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Electrosurgical Devices

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An electrosurgical unit (ESU) passes high-frequency electric currents through biologic tissues to achieve specific surgical effects such as cutting, coagulation, or desiccation. Although it is not completely understood how electrosurgery works, it has been used since the 1920s to cut tissue effectively while at the same time controlling the amount of bleeding. Cutting is achieved primarily with a continuous sinusoidal waveform, whereas coagulation is achieved primarily with a series of sinusoidal wave packets. The surgeon selects either one of these waveforms or a blend of them to suit the surgical needs. An electrosurgical unit can be operated in two modes, the monopolar mode and the bipolar mode. The most noticeable difference between these two modes is the method in which the electric current enters and leaves the tissue. In the monopolar mode, the current flows from a small active electrode into the surgical site, spreads through the body, and returns to a large dispersive electrode on the skin. The high current density in the vicinity of the active electrode achieves tissue cutting or coagulation, whereas the low current density under the dispersive electrode causes no tissue damage. In the bipolar mode, the current flows only through the tissue held between two forceps electrodes. The monopolar mode is used for both cutting and coagulation. The bipolar mode is used primarily for coagulation.

This chapter beings with the theory of operation for electrosurgical units, outlines various modes of operation, and gives basic design details for electronic circuits and electrodes. It then describes how improper application of electrosurgical units can lead to hazardous situations for both the operator and the patient and how such hazardous situations can be avoided or reduced through proper monitoring methods. Finally, the chapter gives an update on current and future developments and applications.

81.1 Theory of Operation

In principle, electrosurgery is based on the rapid heating of tissue. To better understand the thermodynamic events during electrosurgery, it helps to know the general effects of heat on biologic tissue. Consider a tissue volume that experiences a temperature increase from normal body temperature to 45°C within a few seconds. Although the cells in this tissue volume show neither microscopic nor macroscopic changes, some cytochemical changes do in fact occur. However, these changes are reversible, and the cells return to their normal function when the temperature returns to normal values. Above 45°C, irreversible changes take place that inhibit normal cell functions and lead to cell death. First, between 45°C and 60°C, the proteins in the cell lose their quaternary configuration and solidify into a glutinous substance that resembles the white of a hard-boiled egg. This process, termed *coagulation,* is accompanied by tissue blanching. Further increasing the temperature up to 100°C leads to tissue drying; that is, the aqueous cell contents evaporate. This process is called *desiccation.* If the temperature is increased beyond 100°C, the solid contents of the tissue reduce to carbon, a process referred to as *carbonization.* Tissue damage depends not only on temperature, however, but also on the length of exposure to heat. Thus, the overall temperature-induced tissue damage is an integrative effect between temperature and time that is expressed mathematically by the Arrhenius relationship, where an exponential function of temperature is integrated over time [1].

In the monopolar mode, the active electrode either touches the tissue directly or is held a few millimeters above the tissue. When the electrode is held above the tissue, the electric current bridges the air gap by creating an electric discharge arc. A visible arc forms when the electric field strength exceeds 1 kV/mm in the gap and disappears when the field strength drops below a certain threshold level.

When the active electrode touches the tissue and the current flows directly from the electrode into the tissue without forming an arc, the rise in tissue temperature follows the bioheat equation

$$T - T_o = \frac{1}{\sigma \rho c} J^2 t \tag{81.1}$$

where T and T_o are the final and initial temperatures (K), σ is the electrical conductivity (S/m), ρ is the tissue density (kg/m^3), c is the specific heat of the tissue (Jkg^{-1}K^{-1}), J is the current density (A/m^2), and t is the duration of heat applications [1]. The bioheat equation is valid for short application times where secondary effects such as heat transfer to surrounding tissues, blood perfusion, and metabolic heat can be neglected. According to Eq. (81.1), the surgeon has primarily three means of controlling the cutting or coagulation effect during electrosurgery: the contact area between active electrode and tissue, the electrical current density, and the activation time. In most commercially available electrosurgical generators, the output variable that can be adjusted is power. This power setting, in conjunction with the output power vs. tissue impedance characteristics of the generator, allow the surgeon some control over current. Table 81.1 lists typical output power and mode settings for various surgical procedures. Table 81.2 lists some typical impedance ranges seen during use of an ESU in surgery. The values are shown as ranges because the impedance increases as the tissue dries out, and at the same time, the output power of the ESU decreases. The surgeon may control current density by selection of the active electrode type and size.

81.2 Monopolar Mode

A continuous sinusoidal waveform cuts tissue with very little hemostasis. This waveform is simply called *cut* or *pure cut.* During each positive and negative swing of the sinusoidal waveform, a new discharge arc forms and disappears at essentially the same tissue location. The electric current concentrates at this tissue location, causing a sudden increase in temperature due to resistive heating. The rapid rise in temperature then vaporizes intracellular fluids, increases cell pressure, and ruptures the cell membrane, thereby parting the tissue. This chain of events is confined to the vicinity of the arc, because from there the electric current spreads to a much larger tissue volume, and the current density is no longer high enough to cause resistive heating damage. Typical output values for ESUs, in cut and other modes, are shown in Table 81.3.

Experimental observations have shown that more hemostasis is achieved when cutting with an interrupted sinusoidal waveform or amplitude modulated continuous waveform. These waveforms are typically called *blend* or *blended cut.* Some ESUs offer a choice of blend waveforms to allow the surgeon to select the degree of hemostasis desired.

Table 81.1 Typical ESU Power Settings for Various Surgical Procedures

Power-Level Range	Procedures
Low power	
<30 W cut	Neurosurgery
<30 W coag	Dermatology
	Plastic surgery
	Oral surgery
	Laparoscopic sterilization
	Vasectomy
Medium power	
30 W–150 W cut	General surgery
30 W–70 W coag	Laparotomies
	Head and neck surgery (ENT)
	Major orthopedic surgery
	Major vascular surgery
	Routine thoracic surgery
	Polypectomy
High power	
>150 W cut	Transurethral resection procedures (TURPs)
>70 W coag	Thoracotomies
	Ablative cancer surgery
	Mastectomies

Note: Ranges assume the use of a standard blade electrode. Use of a needle electrode, or other small current-concentrating electrode, allows lower settings to be used; users are urged to use the lowest setting that provides the desired clinical results.

TABLE 81.2 Typical Impedance Ranges Seen During Use of an ESU in Surgery

Cut Mode Application	Impedance Range (Ω)
Prostate tissue	400–1700
Oral cavity	1000–2000
Liver tissue	
Muscle tissue	
Gall bladder	1500–2400
Skin tissue	1700–2500
Bowel tissue	2500–3000
Periosteum	
Mesentery	3000–4200
Omentum	
Adipose tissue	3500–4500
Scar tissue	
Adhesions	
Coag Mode Application	
Contact coagulation to stop bleeding	100–1000

When a continuous or interrupted waveform is used in contact with the tissue and the output voltage current density is too low to sustain arcing, desiccation of the tissue will occur. Some ESUs have a distinct mode for this purpose called *desiccation* or *contact coagulation.*

In noncontact coagulation, the duty cycle of an interrupted waveform and the crest factor (ratio of peak voltage to rms voltage) influence the degree of hemostasis. While a continuous waveform reestablishes the arc at essentially the same tissue location concentrating the heat there, an interrupted waveform

TABLE 81.3 Typical Output Characteristics of ESUs

	Output Voltage Range Open Circuit, $V_{peak\text{-}peak}$, V	Output Power Range, W	Frequency, kHz	Crest Factor $\left(\frac{V_{peak}}{V_{rms}}\right)$	Duty Cycle
Monopolar modes					
Cut	200–5000	1–400	300–1750	1.4–2.1	100%
Blend	1500–5800	1–300	300–1750	2.1–6.0	25–80%
Desiccate	400–6500	1–200	240–800	3.5–6.0	50–100%
Fulgurate/spray	6000–12000	1–200	300–800	6.0–20.0	10–70%
Bipolar mode					
Coagulate/desiccate	200–1000	1–70	300–1050	1.6–12.0	25–100%

causes the arc to reestablish itself at different tissue locations. The arc seems to dance from one location to the other raising the temperature of the top tissue layer to coagulation levels. These waveforms are called *fulguration* or *spray.* Since the current inside the tissue spreads very quickly from the point where the arc strikes, the heat concentrates in the top layer, primarily desiccating tissue and causing some carbonization. During surgery, a surgeon can easily choose between cutting, coagulation, or a combination of the two by activating a switch on the grip of the active electrode or by use of a footswitch.

81.3 Bipolar Mode

The bipolar mode concentrates the current flow between the two electrodes, requiring considerably less power for achieving the same coagulation effect than the monopolar mode. For example, consider coagulating a small blood vessel with 3-mm external diameter and 2-mm internal diameter, a tissue resistivity of 360 Ωcm, a contract area of 2 × 4 mm, and a distance between the forceps tips of 1 mm. The tissue resistance between the forceps is 450 Ω as calculated from $R = \rho L/A$, where ρ is the resistivity, L is the distance between the forceps, and A is the contact area. Assuming a typical current density of 200 mA/cm^2, then a small current of 16 mA, a voltage of 7.2 V, and a power level of 0.12 W suffice to coagulate this small blood vessel. In contrast, during monopolar coagulation, current levels of 200 mA and power levels of 100 W or more are not uncommon to achieve the same surgical effect. The temperature increase in the vessel tissue follows the bioheat equation, Eq. (81.1). If the specific heat of the vessel tissue is 4.2 $Jg^{-1}\kappa^{-1}$ and the tissue density is 1 g/cm^3, then the temperature of the tissue between the forceps increases from 37°C to 57°C in 5.83 s. When the active electrode touches the tissue, less tissue damage occurs during coagulation, because the charring and carbonization that accompanies fulguration is avoided.

81.4 ESU Design

Modern ESUs contain building blocks that are also found in other medical devices, such as microprocessors, power supplies, enclosures, cables, indicators, displays, and alarms. The main building blocks unique to ESUs are control input switches, the high-frequency power amplifier, and the safety monitor. The first two will be discussed briefly here, and the latter will be discussed later.

Control input switches include front panel controls, footswitch controls, and handswitch controls. In order to make operating an ESU more uniform between models and manufacturers, and to reduce the possibility of operator error, the ANSI/AAMI HF-18 standard [5] makes specific recommendations concerning the physical construction and location of these switches and prescribes mechanical and electrical performance standards. For instance, front panel controls need to have their function identified by a permanent label and their output indicated on alphanumeric displays or on graduated scales; the pedals of foot switches need to be labeled and respond to a specified activation force; and if the active electrode handle incorporates two finger switches, their position has to correspond to a specific function. Additional recommendations can be found in Reference [5].

Four basic high-frequency power amplifiers are in use currently; the somewhat dated vacuum tube/spark gap configuration, the parallel connection of a bank if bipolar power transistors, the hybrid connection of parallel bipolar power transistors cascaded with metal oxide silicon field effect transistors (MOSFETs), and the bridge connection of MOSFETs. Each has unique properties and represents a stage in the evolution of ESUs.

In a vacuum tube/spark gap device, a tuned-plate, tuned-grid vacuum tube oscillator is used to generate a continuous waveform for use in cutting. This signal is introduced to the patient by an adjustable isolation transformer. To generate a waveform for fulguration, the power supply voltage is elevated by a step-up transformer to about 1600 V rms which then connects to a series of spark gaps. The voltage across the spark gaps is capacitively coupled to the primary of an isolation transformer. The RLC circuit created by this arrangement generates a high crest factor, damped sinusoidal, interrupted waveform. One can adjust the output power and characteristics by changing the turns ratio or tap on the primary and/or secondary side of the isolation transformer, or by changing the spark gap distance.

In those devices that use a parallel bank of bipolar power transistors, the transistors are arranged in a Class A configuration. The bases, collectors, and emitters are all connected in parallel, and the collective base node is driven through a current-limiting resistor. A feedback RC network between the base node and the collector node stabilizes the circuit. The collectors are usually fused individually before the common node connects them to one side of the primary of the step-up transformer. The other side of the primary is connected to the high-voltage power supply. A capacitor and resistor in parallel to the primary create a resonance tank circuit that generates the output waveform at a specific frequency. Additional elements may be switched in and out of the primary parallel RLC to alter the output power and waveform for various electrosurgical modes. Small-value resistors between the emitters and ground improve the current sharing between transistors. This configuration sometimes requires the use of matched sets of high-voltage power transistors.

A similar arrangement exists in amplifiers using parallel bipolar transistors cascaded with a power MOSFET. This arrangement is called a *hybrid cascode amplifier*. In this type of amplifier, the collectors of a group if bipolar transistors are connected, via protection diodes, to one side of the primary of the step-up output transformer. The other side of the primary is connected to the high-voltage power supply. The emitters of two or three bipolar transistors are connected, via current limiting resistors, to the drain of an enhancement mode MOSFET. The source of the MOSFET is connected to ground, and the gate of the MOSFET is connected to a voltage-snubbing network driven by a fixed amplitude pulse created by a high-speed MOS driver circuit. The bases of the bipolar transistors are connected, via current control RC networks, to a common variable base voltage source. Each collector and base is separately fused. In cut modes, the gate drive pulse is a fixed frequency, and the base voltage is varied according to the power setting. In the coagulation modes, the base voltage is fixed and the width of the pulses driving the MOSFET is varied. This changes the conduction time of the amplifier and controls the amount of energy imparted to the output transformer and its load. In the coagulation modes and in high-power cut modes, the bipolar power transistors are saturated, and the voltage across the bipolar/MOSFET combination is low. This translates to high efficiency and low power dissipation.

The most common high-frequency power amplifier in use is a bridge connection of MOSFETs. In this configuration, the drains of a series of power MOSFETs are connected, via protection diodes, to one side of the primary of the step-up output transformer. The drain protection diodes protect the MOSFETs against the negative voltage swings of the transformer primary. The other side of the transformer primary is connected to the high-voltage power supply. The sources of the MOSFETs are connected to ground. The gate of each MOSFET has a resistor connected to ground and one to its driver circuitry. The resistor to ground speeds up the discharge of the gate capacitance when the MOSFET is turned on while the gate series resistor eliminates turn-off oscillations. Various combinations of capacitors and/or LC networks can be switched across the primary of the step-up output transformer to obtain different waveforms. In the cut mode, the output power is controlled by varying the high-voltage power supply voltage. In the coagulation mode, the output power is controlled by varying the on time of the gate drive pulse.

81.5 Active Electrodes

The monopolar active electrode is typically a small flat blade with symmetric leading and trailing edges that is embedded at the tip of an insulated handle. The edges of the blade are shaped to easily initiate discharge arcs and to help the surgeon manipulate the incision; the edges cannot mechanically cut tissue. Since the surgeon holds the handle like a pencil, it is often referred to as the "pencil." Many pencils contain in their handle one or more switches to control the electrosurgical waveform, primarily to switch between cutting and coagulation. Other active electrodes include needle electrodes, loop electrodes, and ball electrodes. Needle electrodes are used for coagulating small tissue volumes like in neurosurgery or plastic surgery. Loop electrodes are used to resect nodular structures such as polyps or to excise tissue samples for pathologic analysis. An example would be the LLETZ procedure where the transition zone of the cervix is excised. Electrosurgery at the tip of an endoscope or laparoscope requires yet another set of active electrodes and specialized training of the surgeon.

81.6 Dispersive Electrodes

The main purpose of the dispersive electrode is to return the high-frequency current to the electrosurgical unit without causing harm to the patient. This is usually achieved by attaching a large electrode to the patient's skin away from the surgical site. The large electrode area and a small contact impedance reduce the current density to levels where tissue heating is minimal. Since the ability of a dispersive electrode to avoid tissue heating and burns is of primary importance, dispersive electrodes are often characterized by their *heating factor.* The heating factor describes the energy dissipated under the dispersive electrode per Ω of impedance and is equal to I^2t, where I is the rms current and t is the time of exposure. During surgery a typical value for the heating factor is 3 A^2s, but factors of up to 9 A^2s may occur during some procedures [2].

Two types of dispersive electrodes are in common use today, the resistive type and the capacitive type. In disposable form, both electrodes have a similar structure and appearance. A thin, rectangular metallic foil has an insulating layer on the outside, connects to a gel-like material on the inside, and may be surrounded by an adhesive foam. In the resistive type, the gel-like material is made of an adhesive conductive gel, whereas in the capacitive type, the gel is an adhesive dielectric nonconductive gel. The adhesive foam and adhesive gel layer ensure that both electrodes maintain good skin contact to the patient, even if the electrode gets stressed mechanically from pulls on the electrode cable. Both types have specific advantages and disadvantages. Electrode failures and subsequent patient injury can be attributed mostly to improper application, electrode dislodgment, and electrode defects rather than to electrode design.

81.7 ESU Hazards

Improper use of electrosurgery may expose both the patient and the surgical staff to a number of hazards. By far the most frequent hazards are electric shock and undesired burns. Less frequent are undesired neuromuscular stimulation, interference with pacemakers or other devices, electrochemical effects from direct currents, implant heating, and gas explosions [1,3].

Current returns to the ESU through the dispersive electrode. If the contact area of the dispersive electrode is large and the current exposure time short, then the skin temperature under the electrode does not rise above 45°C, which has been shown to be the maximum safe temperature [4]. However, to include a safety margin, the skin temperature should not rise more than 6°C above the normal surface temperature of 29–33°C. The current density at any point under the dispersive electrode has to be significantly below the recognized burn threshold of 100 mA/cm^2 for 10 seconds.

To avoid electric shock and burns, the American National Standard for Electrosurgical Devices [5] requires that "any electrosurgical generator that provides for a dispersive electrode and that has a rated output power of greater than 50 W shall have at least one patient circuit safety monitor." The most common safety monitors are the contact quality monitor for the dispersive electrode and the patient circuit monitor. A contact quality monitor consists of a circuit to measure the impedance between the two sides of a split dispersive electrode and the skin. A small high-frequency current flows from one section of the dispersive electrode through the skin to the second section of the dispersive electrode. If the impedance between these two sections exceeds a certain threshold, or changes by a certain percentage, an audible alarm sounds, and the ESU output is disabled.

Patient circuit monitors range from simple to complex. The simple ones monitor electrode cable integrity while the complex ones detect any abnormal condition that could result in electrosurgical current flowing in other than normal pathways. Although the output isolation transformer present in most modern ESUs usually provides adequate patient protection, some potentially hazardous conditions may still arise. If a conductor to the dispersive electrode is broken, undesired arcing between the broken conductor ends may occur, causing fire in the operating room and serious patient injury. Abnormal current pathways may also arise from capacitive coupling between cables, the patient, operators, enclosures, beds, or any other conductive surface or from direct connections to other electrodes connected to the patient. The patient circuit monitoring device should be operated from an isolated power source having a maximum voltage of 12 V rms. The most common device is a cable continuity monitor. Unlike the contact quality monitor, this monitor only checks the continuity of the cable between the ESU and the dispersive electrode and sounds an alarm if the resistance in that conductor is greater than 1 kΩ. Another implementation of a patient circuit monitor measures the voltage between the dispersive electrode connection and ground. A third implementation functions similarly to a ground fault circuit interrupter (GFCI) in that the current in the wire to the active electrode and the current in the wire to the dispersive electrode are measured and compared with each other. If the difference between these currents is greater than a preset threshold, the alarm sounds and the ESU is disconnected.

There are other sources of undesired burns. Active electrodes get hot when they are used. After use, the active electrode should be placed in a protective holster, if available, or on a suitable surface to isolate it from the patient and surgical staff. The correct placement of an active electrode will also prevent the patient and/or surgeon from being burned if an inadvertent activation of the ESU occurs (e.g., someone accidentally stepping on a foot pedal). Some surgeons use a practice called *buzzing the hemostat* in which a small bleeding vessel is grasped with a clamp or hemostat and the active electrode touched to the clamp while activating. Because of the high voltages involved and the stray capacitance to ground, the surgeon's glove may be compromised. If the surgical staff cannot be convinced to eliminate the practice of buzzing hemostats, the probability of burns can be reduced by use of a cut waveform instead of a coagulation waveform (lower voltage), by maximizing contact between the surgeon's hand and the clamp, and by not activating until the active electrode is firmly touching the clamp.

Although it is commonly assumed that neuromuscular stimulation ceases or is insignificant at frequencies above 10 kHz, such stimulation has been observed in anesthetized patients undergoing certain electrosurgical procedures. This undesirable side effect of electrosurgery is generally attributed to nonlinear events during the electric arcing between the active electrode and tissue. These events rectify the high-frequency current leading to both dc and low-frequency current components. These current components can reach magnitudes that stimulate nerve and muscle cells. To minimize the probability of unwanted neuromuscular stimulation, most ESUs incorporate in their output circuit a high-pass filter that suppresses dc and low-frequency current components.

The use of electrosurgery means the presence of electric discharge arcs. This presents a potential fire hazard in an operating room where oxygen and flammable gases may be present. These flammable gases may be introduced by the surgical staff (anesthetics or flammable cleaning solutions), or may be generated within the patients themselves (bowel gases). The use of disposable paper drapes and dry surgical gauze also provides a flammable material that may be ignited by sparking or by contact with a hot active electrode. Therefore, prevention of fires and explosions depends primarily on the prudence and judgment of the ESU operator.

81.8 Recent Developments

Electrosurgery is being enhanced by the addition of a controlled column of argon gas in the path between the active electrode and the tissue. The flow of argon gas assists in clearing the surgical site of fluid and improves visibility. When used in the coagulation mode, the argon gas is turned into a plasma allowing tissue damage and smoke to be reduced, and producing a thinner, more flexible eschar. When used with the cut mode, lower power levels may be used.

Many manufacturers have begun to include sophisticated computer-based systems in their ESUs that not only simplify the use of the device but also increase the safety of patient and operator [7]. For instance, in a so-called soft coagulation mode, a special circuit continuously monitors the current between the active electrode and the tissue and turns the ESU output on only after the active electrode has contacted the tissue. Furthermore, the ESU output is turned off automatically, once the current has reached a certain threshold level that is typical for coagulated and desiccated tissue. This feature is also used in a bipolar mode termed *autobipolar.* Not only does this feature prevent arcing at the beginning of the procedure, but it also keeps the tissue from being heated beyond 70°C. Some devices offer a so-called power-peak-system that delivers a very short power peak at the beginning of electrosurgical cutting to start the cutting arc. Other modern devices use continuous monitoring of current and voltage levels to make automatic power adjustments in order to provide for a smooth cutting action from the beginning of the incision to its end. Some manufacturers are developing waveforms and instruments designed to achieve specific clinical results such as bipolar cutting tissue lesioning, and vessel sealing. With the growth and popularity of laparoscopic procedures, additional electrosurgical instruments and waveforms tailored to this surgical specialty should also be expected.

Increased computing power, more sophisticated evaluation of voltage and current waveforms, and the addition of miniaturized sensors will continue to make ESUs more user-friendly and safer.

Defining Terms

Active electrode: Electrode used for achieving desired surgical effect.

Coagulation: Solidification of proteins accompanied by tissue whitening.

Desiccation: Drying of tissue due to the evaporation of intracellular fluids.

Dispersive electrode: Return electrode at which no electrosurgical effect is intended.

Fulguration: Random discharge of sparks between active electrode and tissue surface in order to achieve coagulation and/or desiccation.

Spray: Another term for **fulguration.** Sometimes this waveform has a higher crest factor than that used for fulguration.

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