*. It allowed for rapid changing of the electrodes. The famed neurosurgeon Harvey W. Cushing (*lower left*) was the first to use the instrument in 1926 demonstrating the remarkable ability to reduce intraoperative hemorrhage. From that point on the perioperative morbidity and mortality associated with intracranial surgery dramatically decreased.

While Bovie, a physicist, and Cushing, a neurosurgeon, are often given credit for the invention of electrosurgery, they were actually only its most effective early promoters (Fig. 2.1). In 1926, Cushing used Bovie's side-by-side ESUs—one, a vacuum tube-based design for cutting, the other, a spark gap version for coagulation—to perform neurosurgery on a patient with an otherwise inoperable vascular myeloma. The results of this and other procedures were published in 1928 [1]. While there are important differences, the original “Bovie” machine served as the model for virtually all subsequently produced electrosurgical units (ESUs) until the invention of solid-state generators and isolated circuits in the 1970s. The principal advantage of such generators is that they can produce lower voltage, and more consistent waveforms while their isolated circuitry allows for the creation and use of systems designed to improve safety, such as impedance monitoring.

It may be a surprise to some that endoscopically directed electro-surgery was first performed as early as 1910. Kelly describes Beer's use of a monopolar instrument to fulgurate bladder tumors under cystoscopic guidance [7]. One of the first attempts at using laparoscopically directed electrosurgery was reported by Fervers, a general surgeon, who in 1933 described electrosurgical adhesiolysis [10]. Several years later, in 1941, Power and Barnes reported the first reported human performance of laparoscopic electrosurgical female sterilization using a monopolar instrument [11].

In the 1970s and early 1980s, there was widespread belief that activated unipolar laparoscopic instruments could arc long and variable distances to adjacent viscera causing significant thermal injury. However, in 1985, Levy and Soderstrom demonstrated that under reasonable conditions, such injuries were infrequent, and that almost all the purported bowel injuries were indeed secondary to physical, not electrical trauma. (It is likely that most or all of these injuries were caused by insertion of trocar cannula systems [12]). In addition, there developed a better understanding of the risks presented by the use of high power outputs (up to 600 W) and the factors, such as "capacitive coupling," that contribute to electrosurgical complications. Since that time, safety has been further enhanced by newer generators with isolated circuits and monitoring systems for the early detection of separation of the dispersive or electrode from the patient.

The concerns around unipolar instrumentation contributed to the further development and popularization of laparoscopic bipolar instruments in the early 1970s by Frangenheim and Rioux [13, 14]. These designs were used essentially unchanged until the early twenty-first century, when a number of proprietary bipolar systems emerged based on the recognition that RF-electrosurgical coagulation and desiccation could be used to predictably seal vessels of substantial size, and with much reduced lateral thermal injury.

RF electrosurgery has now become widely accepted as a highly effective method of cutting and obtaining hemostasis. Bipolar instruments offer some safety advantages when used for the processes of coagulation and desiccation but are in general not useful for cutting or vaporization. Safe and effective application of either requires the use of well-designed equipment and a sound understanding of electrosurgical principles.

## Principles of Electrosurgery

With the advent of surgical lasers, institutional credentialing committees ensured that surgeons clearly demonstrated knowledge of laser physics prior to allowing them to use the equipment in their facilities. Unfortunately, such rigorous requirements have not, to date, been applied to electrosurgery. Consequently, generations of physicians have had extensive experience with an instrument that most do not understand, a factor that likely contributed significantly to the incidence of RF electricity-related surgical complications. Like all energy sources, RF electricity should be respected, not feared. However, for safe and effective use, it is mandatory that the surgeon possess a clear understanding of the principles of electrosurgery.

During RF electrosurgery, the electromagnetic energy is converted in the cells first to kinetic energy then to thermal energy. The desired effect in the tissue is determined by a number of electrical properties as well as factors such as tissue exposure time and the size and shape of the surface of the electrode near to or in contact with the target tissue.

So what is “alternating current?” The answer starts with a description of the requirements for an electrical circuit. For any electrical circuit to exist, there must be a positive and negative pole to create the conditions for movement of ions and/or electrons. In a *DC*, the polarity in the circuit remains constant, as does the flow of the electrons (Fig. 2.2a). Common everyday examples of DC circuits are found wherever the power source is a battery, like a flashlight. When the polarity switches back and forth, which is the case for standard “wall outlet” sources, the term *AC* is used, a circumstance that reflects the alternating polarity of the circuit (Fig. 2.2b).

In North American outlets, the polarity of the output changes 60 times per second, or 60 Hz. This frequency allows us to power our homes and appliances, but also has the ability to depolarize muscle and neural cells as will be discussed later in this chapter. However, if the frequency of the polar change is increased dramatically, in excess of 100,000 Hz, or 100 kHz, the muscles and nerves cannot respond and, in essence, function normally. Furthermore, such frequencies can be used surgically to impact the cells and tissue in a dramatically effective fashion. Because the frequencies typically used for surgery are around 500 KHz, the frequency of amplitude modification (AM) radio broadcasts, the term RF electrosurgery is used (Fig. 2.3).

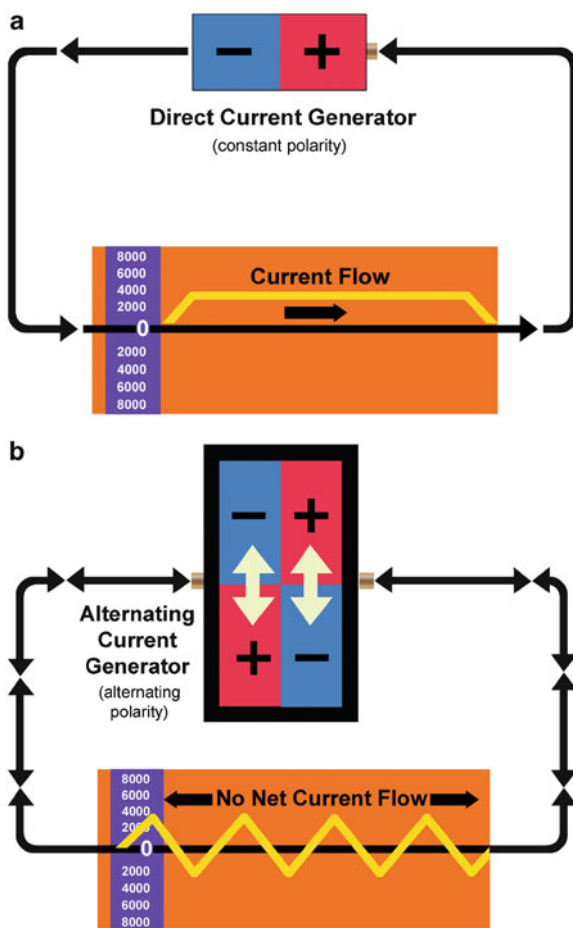


Fig. 2.2. (a, b) Direct vs. Alternating current. The *upper panel* depicts an electrical circuit created by an energy source with constant polarity, a battery, with the resultant unidirectional flow of electrons. The oscilloscope reflects the output with a constant deflection on one side of the “0” line. In the *bottom panel*, the energy source is an alternating current with each pole constantly switching from negative to positive, and a waveform that spends equal amounts of time above and below “0.” As a result, there is no directional flow—the electrons can be perceived to be oscillating, not flowing. This should explain why the term “return” does not apply to alternating current circuits.

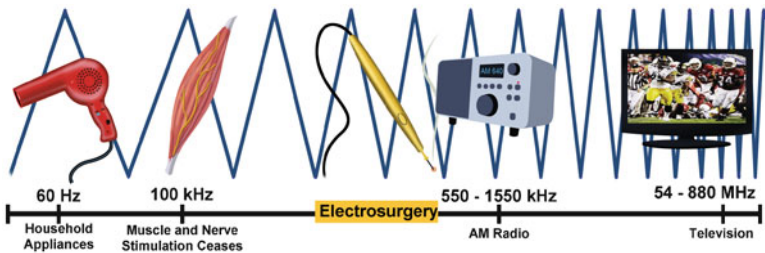


Fig. 2.3. Electromagnetic spectrum. Wavelength shortens as frequency increases. Wall outlets provide a waveform with a frequency of 50–60 Hz (cycles per second). Radiofrequency starts at about 300,000 Hz or 300 KHz and extends through about 3 MHz ( $3 \times 10^6$  Hz). In this frequency neither muscular nor neural cells depolarize.

As with any electrical process, RF electrosurgery requires the creation of an electrical circuit that includes the two electrodes, the patient, the ESU, and the connecting wires (Fig. 2.4). All contemporary RF electrosurgery is “bipolar” for it is necessary to have two electrodes; what differs is the location and purpose of the second electrode (Fig. 2.4). Bipolar *instruments* have both electrodes mounted on the device, usually located on or near to the distal end so that only the tissue located between the two electrodes is included in the circuit. However, with *unipolar instruments* only one electrode is mounted on the device and the entire patient is interposed between this “active electrode” and the large dispersive electrode that is also attached to the ESU, but located relatively distant from the target tissue, typically on the thigh or back. The narrow active electrode concentrates the current (and therefore the power), at the designated site, elevating the intracellular temperature, while the dispersive electrode acts as the other pole, “processing” the same amount of current (and power), but dispersing it over the entirety of the large surface area, so much so that the temperature in the underlying skin does not rise, thereby preventing tissue injury.

The three interacting properties of electricity that affect the temperature rise in tissue are current ( $I$ ), voltage ( $V$ ), and impedance or resistance ( $R$ ) (Table 2.1). (The rationale for use of the letter “ $I$ ” for current likely relates to the French inventor-scientist Ampere who used the term *intensité* to describe the intensity of flow when describing what we now know as an electrical current. Consequently, the letter “ $I$ ” was adopted by Ohm and others when describing current.) Current is a measure of the electron movement across or past a point in the circuit in a given period

## All RF Electrosurgery is “Bipolar” Monopolar vs Bipolar Instrumentation

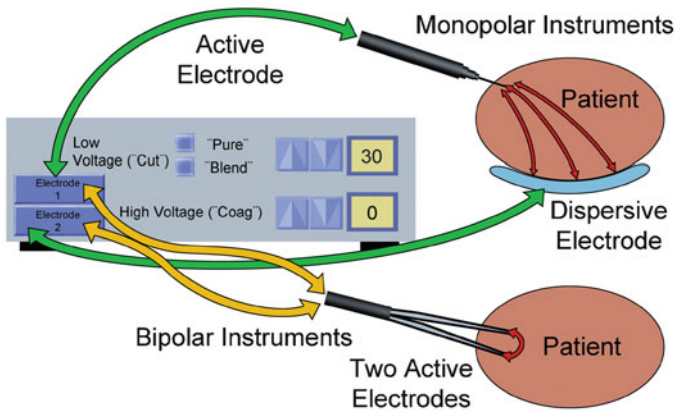


Fig. 2.4. All radiofrequency electrosurgery is “bipolar,” it is the location and purpose of the second electrode that varies. Monopolar instruments are used in monopolar systems (*top*). One of the two electrodes in such systems is designed to concentrate the current/power to achieve a surgical effect (“active” electrode), while the second electrode is placed remotely on the patient to disperse the current (“dispersive” electrode) thereby preventing the elevation of tissue temperature. Monopolar systems include the entire patient in the circuit, a circumstance that offers the opportunity for current diversion. Bipolar systems include both electrodes in the hand instrument (*bottom*). In most (but not all) instances, both electrodes are of small enough surface area to act as “active” electrodes thereby creating a surgical effect. In some instances, the electrode on the instrument serves as a dispersive electrode (see Figs. 2.2–2.13). The only part of the patient involved in the circuit is that adjacent to the electrodes, a circumstance that makes current diversion a virtual impossibility. Note that the same generator can usually support both systems (see also Fig. 2.7).

of time. It is measured in *amperes*. Voltage describes the electrical differential created between two points in a circuit that determines with what pressure the electrons are “pushed” within the circuit, including the parts of the circuit that comprise tissue. It is measured in *volts*. Resistance is measured in *ohms*, and is a reflection of the difficulty a given substance (e.g., tissue or the composition of the electrical wires) presents to the passage of electrons. The term resistance is generally reserved for DC while for AC, the term *impedance* is generally used. In a given circuit,

Table 2.1. Definitions of variables commonly used in the description of RF electrosurgery that can impact effect on cells and tissue.

Variable	Definition	Units
Current ( <i>I</i> )	Flow of electrons past a point in the circuit/unit time	Amperes (coulombs/second)
Voltage ( <i>V</i> )	Difference in electrical potential between two points in the circuit; force required to push a charge along the circuit	Volts (joules/coulomb)
Impedance (resistance) ( <i>R</i> )	Degree to which the circuit or a portion of the circuit impedes the flow of electrons	Ohms
Power ( <i>P</i> )	Work; amount of energy per unit time. Product of <i>V</i> and <i>I</i>	Watts (joules/second)
Energy	Capacity of a force to do work; cannot be created or destroyed	Joules (watts/second)

Table 2.2. Equations useful for the understanding of RF electrosurgical principles and calculation of impact on tissue.

Variable	Equation	Units
Ohm’s law	Current $I = V/R$	Amperes (coulombs/second) <sup>a</sup>
	Voltage $V = IR$	Volts (joules/coulomb)
	Impedance $R = V/I$	Ohms
Power ( <i>P</i> )	$P = V \times I$	Watts (joules/second)
	$P = V \times V/R = V^2/R$	Watts (joules/second)
	$P = I \times IR = I^2/R$	Watts (joules/second)
Energy ( <i>Q</i> )	$Q = P \times t$ (second)	Joules (watts/second)

<sup>a</sup>A coulomb is the charge transferred by a current of 1 A for 1 s

these properties are related by *Ohm’s law*— $I = V/R$  first described by Georg Ohm in 1827 [15] (Table 2.2).

An effective hydraulic analogy explaining Ohm’s law has been designed by Roger Odell. The height of the water tower above the ground creates a pressure differential that can then be exerted upon the water in the outflow pipe (Fig. 2.5). This pressure differential can be analogized to voltage—the higher the tower, and that on the ground the greater the pressure differential between that on the water in the tower. When the spigot is opened, the water is allowed to flow, a process that is analogous to activating an electrical circuit (turning it on). (For DC this analogy is sound, but for AC, the flow actually oscillates back and forth with the

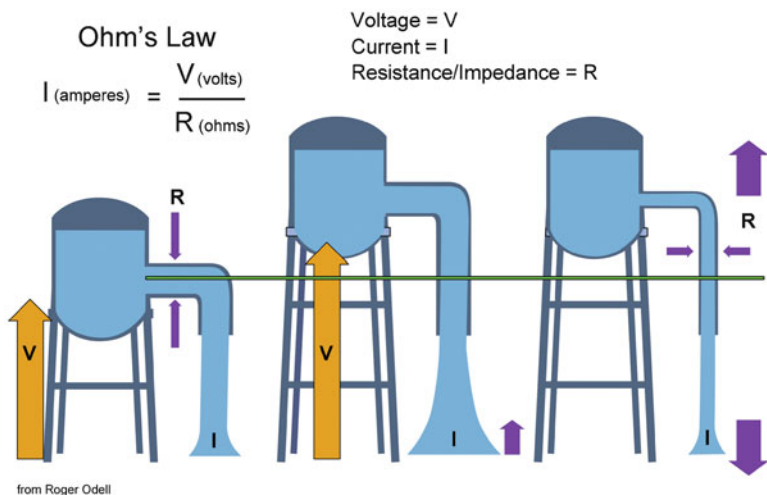


Fig. 2.5. Hydraulic analogy to explain Ohm's law. The height of the water tower serves as a surrogate for voltage ( $V$ )—a pressure differential between two points in a circuit. The amount of water that flows through the spigot per unit time represents current ( $I$ ). The resistance or impedance to the flow of water is represented by the diameter of the spigot ( $R$ ). If the voltage is increased (increasing the height of the water tower) and the impedance is held constant, current will increase proportionately (*middle*). If the voltage is held constant, and impedance increased, current will decrease. This is the reason for standard ESUs to lose efficiency when they encounter highly impendant tissue. Newer generators sense the increased impedance and increase the voltage thereby keeping power constant. To apply this concept to a RF output, imagine that it depicts what is happening during the course of about 1/500,000th of a second.

changing polarity of the generator, a fact that has to be considered when understanding this analogous situation.) The width of the spigot or pipe has a direct effect on the amount of water that can flow and, consequently, is analogous to the terms “resistance” and “impedance.” If widened (reducing impedance), flow would be increased because there is reduced resistance to the flow of water. Electrosurgical resistance or impedance is impacted by a number of factors throughout the circuit, but, most importantly, by tissue characteristics. Hydrated tissue that contains ions has the lowest impedance, while dehydrated (desiccated) tissue or any tissue with lower ionic content (such as scarred tissue or fat) will have

higher impedance and provide increased resistance to the flow of the current just as the narrow pipe in our water tower analogy reduces the rate of flow of the water from the tower.

Another important equation to the understanding RF electrosurgery is that which defines the relationship between voltage ( $V$ ), current, ( $I$ ), and power ( $W$ ). Power in effect is a measure of work per unit time ( $W = V \times I$ ). If Ohm's Law is used to substitute for current ( $I$ ), then power in watts can be expressed in another way: [ $W = V(V/R)$ ] or ( $W = V^2/R$ ). This demonstrates that power rises exponentially with increases in voltage and decreases inversely with increases in resistance or impedance.

These relationships are helpful in explaining a number of features of RF electrosurgery. For example, the ratio of voltage to current is largely responsible for the differing effects on tissue, given similar electrode size and shape as well as tissue exposure time. In general, the "pressure" of increased voltage enhances the ability of the current to arc from the electrode to tissue when there is a gap between them. When there is contact between the electrode and tissue, increased voltage forces more energy into the tissue, a circumstance that generally fosters a deeper or larger amount of thermal injury. The second equation shows how, at a given ESU output in watts, the voltage in the circuit will diminish if the tissue resistance increases, a feature that also decreases the power output from the ESU. This helps to explain how the cutting or coagulating characteristics of an electrode may change as tissues with different resistance are encountered. Newer ESUs can measure the impedance in tissue, and, as it rises or falls, can vary the voltage to maintain the output to be consistent with the desired power setting.

Perhaps the most important concept for the surgeon is that of power or current density, for control of this variable is what governs the impact of RF energy on tissue. It can be analogized the use of a magnifying glass to focus the power from a defined area of sunlight to one point, a process used by children for centuries to thermally carve one's initials into a piece of wood, or by campers to start a fire (Fig. 2.6). Simply put, current density is the amount of current per unit area; power density is simply proportional to the square of current density. Very high current density concentrated at the tip of an electrode can be used to heat and vaporize cells, slightly lower current density may desiccate and coagulate, while the same current spread over a large area may have no impact on the cells, the circumstance created by the design of a dispersive electrode.

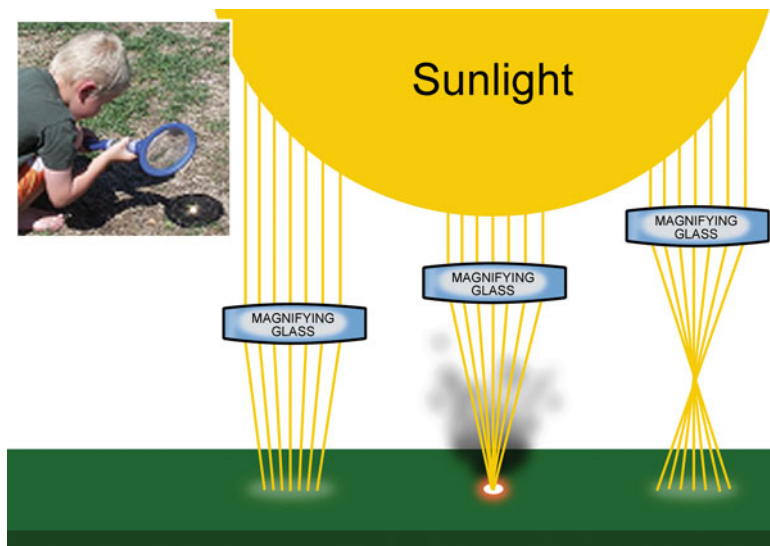


Fig. 2.6. Current/power density. RF electrosurgery is basically the control of power density, or current density and the sites of interface between the electrodes and the tissue. It can be analogized to the use of a magnifying glass, sunlight, and a wooden surface. If the light is kept relatively defocused (*right and left*) temperature in the wood does not increase, but if the light, and therefore the electromagnetic energy, is focused adequately (*middle*) the temperature of the wood increases to the point that it can burn.

## Electrosurgical Generators

The ESU converts the low-frequency AC from a wall outlet (60 Hz in North America) into higher-voltage RF output, typically from 300 to 500 kHz (Fig. 2.7). Such ESUs are also capable of producing a number of different waveforms that allow the surgeon to change the impact of the energy on the targeted tissue. Features of the ESU output can be displayed on an oscilloscope (Fig. 2.8). The wave is generally symmetrical above and below “0” volts reflecting the continuously alternating polarity inherent to an AC. While the peak voltage generated is calculated by measuring the distance from the baseline to the apex of the wave, outputs are typically reported as the voltage differential between a peak and a trough or the “peak-to-peak” voltage. This image of the oscillating wave, below and above 0 V, should help the reader

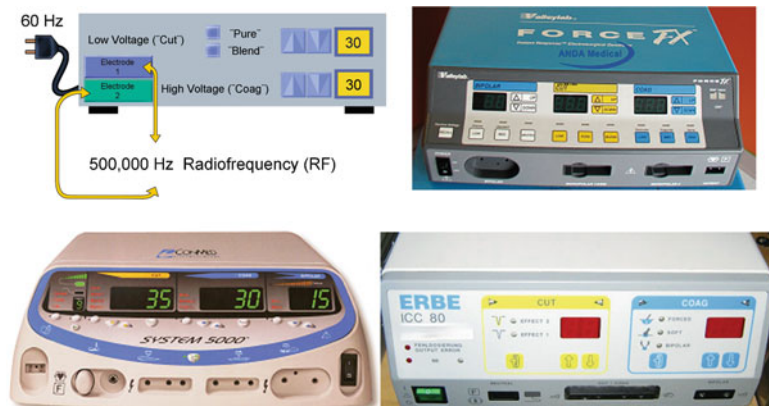


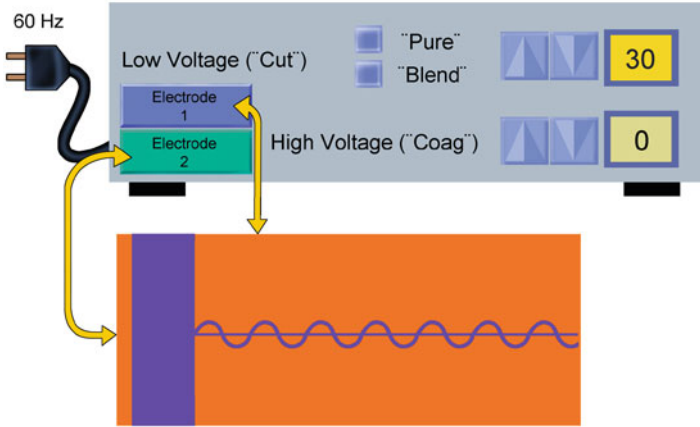
Fig. 2.7. A stylized electrocautery unit (ESU) is depicted in the *upper left*. It converts alternating current from a wall source (50–60 Hz), to a radiofrequency output, typically about 500 KHz (500,000 Hz). The circuit is formed using two outlets. The three commercial examples shown each have similar colors for waveforms used for monopolar instrumentation—a low-voltage (“cut”) output coded in *yellow* and a modulated high-voltage output (“coag”) coded in *blue*. The “Force FX” (*upper right*) and the “System 5000” (*lower left*) each have a bipolar output that is coded in *blue*, even though the bipolar outputs are low voltage, similar to those of the *yellow-coded* “cut” outputs.

understand that the current in RF electrosurgery does not flow in one direction via the active and dispersive electrodes, but instead should be perceived as electrons (in the wires and ESU) or ions (in the tissue) rapidly oscillating back and forth.

All modern ESUs have ports for the two electrodes in the circuit, and controls that allow the surgeon to set the power output for each of the waveforms. While most North American-made ESUs have two outputs labeled *cut* and *coagulation* (or “coag”), these terms do not accurately reflect the appropriate use of the energy, a feature that tends to add to confusion regarding the properties and purpose of the different waveforms.

The output labeled “*cut*,” when set at “*pure*,” provides a continuous and relatively low-voltage waveform. As it is seen on the oscilloscope (Fig. 2.8a), the ESU output is in the form of a sine wave, reflecting both the continuous output from the generator, and the rapidly switching polarity of the AC.

**a** Waveform - Low voltage, continuous



**b** Waveform - High voltage, modulated, dampened

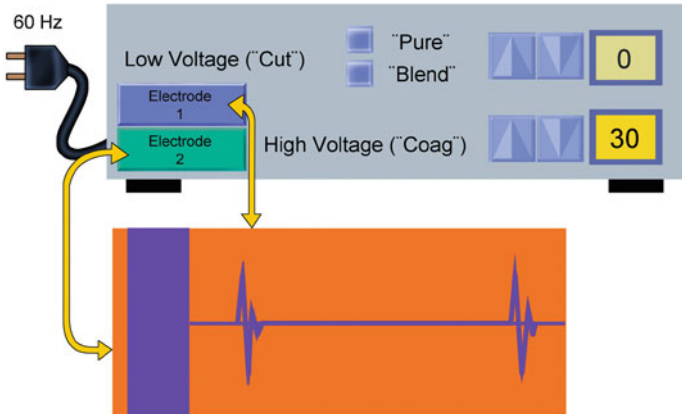


Fig. 2.8. The two basic waveforms are shown. **(a)** The image shows a low-voltage, continuous output in the form of a sine wave that is unfortunately called "cut" in North America, giving the false impression that it uniquely is designed for cutting tissue. **(b)** This panel shows a modulated (low duty cycle, typically about 6%), dampened, and high-voltage waveform that is also mischaracterized with the name "coag" in North American systems.

The so-called “*coagulation*” waveform is an interrupted, dampened, and relatively high-voltage waveform (Fig. 2.8b). Typically, the current is “on” only 6% of the time, referred to as a 6% *duty cycle*, and further described below.

Originally, *blended* outputs were created by combining the waveforms of two physically separate generators that produced the continuous low-voltage and modulated high-voltage waveforms described above. However, all modern ESUs create their “blended” outputs by producing interrupted (or modulated) versions of the continuous or pure “cut” waveforms. The term *duty cycle* is used to describe the percentage of time that the ESU is producing a waveform—if it is 80% of the time, it is referred to as an 80% duty cycle (Fig. 2.9a, b). When the current is interrupted, and therefore reduced, while the wattage is held constant, the generator increases the voltage of the output ( $W = V \times I$ ). Alternatively stated, as the duty cycle diminishes, the voltage rises provided wattage is constant. In the water tower analogy, use of a “Blend” output is equivalent to slightly elevating the level of the tower while intermittently turning the water flow on and off at the tap. The flow of the water will pulse, and it will flow with a slightly higher pressure. Typically it is possible for the operator to vary the tissue effect by selecting from one or a number of blend modes that vary the duty cycle from, for example, 80–50%. This explanation also should facilitate understanding of the “coag” output, its low duty cycle, and relatively high voltage when set at the same power output on the ESU.

It is important to realize that all ESUs are not created equal. The duty cycles of the various “blend” modes vary from machine to machine. The peak voltages generated in any of the modes may vary significantly, depending, in part on the purpose for which the machine was designed. For example, machines designed for operating room use generally provide peak voltages for the continuous and blended outputs significantly higher than machines designed for office use.

Most ESUs designed for operating room use are capable of supporting bipolar instruments. This means that the dual wire bipolar cords attached to the bipolar instrument plug into the ESU and that there is a power output control specifically for the bipolar instrument (Fig. 2.7). Most modern generators provide only a continuous waveform from the bipolar outlets that is identical to the “cut” waveform. The reasons for this will be explained in subsequent sections.

There are a number of different ESU’s on the market that are designed to support proprietary bipolar instruments such as Ligasure® (Covidien),

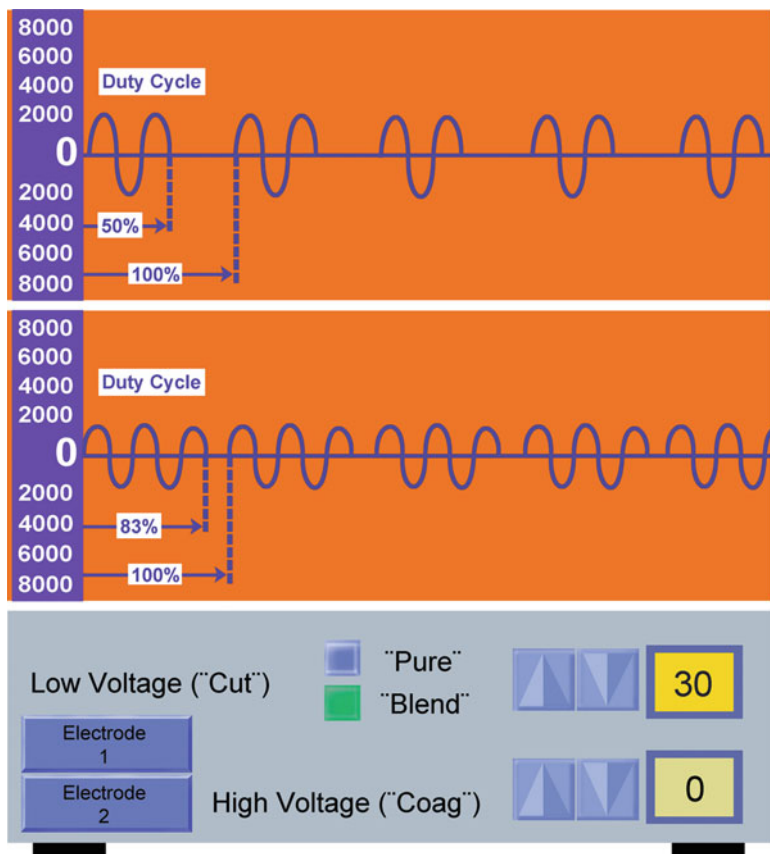


Fig. 2.9. Duty cycle. The proportion of time that the ESU is actually producing current is termed the “duty cycle.” “Blended” currents are actually modulated low-voltage waveforms, NOT combinations of the “coag” and “cut” waveforms. On the *top panel*, there is output 50% of the time, whereas in the *middle panel*, it is 83% of the time. Note that to preserve the power equation ( $P = V \times I$ ), with the decrease in current, there is a proportional increase in voltage with the lower duty cycle waveform.

PlasmaKinetics® (Olympus-Gyrus), and EnSeal® (Ethicon Endosurgery) (Fig. 2.10). These generators are designed with microprocessors that work with the bipolar device to measure impedance or temperature and vary features of the output such as voltage to customize the coagulation effects on the target tissue.



Fig. 2.10. Proprietary electrosurgical units. Depicted are three ESUs designed to run proprietary bipolar systems: The PlasmaKinetic system (Olympus-Gyrus, Inc.), *upper left*; the EnSeal system (Ethicon Endosurgery, Inc.), *upper right*; and the Force Triad that supports the LigaSure system (Covidien, Inc.), *lower left*. There are a number of different ESU's on the market that are designed to support proprietary bipolar instruments.

## The Circuit: The System

Performance of electrosurgery requires the formation of an electrical circuit that includes the ESU, the electrodes and connecting wires, and, of course, the patient. The original systems were *ground referenced* meaning that the “ground” was an inherent part of the circuit, but all contemporary electrosurgical systems use isolated circuits, which means that the “ground” is excluded (Fig. 2.11).

At the risk of redundancy, a fundamental concept to have in mind when considering the circuits created for RF electrosurgery is that in each instance there must be two electrodes. Consequently *all RF electrosurgery is bipolar*. Whereas all systems have at least one of the electrodes designed to concentrate current sufficient to elevate local tissue and cause a surgical effect—what differentiates the systems is the location and purpose of the second electrode. This concept should also

## Isolated vs Ground-Referenced Systems

All currently produced ESUs create isolated circuits

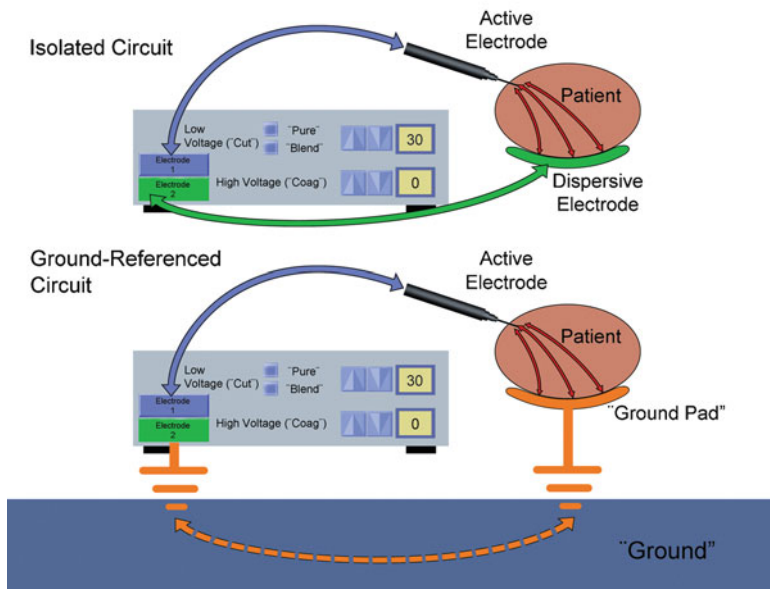


Fig. 2.11. Isolated vs. ground-references systems. Contemporary systems sold for operating room use are all designed with isolated circuits. Ground references systems depend on the “ground” to complete the circuit, a circumstance which brings into play the opportunity for current diversion through any potential circuit including EKG electrodes, and stirrups or other components of an operating room table.

include the notion that the part of the patient involved in the circuit is different between systems. For systems that use monopolar instruments the entire patient is involved, whereas in those systems that are designed for use with bipolar instruments, it is only the tissue interposed between the two electrodes that is involved in the circuit. These fundamental differences are responsible for a number of safety and performance differences between these systems (Fig. 2.4).

### *Monopolar Instruments and Systems*

Monopolar systems include two separate monopolar instruments in the circuit, the *active electrode* and the *dispersive electrode*, between

which is interposed the entire patient (Fig. 2.4). The active electrode is designed to focus the current or power on the surgical target thereby creating the desired tissue effect. The dispersive electrode is positioned on the patient in a location remote from the surgical site and is relatively large in surface area, a design that serves to defocus or disperse the current thereby preventing tissue injury.

Active electrodes can have many designs, but those with a point, hook, narrow tip, or bladed edge are generally used to concentrate current and power, for the purpose of tissue vaporization and cutting (Fig. 2.12). When the active electrode has a slightly larger surface area, such as the side of a blade or when it is shaped like a ball or is in the form of a grasper, the same output used for cutting will result only in local coagulation and desiccation, and, consequently, can be used for the purpose of hemostasis. A better name for the active electrode might be



Fig. 2.12. “Active” electrodes in monopolar instruments. Monopolar instruments comprise only one electrode. The *top* is a hand-held electrode for open surgery. Note that there are three prongs on the plug—only one is necessary, but some systems are designed to include monitoring systems (for impedance for example). *Lower right* is a laparoscopic monopolar instrument with a hook electrode and an insulated shaft. In the *lower left* is a multitined monopolar electrode in a monopolar instrument designed for ablation of large volumes of tissue—so-called radiofrequency ablation (see Chap. 9).

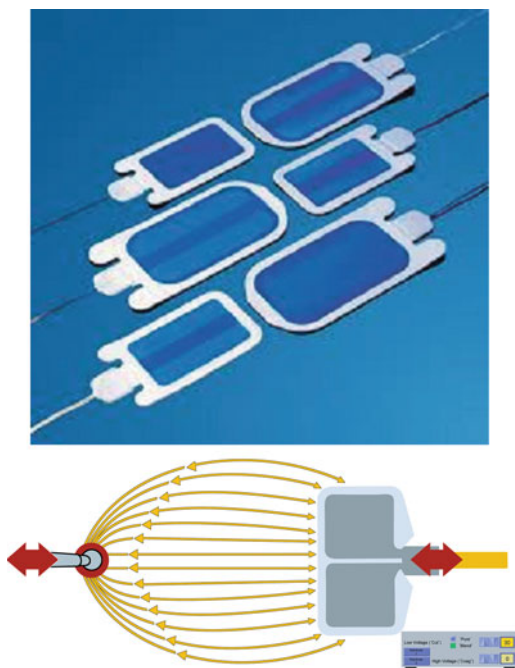


Fig. 2.13. Dispersive electrodes. Several dispersive electrodes are shown (*top*). Note that some actually comprise two separate electrodes, the so-called “split pad” that allows for the detection of a partial detachment if the ESU is capable of measuring and comparing the impedance in each electrode. Note the diagram below demonstrating the bidirectional nature of the current and the fact that the same current is focused by the active electrode (*left*) and diluted by the dispersive electrode (*right*).

the “power or current concentrating electrode,” but for most this would be a mouthful so we will use “active electrode” in this book even though dispersive electrodes can become “active” as discussed below.

Dispersive electrodes are almost always designed with an adhesive to facilitate continuing contact with the patient and prevention of a clinically significant local thermal effect (Fig. 2.13). However, if there is partial detachment, the current or power density will increase, and the dispersive electrode can become “active” and capable of creating thermal injury, often called a “burn.” Most (but not all) ESUs sold in the past 20 years are designed to measure the impedance at the level of the dispersive

electrode, a function that also requires specialized dispersive electrode design. Usually this is in the form of a “split pad” which, effectively, is two dispersive electrodes in one (Fig. 2.13). A difference in the measured impedance in the two dispersive electrodes will generally reflect partial attachment (or detachment) and the machine will not start, or, if already “on,” will shut off automatically.

Hopefully this description will help the reader understand the reason that the terms “return” and “ground,” when used to describe the electrode designed to disperse current, are both inaccurate and confusing. The continuously switching polarity of ACs means that there is no net electron flow. Consequently, neither electrode should be perceived as being dedicated to “return” current or electrons to the ESU. Virtually, all ESUs designed for the operating room and sold in the last 30 or more years have isolated circuits, and there is no reference to “ground” in the system.

## *Bipolar Instruments and Systems*

Simply put, bipolar systems are designed to use instruments designed with both electrodes positioned on the same surgical device (Fig. 2.14). Consequently, instead of a single wire connecting the ESU and the dispersive electrode and another linking the ESU to the “active” electrode, both are contained in one cable that joins the generator to the bipolar instrument. A fundamental concept is that the only part of the patient involved in the circuit is the tissue interposed between the two electrodes, a design that prevents complications related to current diversion and provides more accurate measurements of local tissue parameters such as temperature and impedance. However, bipolar systems also have limitations, as it is more difficult to include a method for electrosurgical vaporization and cutting into the design.

The simplest bipolar instruments contain two flat monopolar electrodes, electrically isolated from each other in the device. The electrodes are generally flat and in some fashion articulated, a design that allows the surgeon to grasp and compress tissue. With this configuration, both electrodes are “active” in that they are equally capable of elevating as the local temperature sufficiently to cause the processes of coagulation and desiccation discussed below. Most of the proprietary systems are based on this concept but include a sliding mechanical knife if they are designed to both coagulate and cut tissue. In addition, these proprietary

a

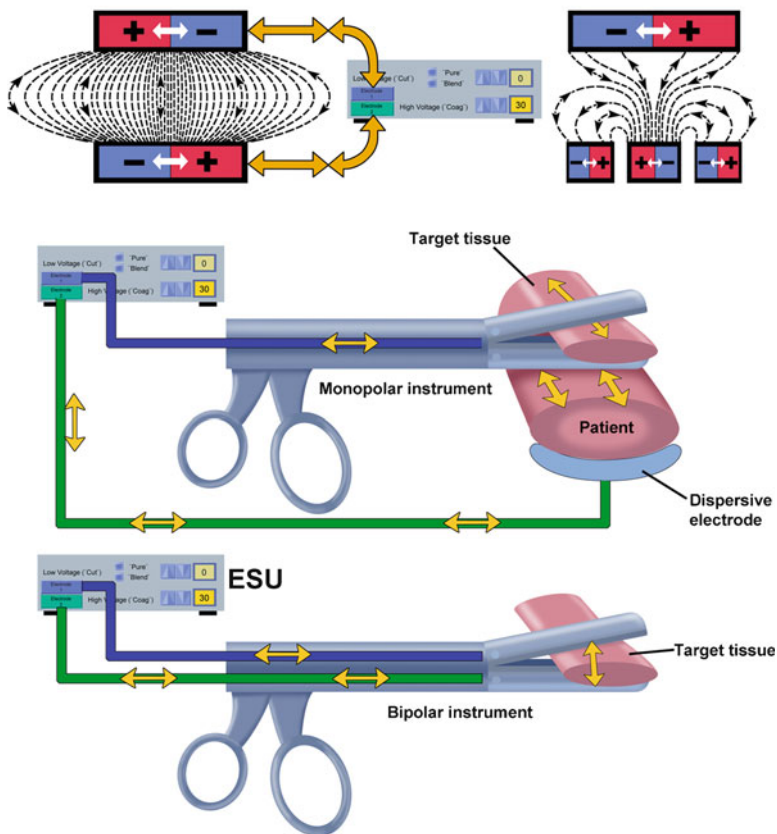


Fig. 2.14. Bipolar versus monopolar instruments. The two electrodes in a bipolar instrument constantly change polarity, at a rate determined by the generator, generally about 500 MHz. ((a), top left). Some bipolar instruments have a more complicated design or arrangement of the two electrodes. In the example ((a), top right), the upper and lower left and right components are really one “electrode” while the second electrode is in the middle of the bottom row, an arrangement that can result in cutting activity because the lower middle component creates a high current density. The lower figures in (a) show that two instruments that may seem similar in design are actually quite different, the top instrument is monopolar as the jaws of the grasper are joined creating a single electrode. Note that there is a dispersive electrode that the entire patient is involved in the circuit, and that there is one wire into the instrument. The bottom instrument is actually bipolar—the two wires entering the instrument from the generator each connect to one of the jaws that are insulated from each other. Only the tissue between the jaws becomes part of the circuit. (b) These differences are demonstrated with real instruments, a monopolar grasper (A) and a bipolar grasper (B). Note in the lower right panel that there is an insulator between the jaws in (B) that is not present in (A). In the lower left panel, the single electrosurgical “post” of a monopolar instrument is shown, while the double wire and multiple prongs for the bipolar instrument are shown in (B).

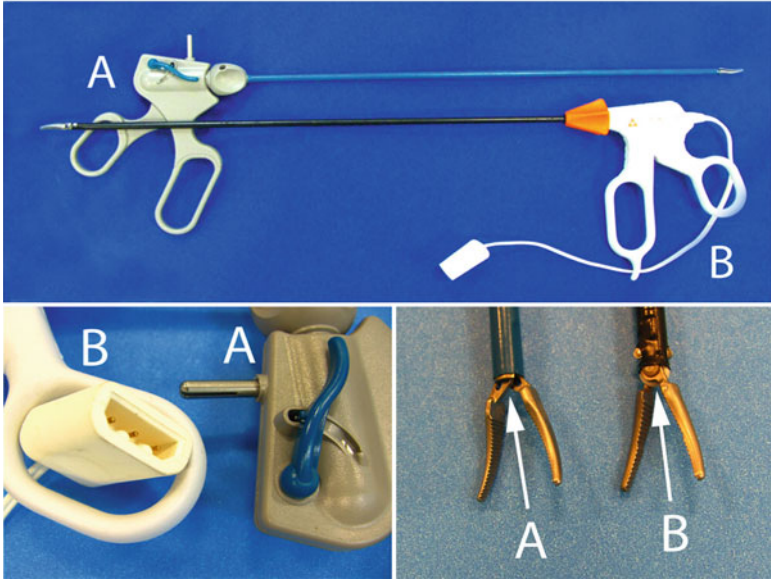
**b**

Fig. 2.14. (continued)

systems measure local tissue impedance and/or temperature in an attempt to more accurately define an “end point” for vessel sealing, based on the knowledge that certain temperature thresholds or high impedance levels are associated with complete tissue coagulation and desiccation. The details of these systems are discussed in a later chapter.

While it is difficult to design bipolar instruments for cutting, it is possible, and there are a number of such systems currently marketed. One approach is to design the instrument so that when placed on tissue an electrode with a relatively large surface area is in contact with tissue, while simultaneously a narrow blade or needle electrode is used to cut. Another is a design that joins both “grasping” components into one electrode, while a blade that is positioned along the tissue serves as the active electrode. A bipolar needle electrode is shown in (Fig. 2.15).

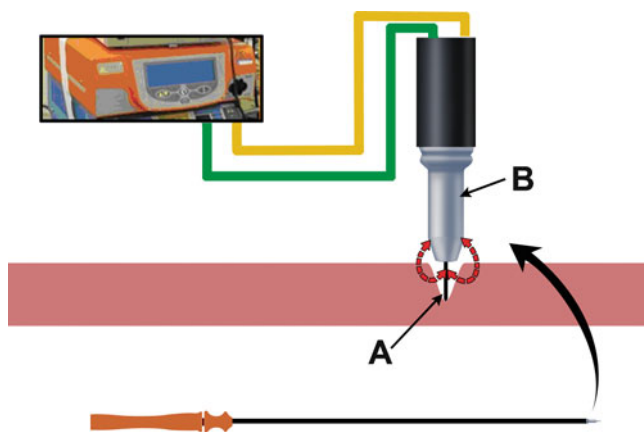


Fig. 2.15. Bipolar cutting instrument. This graphic depicts another bipolar instrument designed for cutting. The needle electrode (A) is isolated from the larger and proximal dispersive electrode (B). The instrument is connected to the proprietary ESU by a dedicated cable. The *red dotted lines* pathway demonstrates the current pathway between the two electrodes; the zone of vaporization is depicted around the needle electrode.

## Effect of Temperature on Cells and Tissue

Understanding the surgical applications of RF electricity requires a basic understanding of the effects of temperature on cells and tissue (Fig. 2.16). Normal body temperature is  $37^{\circ}\text{C}$  and all of us, from time to time, when we have infections, experience temperature elevations that can reach as high as  $40^{\circ}\text{C}$  or so without damage to the structural integrity of our cells and tissue. However, when cellular temperature reaches  $50^{\circ}\text{C}$  cell death will occur in approximately 6 min [16] and if the local temperature is  $60^{\circ}\text{C}$  cellular death is instantaneous [17].

So what happens at  $60^{\circ}\text{C}$ ? Between about 60 and  $95^{\circ}\text{C}$  (in effect, below 100 degrees C) two simultaneous processes occur that are of interest to surgeons. The first is protein denaturation that occurs secondary to the impact of temperature on the hydrothermal bonds that exist between protein molecules. When the local temperature is as low as  $60^{\circ}\text{C}$ , these bonds are instantaneously broken but then quickly reform, as the local temperature cools. This ideally leads to a homogenous coagulum, a process that is typically called “coagulation.” The other

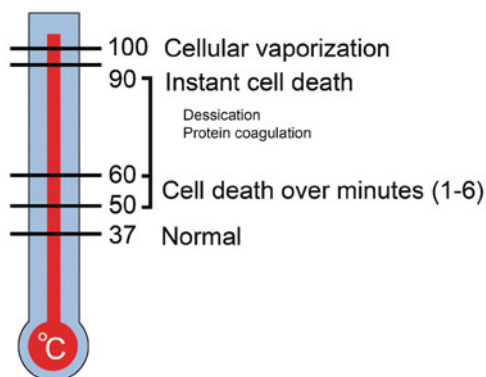


Fig. 2.16. Impact of temperature on cells and tissue. Normal body temperature is 37°C, and if cellular or tissue temperature reaches 50°C for 6 min, cell death occurs. If the temperature reaches 60°C, cell death occurs instantaneously. If the temperature is less than 100°C, but at least 60°C, the mechanisms involved in cell death include cellular desiccation and protein coagulation. When the intracellular temperature reaches 100°C, cellular vaporization occurs secondary to a liquid–gas conversion to steam.

effect is dehydration or *desiccation* as the cells lose water through the thermally damaged cellular wall. From a gross and microscopic perspective, so-called *white coagulation* is the result of a process similar to boiling the white of an egg—a white, homogenous coagulum. Microscopically it has been demonstrated that protein bonds are formed creating the homogenous, gelatinous structure. Such a tissue effect is useful for occluding tubular structures such as fallopian tubes, or blood vessels for the purpose of hemostasis.

If the intracellular temperature rises to 100°C or more, a liquid–gaseous conversion occurs as the intracellular water boils forming steam. The subsequent massive intracellular expansion results in explosive vaporization of the cell with a cloud of steam, ions, and organic matter. It is suspected that the explosive force results in acoustical vibrations that contribute to the cutting effect through the tissue.

When the local temperature reaches higher levels, such as temperature reaches 200°C or more, the organic molecules are broken down in a process called *carbonization*. This leaves the carbon molecules that create a black and/or brown appearance, sometimes referred to as “black coagulation.”

## Effect of Alternating Current on Cells

The process called electrosurgery is based on the ability of the RF current to elevate cellular, and, consequently, tissue temperature to attain the desired tissue effect. Understanding how this occurs starts with the knowledge of the impact of RF electromagnetic energy on intracellular components.

There are at least two basic mechanisms whereby RF electricity increases cellular and tissue temperature. The most important is by the conversion of electromagnetic energy to mechanical energy, which then is converted to thermal energy by frictional forces. A second, and likely less important mechanism, is resistive heating, where current flowing across a resistor causes an increase in the temperature of that resistor. These mechanisms will be discussed below. A third and indirect mechanism of tissue heating is conductive heat transfer, the tissue adjacent to that which undergoes the direct effects of RF electricity.

### *Conversion of Radiofrequency Electromagnetic Energy to Mechanical Energy*

Cellular cytoplasm contains electrically charged particles or ions in the form of atoms and molecules (Fig. 2.17). Cations are small, positively charged atoms like sodium, potassium, and calcium, while the anions include atoms such as chlorine as well as large, negatively charged protein molecules. If a DC, with its constant polarity, is applied to the cell, the cations tend to migrate toward the direction of the negative electrode while the anions orient to the positive electrode as unidirectional current flow is established (Fig. 2.17, top panel). This is called the *galvanic effect*, and has no known medical purpose.

When an AC, with its continuously switching polarity, is applied to the cell, the anions and cations migrate to the positive and negative poles respectively, but, rather than maintaining an orientation within the cell, they oscillate in synchrony with the changing polarity of the output (Fig. 2.17, bottom panel).

If the frequency of the AC is relatively low (20–30 kHz), the impact of the RF energy will incite depolarization of muscles and nerves and the creation of action potentials that result in muscle fasciculation and related pain, a process known as the *Faradic Effect*. It is thought that this

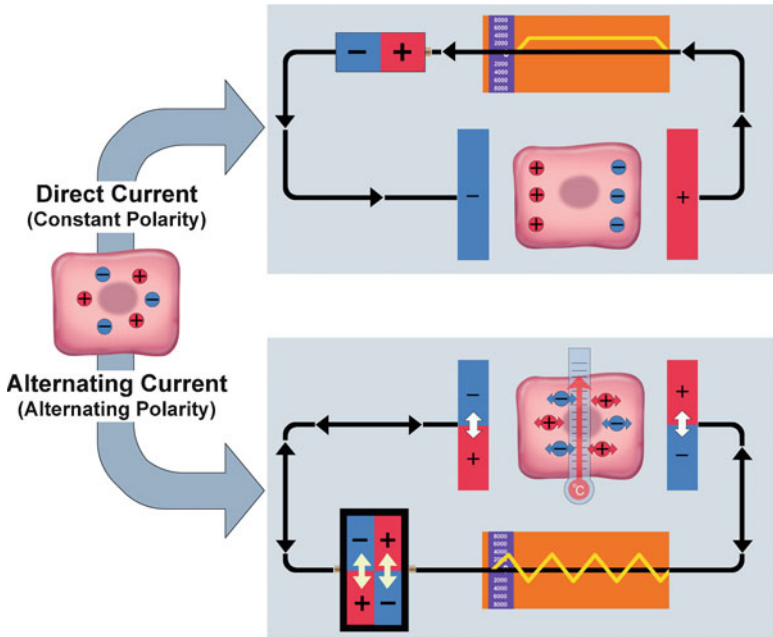


Fig. 2.17. Cellular response to constant and alternating polarity (direct and alternating current). Cells contain anions (negatively charged) and cations (positively charged). When a direct current is applied to a cell (*top right panel*), the anions tend to migrate within the cytoplasm toward the positive pole and the cations to the negative pole. However, when the polarity changes 500,000 times per second, the electromagnetic energy is converted to mechanical energy as the molecules rapidly oscillate within the cytoplasm (*bottom right panel*). With this rapid motion and, especially in the instance of large protein molecules, frictional forces result in the conversion of the mechanical energy to thermal energy.

depolarization is initiated through voltage-gated sodium and/or calcium ion channels that exist within neural and muscular cell membranes. However, nerve and muscle membranes are not sensitive to the very short duration “pulses” characteristic of the high-frequency electromagnetic energy in the RF spectrum. Consequently, when RF (100 kHz–3.0 MHz), AC is applied across the cell, the pulse duration is so short that the sodium and calcium ionic channel gates do not open, and cellular membrane depolarization doesn’t occur. Instead, the electromagnetic energy is converted into mechanical energy as the cations and anions rapidly oscillate within the cellular cytoplasm

(Fig. 2.17). Almost immediately, this mechanical energy, and especially that created by the large oscillating proteins, is converted, by frictional forces, into thermal energy that, in turn, results in elevation of intracellular temperature. The impact of these changes was discussed above, and the degree of temperature elevation depends on a number of factors that affect the amount of Joules of energy deposited in a given tissue volume. If the temperature rises to between about 60 and 95°C, desiccation and protein coagulation occur, while if the temperature reaches 100°C cellular vaporization results (Fig. 2.18). The factors involved in creating these different surgical effects are discussed in the next section. In some instances, RF electricity may be associated with muscle depolarization. The exact reasons for such stimulation are not known, but could include the influence of stray lower frequency arcs to tissue, or rectification, the conversion of AC to DC [18].

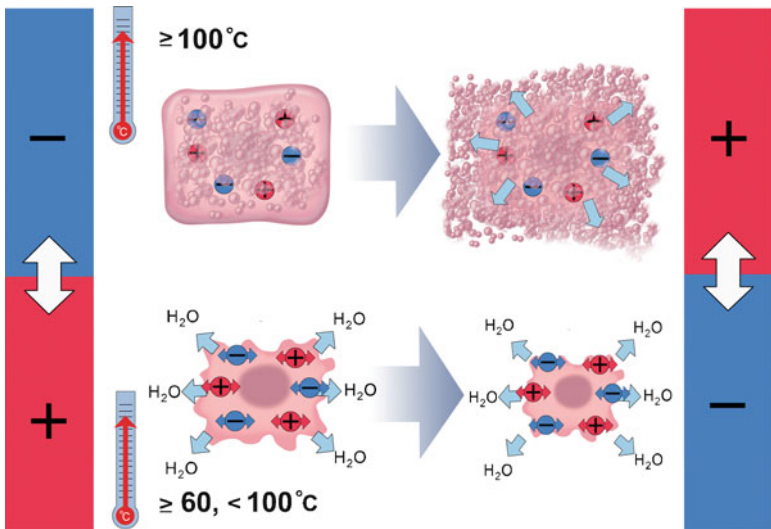


Fig. 2.18. Impact of elevated temperature on cells. If enough energy is transmitted to the cell sufficient to increase the temperature to at least 60°C, but below 100°C, there is loss of cellular water (desiccation) through the damaged cell wall (*bottom*). On the other hand, if the temperature meets or exceeds 100°C (*top*), the intracellular water turns to steam, there is massive expansion of the intracellular volume, and the cell explodes in a cloud of steam, ions, and organic matter—the process of vaporization.

## *Resistive Heating*

When either AC or DC flows through a resistor, the resulting effect is the generation of heat, much like the response of a filament in a light bulb. Alternately stated, the resistance of the tissue converts the electric energy of the voltage source into thermal energy that causes the tissue temperature to rise. This relationship is defined in *Joules Laws* after the nineteenth century English physicist James Precott Joule (Table 2.2). It is likely that this mechanism comes into play after the primary mechanism of ionic oscillation described above results in increased tissue impedance by virtue of cellular dehydration or desiccation. In the process of fulguration, superficial coagulation is achieved very quickly, but subsequently tissue temperature rises to levels not seen with typical cutting or “white” coagulation. Consequently, it is likely that the very high temperatures reached are secondary to resistive heating.

## Tissue Effects of Electrosurgery

The concepts around creation of a given tissue effect using RF electricity are extensions of the impact of the energy on cells. The tissue effects depend upon a number of factors including the power output of the ESU, the waveform of the output, the impedance of the target tissue, the area of the electrode interfacing with the tissue, and the proximity of the electrode to the target tissue (contact or noncontact). Another factor is the distension medium utilized for the procedure. The basic principles will be discussed under the appropriate headings; then will follow a discussion of the factors that modify the tissue effect.

## *Cutting*

Formation of a tissue incision with RF electricity is simply the process of linear vaporization. Vaporization of tissue is best achieved with a continuous, low-voltage waveform, using a unipolar instrument with a narrow, pointed or blade-shaped electrode held near to but not in contact with the tissue. The generator is activated, allowing the thin electrode to concentrate the current and therefore the power at its tip—a high power density. The current then arcs between the electrode and the tissue, rapidly elevating the local intracellular temperature to more than 100°C causing

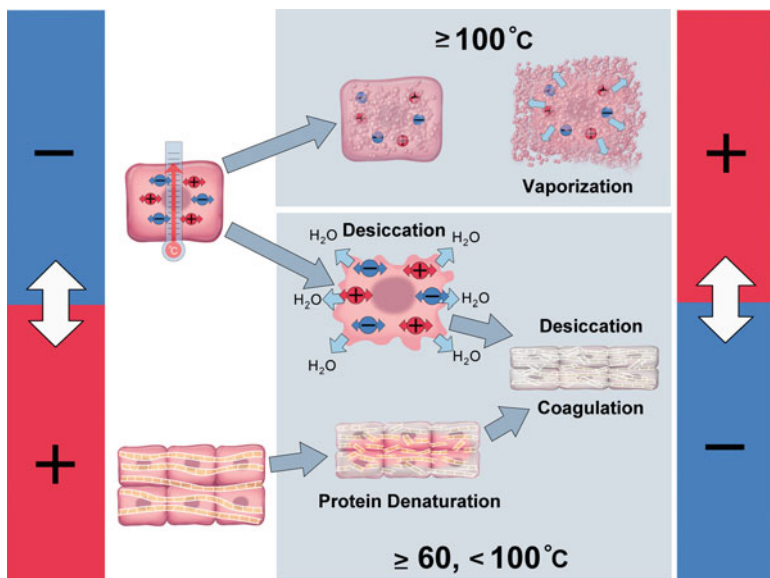


Fig. 2.19. Impact of elevated temperature on tissue. To understand the formation of an electrocautery-induced vessel seal, it is important to understand the tissue impact of elevation of tissue temperature at least  $60^{\circ}\text{C}$ , but below  $100^{\circ}\text{C}$ . The first is tissue desiccation, which is just the tissue manifestation of mass cellular dehydration and resulting volumetric shrinkage. The second is the rupture of hydrothermal bonds or crosslinks and reformation of these in a random fashion that includes bridging the gap between two opposing tissue surfaces. Provided these tissues are somewhat similar in protein content, the result will be a strong seal, as if the vessel walls were compressed and welded together. Cutting or transection of tissue electrocautery requires the establishment of a localized zone of vaporization followed by linear extension of this zone keeping the electrode within the vapor or steam “pocket” or “envelope” created by the vaporized tissue.

focused cellular vaporization and the creation of a local “plasma cloud” of steam, ions, and organic matter. To extend this zone of vaporization and form an incision, the electrode is advanced, keeping its tip or edge and the target tissue within the plasma cloud or “steam envelope” (Fig. 2.19). Because the voltage is low and the current dissipates rapidly with distance from the active electrode, the thermal damage on each side of the cut zone is minimal, provided the use of both appropriate equipment and surgical technique.

The actual depth and extent of adjacent coagulation injury incurred in association with an electrocautery created incision is dependent upon a

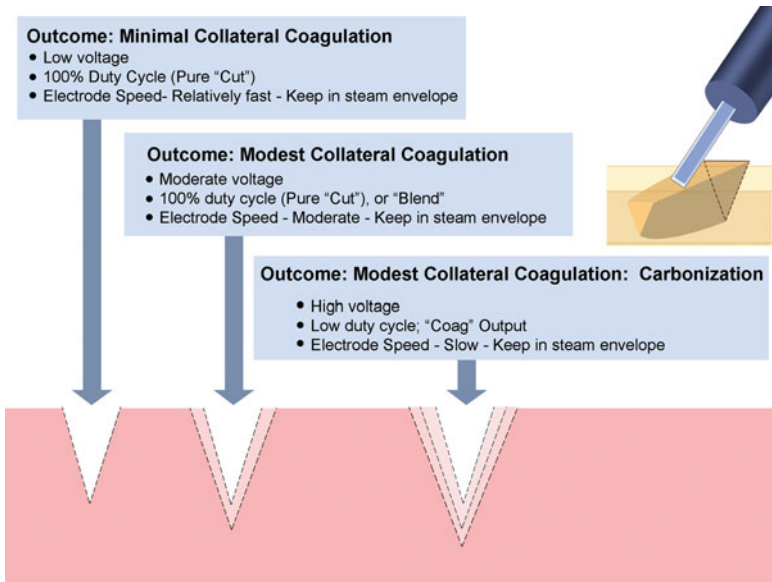


Fig. 2.20. Factors affecting depth and characteristics of adjacent coagulation when cutting tissue using RF electrosurgery. The major characteristics are the voltage, the waveform, and the electrode speed. In general, the slower the speed, the more energy delivered to adjacent tissue. However, if the speed of the electrode is too fast, it will get ahead of the steam envelope, a circumstance that results in contact with the tissue, transiently lower current density, and the creation of a zone of desiccation and coagulation. Higher voltage can be created by using a lower duty cycle, or turning up the generator (or both). The result is more adjacent coagulation injury. If a modulated high-voltage ("coag") waveform is used, everything else being equal, there will be more collateral coagulation and carbonization as very high local temperatures can be reached.

number of factors including power output, electrode size and shape, waveform and peak voltage, and the speed and skill of the surgeon. Consequently, descriptions of the depth of coagulation injury should take the existence of such variables into consideration (Fig. 2.20). While the minimum depth of thermal injury has been described as low as a few microns [19], more typical reported peritoneal injury studies suggest depth of thermal injury from less than 200  $\mu\text{m}$  for pure cutting waveforms [20] to 300  $\mu\text{m}$  for blended waveforms [21]. Such injury depths no doubt, reflect, in part, the rather high peak voltage outputs of the generators currently in general use.

While bipolar cutting instruments exist, they are difficult to design because of the requirement for the two electrodes to be oriented in a way

that allows efficient vaporization to occur. Bipolar needle-tipped instruments require that the surgeon maintain the instrument in an orientation that maintains tissue contact with the dispersive electrode (Fig. 2.15). Some innovative electrosurgical sealing and transection instruments that use bipolar cutting techniques have been designed. These instruments require the use of waveforms designed to overcome the high impedance of the coagulated tissue.

## *Desiccation and “White” Coagulation*

As described previously, two simultaneous processes occur when tissue temperature is maintained at 50°C for at least 6 min, or instantaneously at 60–95°C—protein coagulation and dehydration or desiccation. Unlike the case for vaporization, the cellular proteins are altered but not destroyed. While two distinct intracellular effects are occurring simultaneously, many use either the term coagulation or desiccation to describe both processes.

Effective coagulation for the purposes of sealing vessels or other lumen-containing structures requires contact of the electrode with tissue. When a blunt or flat electrode is placed in contact with the tissue, all the energy on that electrode is made available for conversion to intracellular heat by the processes described previously in this section. In conjunction with properly selected power outputs, the power density is high enough to cause instantaneous coagulation and desiccation, but not so high as to elevate the intracellular temperature to 100°C where vaporization would occur (Fig. 2.21).

Although any waveform may be used to create tissue coagulation and desiccation, a continuous low-voltage output (“cut”) results in a predictable zone of coagulation with higher quality and consistency than that achieved with the output labeled “coagulation.” There are a number of reasons for this apparent paradox. First, compared to low-voltage waveforms, the modulated “coagulation” waveform results in an uneven amount of protein bonding, limiting the ability to, for example, achieve complete occlusion of a blood vessel (Fig. 2.22). In addition, such waveforms cause the more superficial layers of the tissue to become rapidly coagulated, increasing impedance, thereby preventing further transmission of the energy to the deeper layers of the tissue [22]. Finally, the temperature generated near the electrode may exceed 200°C, causing carbonization and breakdown of molecules to sugars, a process that

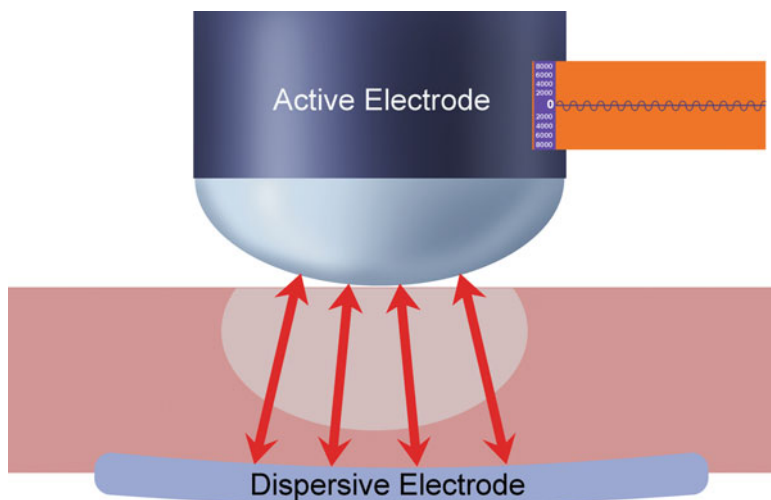


Fig. 2.21. Coagulation with low-voltage continuous waveform ("cut"). The process of tissue coagulation is best achieved using a continuous low-voltage output.

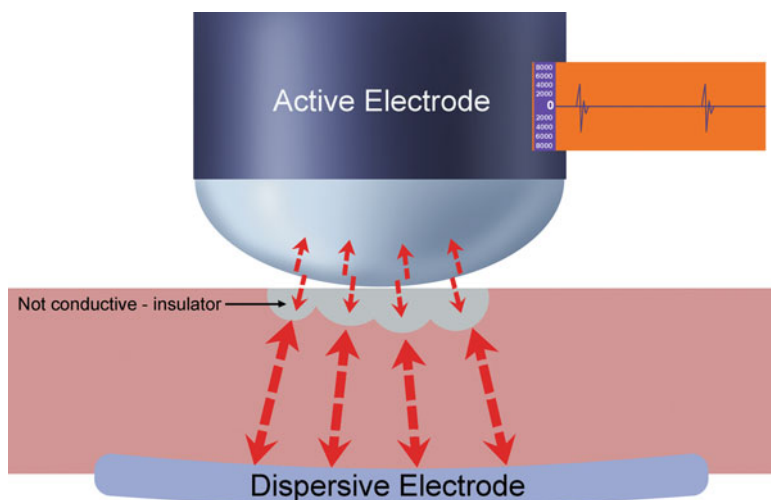


Fig. 2.22. Coagulation with modulated high-voltage waveform ("coag"). This figure demonstrates the impact of modulated high-voltage waveforms on tissue when coagulation is attempted. The intermittent output from the 6% duty cycle waveform causes a brief and superficial elevation of tissue temperature, sufficient to cause focal coagulation, desiccation, and, in many instances, carbonization. The next time a burst or arc returns to this area, the tissue impedance has risen sharply, so the current is blocked or diverts to a less impedant zone of tissue. This approach creates a superficial and inhomogeneous zone of desiccation and coagulation, not suitable for vessel sealing.

facilitates adherence of the electrode to tissue, allowing the eschar to be pulled off with removal of the electrode, a process that can disrupt the already suboptimal vessel seal and cause bleeding.

As a result of these considerations, coagulation should be performed with monopolar or bipolar instruments containing electrodes that have a relatively large surface area, and using the continuous and relatively low-voltage “cutting” waveform. If a blood vessel is to be coagulated, it should be first coapted by compressing it against adjacent tissue or, preferably, by grasping it with a forceps (Fig. 2.23). These maneuvers facilitate the formation of a vascular seal by preventing the flow of blood from removing heat from the site, and juxtapose the vessel walls, thereby allowing the vascular seal to be created.

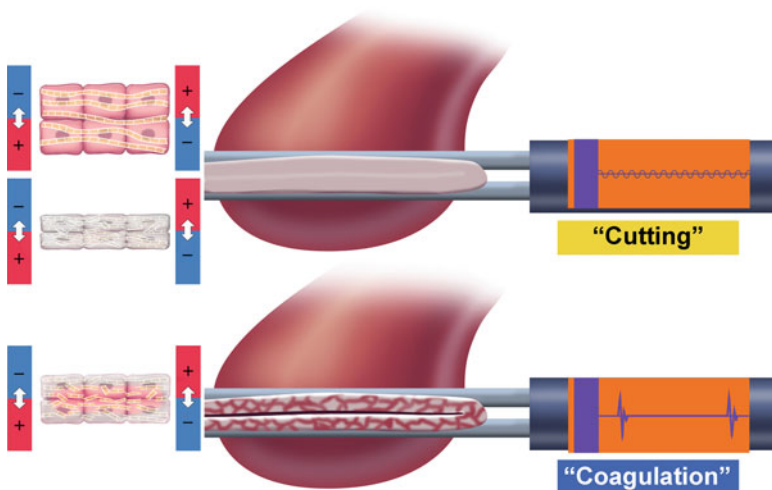


Fig. 2.23. Use low voltage (“cut”) to seal vessels. This figure demonstrates the difference between using low-voltage continuous outputs, and modulated high-voltage outputs when trying to seal a vessel. The low-voltage output (*top*) results in a homogenous vessel seal. The modulated high-voltage output (*bottom*) creates a superficial and inhomogeneous zone of desiccation and coagulation as well as carbonization and caramelization as proteins are reduced to sugars. This combination creates a poor vessel seal, and facilitates sticking of the tissue to the forceps, a process that facilitates disruption of the seal with forceps removal.

## Fulguration

Fulguration is a process whereby the tissue is superficially coagulated by repeated high-voltage electrosurgical arcs that continue to elevate the temperature by resistive heating to beyond  $100^{\circ}$ , reaching levels of  $200^{\circ}\text{C}$  and more. In addition to coagulation and desiccation, there is breakdown of the organic molecules into their atomic components including carbon that results in the addition of a dark hue to the coagulated tissue that is called “carbonization.” This process probably requires local temperatures of  $400^{\circ}\text{C}$  or more has also been described as *spray coagulation* or *black coagulation* (Fig. 2.24).

The process of arcing the current between the electrode and tissue is accomplished using the modulated high-voltage waveform labeled “coagulation” on most North American ESUs. Remember that this waveform has a very low duty cycle (typically 6%) but very high voltage that effectively manifests as pulses of high voltage current. The active electrode is held a few millimeters away from the tissue at a distance sufficient to allow ionization of the media in the electrode–tissue gap with subsequent establishment of visible arcs between the two structures

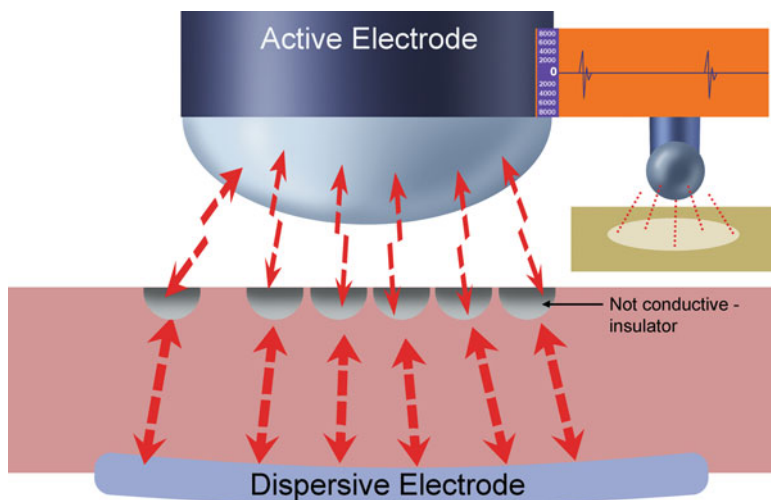


Fig. 2.24. Fulguration (“coag”). The process of fulguration is best performed with the high-voltage modulated outputs called “coag” on most ESUs. It is best to hold the electrode near to but not in contact with tissue. Care should be exercised as this arrangement can create an “open circuit” situation that can facilitate capacitive coupling.

(electrode and tissue). Unlike the case of low-voltage continuous current, the interrupted high-voltage discharges identify variable paths to the tissue and manifest in what appears to be a spraying effect onto an area of tissue that is much larger than the electrode itself. When a current pulse impacts a focal area of tissue, intracellular temperatures increase, but then reduce again because of the lack of sustained current in that focal area. The result is a relatively diffuse, inhomogeneous zone of elevated tissue temperature causing coagulation and carbonization that is limited to the superficial tissue layers, typically to a depth of about 0.5 mm. The rapid, superficial nature of this type of coagulation raises tissue impedance, inhibiting propagation of the thermal effect by preventing the current from including the deeper layers of the tissue. Consequently, this type of coagulation is most preferred for the arrest of capillary or small arteriolar bleeding over a large surface area.

## Variables Impacting the Tissue Effects of Electrosurgery

After the basic principles of electrosurgery are understood, the next step is to learn how to modify the tissue effects by changing one or more aspects of technique. Familiarity with these variables is essential for safe and effective application of RF electricity.

### *Power Density*

The power density is the total wattage striking the tissue per unit area of the electrode adjacent to or in contact with that tissue. This variable is of paramount importance in the performance of electrosurgery. Power density is determined by a combination of the shape and size of the electrode and the power settings and output of the ESU.

### Electrode Surface Area

As discussed previously, the power density required to vaporize tissue must be very high, which in turn requires the use of an electrode with a very small surface area. Some electrodes may be designed to serve a dual purpose. For example, a blade-shaped electrode may be employed as a cutting device if the blade's narrow edge is held near to the tissue, creating a zone of high power density. Alternatively, by placing the breadth of the blade in contact with the tissue, the resultant

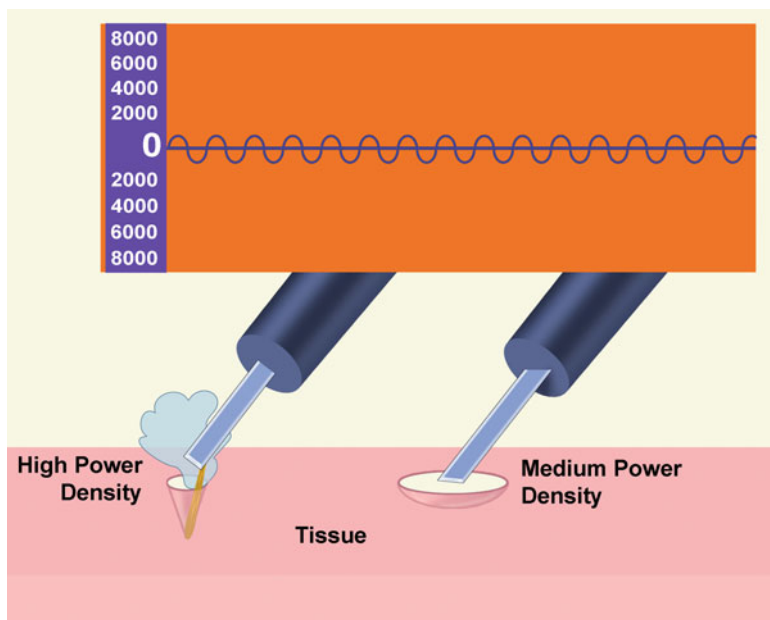


Fig. 2.25. Changing current/power density with a blade electrode. A blade electrode demonstrates that it is the current/power density, not the waveform, that is responsible for the difference between vaporization and coagulation. Using the same low-voltage output, the edge of the blade (*left*) focuses the current/power on the tissue while at the same output, the side of the blade defocuses the current/power. The result is vaporization/cutting with the blade edge and tissue desiccation/coagulation with the side of the blade.

lower power density can be used for coagulation (Fig. 2.25). Note that if the leading edge of the blade is used for cutting purposes, the flat sides may contact the edge of the incision as the electrode is passed through tissue, creating an additional degree of adjacent tissue coagulation. Depending upon the clinical situation, this effect may be either an advantage or disadvantage.

As discussed previously, the electrode at the other end of the power density spectrum is the *dispersive electrode*. Given the same power output and waveform, such electrodes properly attached to the patient dissipate the current so much that there is no thermal effect on cells and tissue.

Fulgurating electrodes are preferably similar to those designed for coagulation, or can be shaped in the form of a ball. This reduces the power density, and facilitates the spraying effect created by the high-voltage output.

## Electrosurgical Generator Power Output

An understanding of the output characteristics of the ESU will enable the surgeon more effectively to vary the power density. It is important to know that different generator brands have different output characteristics with varying peak voltages and variable duty cycles at the blend settings. These variables will, in many instances, affect subtleties of technique and the effect on tissue. Virtually all ESUs have a means by which the output in watts may be controlled or set. Contemporary ESUs have an LED screen that reveals the exact wattage, while older systems that may still be in use have a logarithmic scale from 1 (lowest) to 10 (highest), making exact settings and adjustments more difficult.

As discussed previously in this chapter, power output is proportional to both the voltage and current. In most instances, the appropriate power output for cutting will be the minimum amount necessary to create the power density at the electrode tip that results in desired combination of vaporization and coagulation. When using RF electricity to fashion an incision, more power means more voltage and increased coagulation adjacent to the cut area.

The voltage may be incrementally increased without changing the power settings by using “*blended waveforms*” with their increased peak voltage. Such waveforms result in greater thermal injury around an incision because the higher voltage pushes more joules of energy into tissue and the interrupted nature of the current dictates a slower cutting speed. This effect may be exploited when hemostasis is necessary along an incision line or when transecting tissue that has relatively high impedance.

## *Tissue Impedance or Resistance*

Whereas each component of an electrical circuit contributes to impedance, tissue impedance is the one most important to the surgeon. Highly conductive tissues have a high water content and offer little resistance to the passage of current and the creation of a desired tissue effect. However, it is the tissue itself that provides the greatest degree of variability. Tissue that offers high impedance is generally low in fluid content and therefore relatively nonconductive. Tissue such as bone, calloused skin, fat, or any previously desiccated tissue will impede passage of current and therefore will inhibit the creation of an electrosurgical effect.

If it is necessary to cut through tissue with relatively high impedance, increasing the voltage by raising the power output or decreasing the duty cycle is usually effective. In such cases, the current is pushed through the relatively resistant tissue with greater force.

## *Waveform*

The impact of RF energy on tissue effect is also related to the waveform of the output of the ESU. Throughout this chapter we have emphasized the fact that the labels of the settings on the ESU are frequently misleading (e.g., “cut,” “coagulation”), so an understanding of the underlying rationale is important. In addition, it should be emphasized that the “coagulation” output by virtue of its much higher voltage (typically 3× compared to “cutting” for a given wattage) is associated with higher risks of instrument insulation breakdown and current diversion. Consequently, in the few instances where such outputs are necessary, increased care should be taken to protect adjacent and surrounding tissue.

### High Voltage, Modulated, and Dampened (“Coagulation”)

The principle use of this modulated high-voltage waveform is for the process of *fulguration*. Some contemporary generators have a number of additional selections or controls that are labeled in a number of ways, such as “fulgurate” or “spray.” In general, “spray” has the lowest duty cycle and the highest peak voltage. As will be discussed in later chapters, and especially during laparoscopy, use of these high voltages should be selective and the operator should understand the increased risks of insulation damage and capacitive coupling.

There are circumstances when high-voltage waveforms may be useful or necessary for efficient cutting. One such instance occurs when it is necessary to transect high impedance surgical targets such as fat, scars, and tissue that are previously desiccated. In such circumstances, the surgeon can increase the wattage output on the ESU or an output of similar wattage can be selected with higher voltage such as the “blend” settings or the highly modulated “coagulation” output. Indeed, the waveform used for inert gas enhanced electrosurgery (e.g., Argon Beam Coagulator®) is a modulated high-voltage output.

## *Low-Voltage Continuous or Modulated (“Cutting”)*

The low-voltage continuous outputs are generally the most efficient and effective for either cutting (linear vaporization) or for coagulation/desiccation, including sealing blood vessels.

For tissue transection, the continuous low-voltage outputs (“cut”) are generally both effective and safe. As previously stated, higher-voltage waveforms may be necessary when it is necessary to cut high impedance surgical targets such as fat, scars, and tissue that are previously desiccated. In such circumstances, the “blend” settings provide a slightly higher voltage and are an alternative to increasing the power output.

As described previously in this chapter, when the desired tissue effect is coagulation the generator output should be the low-voltage continuous output provided by the “cut” setting. Such waveforms, by virtue of their low voltage and continuous output, provide the most homogenous and deep coagulation and desiccation, and, therefore, are the best for creating a vascular seal. For proprietary bipolar systems, such outputs are intrinsically set—the surgeon has no control, and for the vast majority of generic ESUs, the bipolar outputs are also predetermined to have continuous low-voltage output (despite the “blue” color coding applied to most North American systems). However, when using unipolar instruments for coagulation, regardless of the approach (laparoscopic or laparotomic) the “yellow” low-voltage “cut” setting should be selected when sealing blood vessels.

## *Time on or Near Tissue*

The amount of energy imparted to a given volume of tissue is directly related to the time the activated electrode is near to or in contact with that tissue, provided the voltage is low enough to prevent proximal coagulation, as discussed above. The circumstance is somewhat obvious for tissue coagulation, but it can impact the tissue effects of cutting as well. For example, if, when used for cutting, the electrode is moved very slowly through tissue, there will occur a greater degree of collateral thermal injury. However, moving the electrode too quickly will also result in increased thermal injury if the electrode moves ahead of the steam or vapor cloud and touches the tissue reducing the power density causing coagulation (Fig. 2.20).

## *Electrode–Tissue Relationships*

An important factor in the performance of electrosurgery is the relationship of the active electrode to the target tissue. For the process of cutting, which we are portraying as linear vaporization, the relationship between the electrode and tissue could be described as *near-contact*. In this relationship, the current arcs between the active electrode and the tissue within the steam envelope generated by the vaporized intracellular contents. If the electrode is held too far from the tissue, no arcing and, therefore, no vaporization will occur. On the other hand, if the electrode touches the tissue, the power density decreases and coagulation will occur, creating a greater degree of thermal injury to the tissue adjacent to the incision line.

As previously described, fulguration is also a non- or near-contact electrosurgical activity facilitated by the use of the high-voltage, modulated waveform, usually with a short (e.g., 6%) duty cycle. Because of the higher voltage, the electrode can be held a millimeter or more from the target, while the current is “sprayed” onto the tissue. The distance that the electrode is held from the tissue is dependent in part upon the specific generator and the peak voltage in the “coagulation” setting.

For practical purposes, the processes of clinically effective white coagulation and desiccation are best achieved when there is contact between the electrode and the tissue. Implicitly, such electrodes have a flattened surface that facilitates creation of the required lower power density. In most instances, the instruments (both bipolar and monopolar) are designed as articulated grasping forceps that can compress the tissue between their jaws thereby coapting blood vessels to facilitate hemostatic sealing when activated, a process called coaptive coagulation.

Another important concept is compressed tissue volume. The larger the tissue thickness between the jaws of an RF electrosurgical instrument, regardless of its fundamental design (monopolar or bipolar), the greater the number of Joules of energy that will be required for complete coagulation and desiccation. What this means is that thicker pedicles will result in more lateral extension of the electrosurgical thermal injury, a factor that may be enhanced with monopolar instruments. Such an effect may have little clinical relevance in some situations, but, when operating near vital structures, injury could occur.

## *Media Between Electrode and Tissue*

An often-forgotten component of the electrical circuit is the medium that exists between the electrode and the tissue, provided near-contact technique is used. The arc between electrode and tissue occurs only when the electrical field between the active electrode and the tissue becomes strong enough to ionize the intervening medium. These ions collide with other molecules until the charge crosses the gap between electrode and tissue, completing the circuit (Fig. 2.26).

Different media possess varying ionizing capabilities. For example, the CO<sub>2</sub> medium employed for most laparoscopy cases is only 70% as effective as room air at transmitting a charge. On the other hand, the

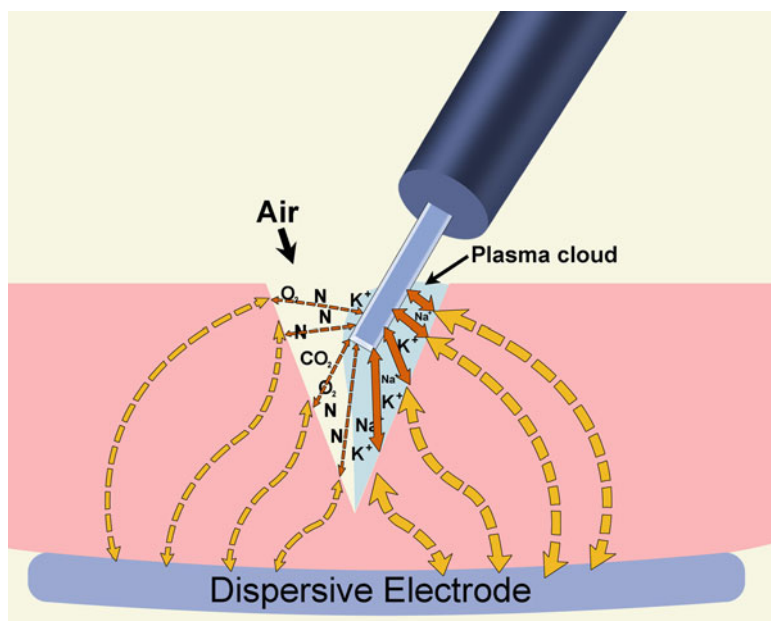


Fig. 2.26. Media and electrosurgery. The electrical properties of the media (air, CO<sub>2</sub>, water, saline, etc.) around the active electrode are included in the electrical circuit, especially if the electrode is held off the tissue. Consequently, the impedance in a steam envelope or “plasma cloud” that includes sodium, potassium, and other ions (*right side above*), is much lower than that of air that is largely nitrogen and oxygen or especially carbon dioxide that comprises most laparoscopic environments. With monopolar systems, saline or blood around the electrode can make it function like a dispersive electrode, severely impeding performance.

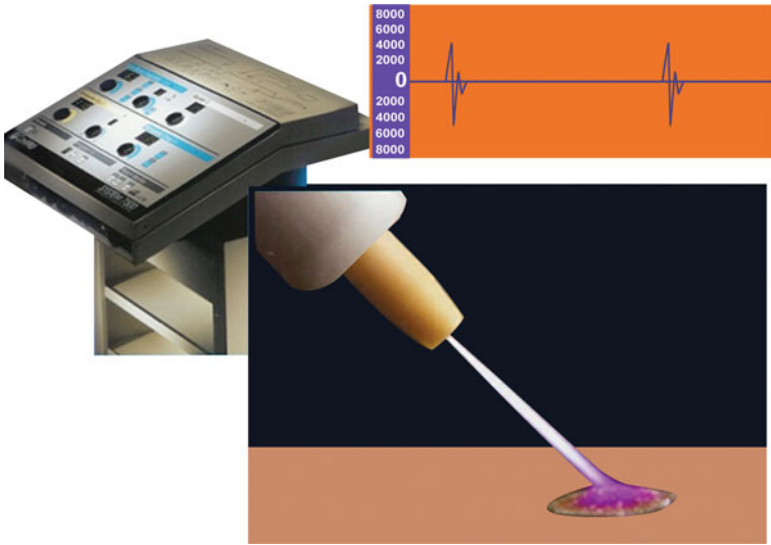


Fig. 2.27. Argon beam coagulator. Argon interposed between the electrode and the tissue is a medium that facilitates arcing of the current between the target and the active electrode. This is exploited in the argon beam coagulator and other similar systems that actually use a modulated low-voltage output to cut tissue at a distance from the electrode. The current ionizes the otherwise inert argon gas, creating a zone of low impedance through the air between the active electrode and the tissue.

plasma cloud that results from cellular vaporization contains large numbers of ions, a feature that makes it highly conductive. Argon gas also promotes conductivity of electrical current, a feature that is exploited by the Argon Beam Coagulator (Fig. 2.27), which is essentially an instrument that allows arcing of high-voltage outputs to occur from a distance of 1 to 2 cm.

### Other Important Variables

There are other concepts important for the effective use of electrosurgery. For example, active electrodes must be kept shiny and free of carbon, as carbon deposits act as insulators impeding the flow of current. In addition, a moist electrode and tissue will facilitate the formation of the steam envelope necessary for effective vaporization and cutting, a characteristic exploited in electromicrosurgery.

## Summary

RF electrosurgery used appropriately allows the surgeon to perform a wide spectrum of procedures safely, effectively, and with minimal undesired tissue trauma. Used without proper care, education, and training, electrosurgery, like other instruments and energy sources, has the potential to cause excessive tissue trauma, and increased operative morbidity, sometimes of a life-threatening nature. This chapter provides the reader with a fundamental knowledge of the scientific principles of RF electrosurgery that will facilitate understanding of the systems and techniques discussed elsewhere in this volume.

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