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"Current thoughts" in electrosurgery

K. Wang, A.P. Advincula *

Department of Obstetrics and Gynecology, University of Michigan Medical Center, USA

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Abstract The ongoing desire to improve hemostasis and efficiency during surgery is manifested in the rapid development of electrosurgical technology. These changes have brought about a wide variety of devices available to the practicing surgeon during both open and endoscopic cases. Depending on the instrument chosen, various clinical effects ranging from simple coagulation to the sealing of large vascular bundles are obtained. However potential pitfalls or complications also exist. A thorough understanding of the pros and cons of these technological advancements can improve the operative experience for both surgeon and patient.

1. Introduction

The concept of using heat to stop bleeding goes back hundreds of years. As technology evolved, a variety of devices which used electricity as a means to heat tissue and control bleeding were created. These advancements eventually developed into modern-day electrosurgery. Having replaced the use of the laser as the most commonly used power supply of today, this energy source facilitates surgery by offering a means to dissect and cauterize tissue more efficiently. It is used in all surgical specialties to minimize blood loss and reduce surgical time. Through the years, researchers have worked to improve this energy modality-minimizing adverse effects while enhancing its execution both in open and endoscopic cases.

* Corresponding author. Minimally Invasive Surgery Program and Fellowship, Department of Obstetrics and Gynecology, University of Michigan Medical Center, L 4000 Women's Hospital, 1500 East Medical Center Drive Ann Arbor, MI 48109, USA. Tel.: +1 734 764 8429; fax: +1 734 647 9727.

E-mail address: aadvincu@umich.edu (A.P. Advincula).

2. History of electrosurgery

While the current techniques of electrosurgery were not developed until the early 20th century, its conception began in the early 19th century when French physicist, Becqueral first used electrocautery. Rather than using boiled oil to achieve hemostasis, he passed direct current (D.C.) through a wire thereby heating it and effectively cauterizing tissue upon contact. In 1881, an important development in electrosurgery occurred when D'Arsonoval pioneered the use of an alternating electrical current (A.C.). This French biophysicist discovered that at a higher frequency, alternating electrical current could pass through the human body without causing painful electrical shock. Rather than causing muscle stimulation, electrical current at a frequency of 200 kHz or higher generated heat in tissue.

Between 1890 and 1910, Nagelschmidt, a German physician, first introduced the concept of "diathermy" to explain how high frequency electrical current created heat in the body through the agitation of molecules. In other words, excited cellular ions collided with each other and released energy in the form of heat. Applying this knowledge, he then developed diathermy machines that were capable of producing the following therapeutic tissue effects: fulguration, desiccation, and cutting. It was not until the late 1920's that collaboration

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between physicist, William T. Bovie and neurosurgeon, Harvey Cushing resulted in the predecessor of today's electrosurgical units. This prototype offered a means to prevent death from hemorrhage in the operating room during surgery for vascular brain tumors by offering a tool for both cutting and coagulation. This electrosurgical unit model was used until 1968 when a smaller model was developed by Valleylab, a company which has since produced today's platform of electrosurgical units [1].

3. Mechanism

To comprehend the mechanism of electrosurgery, one must understand the basics of electricity. Atoms are composed of electrons, protons, and neutrons [2]. Electrical current flows when electrons from one atom move to an adjacent atom through a circuit. Voltage is the necessary force that mediates or drives this electron movement. Heat is produced when electrons encounter resistance. In order for current to flow, a continuous circuit is needed. All of this leads to three basic principles of electricity: 1) electricity always takes the path of least resistance, 2) electricity always seeks ground, and 3) electricity must have a complete circuit to do work. Much of the understanding of how electrosurgery works and its associated complications is rooted in these absolutes.

In the operating room, this circuit is composed of the patient, electrosurgical generator, and the active and return electrodes. The electrosurgical unit is the source of the voltage. As the active electrode conducts electrons to the patient, the patient's tissue provides resistance (impedance) to current flow, thereby producing heat and the resulting tissue effect. Finally, the electrons return to the electrosurgical unit through either the conducting instrument itself or a patient return electrode [2–4].

Modern-day electrosurgery is the utilization of alternating electrical current at radiofrequency levels. This current passes through a conductive element to the target tissue in order to achieve certain surgical effects [3]. Electrical energy is converted to heat in tissue as the tissue resists the flow of current from the electrode. Three clinical tissue effects are possible with today's electrosurgical units — cutting, fulguration, and desiccation [5]. Achieving these effects depend on the following factors: current density, time, electrode size, tissue conductivity, and type of current waveform [4,6].

3.1. Current density

As expected, the greater the current that passes through an area, the greater the effect will be on the tissue. Also, the greater the amount of heat that is produced by the current, the greater the thermal damage on tissue.

3.2. Time

The length of time a surgeon uses an active electrode determines the amount of tissue effect. Too long an activation will produce wider and deeper tissue damage. The converse is also true and will result in an absence of the desired tissue effect if activation time is too short. Similarly, the speed with which an electrode is moved will result in either less or more coagulation and thermal spread.

3.3. Electrode size

With respect to electrode size, smaller electrodes provide a higher current density and result in a concentrated heating effect at the site of tissue contact. For example, a needle electrode will have greater heating effect compared to a ball electrode set at the same power settings on the same tissue type. Following the same logic, patient return electrodes used in monopolar electrosurgery are large relative to the active electrode in order to disperse the current that is returning to the electrosurgical unit and minimize heat production at this return electrode site [4–6].

3.4. Tissue conductivity

Various tissue types have a different electrical resistance which affects the rate of heating. Adipose tissue and bone have high resistance and are poor conductors of electricity; whereas, muscle and skin are good conductors of electricity and have low resistance [5,7].

3.5. Current (energy) waveforms

The final determinant of how tissue responds to electrosurgery is current type. Electrosurgical generators produce three different waveforms — cut, blend, and coagulation. A variation in waveform mediates corresponding changes in tissue effects.

A cut waveform consists of continuous radiofrequency sine waves which incorporate higher current but lower voltage than coagulation waveforms at the same power setting. This high current, low voltage waveform produces a local and intense heating effect that vaporizes tissue with the least effect on coagulation (hemostasis). Tissue temperatures can exceed 100 °C [6]. A cutting current power setting must be between 50 and 80 W to be effective. Ideally, the electrode is held slightly away from the tissue to create a spark gap or steam envelope through which the current arcs to the tissue. This spark gap results from heating up the atmosphere between the electrode and the tissue. In general, the use of a cutting current produces less charring and tissue damage when compared to a coagulation current [8].

A blend waveform is a modification of the cutting waveform and is used when hemostasis is needed while cutting [3,4]. Although the total energy remains the same, the ratio of voltage and current is modified to increase hemostasis during dissection. In other words, by interrupting current and increasing the voltage, the waveform becomes non-continuous. This waveform type consists of a combination of both cutting and coagulation waveforms [2]. Higher blend settings translate into more time between bursts of current and greater coagulation as seen in the following examples: Blend 1 (80% cut, 20% coagulation); Blend 2 (60% cut, 40% coagulation); and Blend 3 (50% cut, 50% coagulation).

A coagulation waveform is composed of intermittent bursts of radiofrequency sine waves which have higher voltage and lower current than a cut waveform of the same power setting. This interrupted or dampened waveform has a duty cycle that is on about 6% of the time. Coagulation currents can produce spikes of voltage as high as 9000 V at 50 W. Tissue is heated when the waveform spikes. In between spikes, the tissue cools down thus producing the coagulation effect during the 94% off cycle of the waveform. This higher voltage is required for the current to pass through the highly resistant and desiccated tissue [9]. It is possible to cut tissue using coagulation currents at high power; however this will result in greater charring and tissue damage. Typically, the coagulation current is effective with the power setting in the range of 30 to 50 W [4].

The most common use of coagulation current is during *fulguration* of an area in the surgical field that is oozing such as a capillary or arteriole bed where a discrete bleeder cannot be identified. Fulguration is non-contact coagulation which also utilizes a spark gap to mediate the tissue effect which results in heating and necrosis as well as greater thermal spread. *Desiccation* is another form of coagulation in which direct contact with the tissue is made during application of the electrosurgical current thereby resulting in all of the electrical energy being converted into heat within the tissue. This is in contrast to both the cutting and fulguration currents which loose a significant amount of electrical energy during creation of the spark gap. The end result is deeper necrosis and greater thermal spread.

4. Electrosurgical units

Currently two types of electrosurgical units have been manufactured: the ground-referenced generator and the isolated solid-state generator. For ground-referenced systems, electrical current passes through the patient and it is the earth ground that completes the electrosurgical circuit. While the current is meant to return to the ground through the dispersive pad attached to the patient, it can pass through any grounded object in contact with the patient [2,6]. Patients in the operating room are usually separated from the ground by an insulated rubber mattress. However, stray current can flow through alternate ground sites especially if these represent a pathway of least resistance. Potential pathways include the OR table, IV stands, stirrups, electrocardiogram electrodes, OR staff, and miscellaneous equipment [3–5]. This increases the risk for alternate site burns as well as return electrode burns, particularly if the current is sufficiently concentrated and not adequately dispersed at the return site. As a result of concerns over accidental burns, a major complication of early electrosurgical units, the isolated generator system was developed in the 1970's. With this type of electrosurgical unit, the current passes through the patient and must return to the generator through a dispersive pad. Alternate pathways are avoided by not connecting the return electrode to the ground [2,6,8]. Activation of the electrosurgical unit is either hand or foot mediated. Energy from the electrosurgical unit is delivered as either monopolar or bipolar electrical current.

4.1. Monopolar electrosurgery

Monopolar electrosurgery is the most commonly used modality in surgery. Classically represented by the Bovie pencil, the active electrode is located at the surgical site while the return electrode is located elsewhere on the patient's body. While current flows through the patient, a return electrode is necessary to complete the circuit and disperse the electrical current and prevent alternate burn sites [4,10]. Through modification of its waveform, the clinical effects of cutting, fulguration, and desiccation are possible. Examples of monopolar instruments are loops, needles, and balls.

4.2. Bipolar electrosurgery

In comparison to monopolar, with bipolar electrosurgery, both active and return electrodes are located at the site of surgery, typically within the instrument tip. The classic example is the two tines of forceps which are the active and return electrode and represent the entire circuit. In this case, current does not flow through the patient. Only the tissue held between the two tines is included in the circuit and is the site of tissue effect. This technique refined the area of coagulation and minimized damage to surrounding tissue when compared to monopolar electrosurgery [1,11]. Most bipolar units use a lower voltage waveform to achieve hemostasis and avoid collateral tissue damage [2]. Since the return electrode is included in the circuit at the site of surgery, the dispersive patient return electrode pad is unnecessary [4,6]. As a result of the way bipolar electrosurgery is designed, many of the problems seen with its monopolar counterpart are avoided. Disadvantages of bipolar electrosurgery include increased time needed for coagulation compared to monopolar electrosurgery due to the lower power setting; charring; and adherence to tissue with incidental tearing of adjacent blood vessels [9].

5. Hazards of electrosurgical units

When used properly, electrosurgical units are safe and unintended injuries are uncommon. However, certain hazards are possible. One such hazard is *fires*. Electrosurgical devices are the most common source of ignition for operating room fires and explosions [2,7]. Approximately 100 surgical fires are reported each year. The risk for an intra-operative fire is greatest during induction of anesthesia. Electrosurgical units can ignite nearby paper, cloth, flammable liquids such as Betadine or 70% alcohol preps, or gaseous anesthetics when in proximity with an oxygen-rich environment [2].

As discussed earlier, electrosurgical units, when generating a monopolar electrical current, can be responsible for both return electrode and alternate site burns.

5.1. Return electrode burns

The most common site of injury with the use of monopolar electrosurgery is at the patient return electrode. The return electrode must be of low resistance with a large enough surface area to disperse the electrical current without generating heat. If the patient's return electrode is not large enough to disperse the current safely, has dried out, or is not completely in contact with the patient's skin, then the current exiting the body can have a high enough density to produce an unintended burn. The quality of contact between the return electrode and the patient's skin can be compromised by excessive hair, adipose, bony prominences, presence of fluid/lotions, or scar tissue. Therefore, it is important that the return electrode be placed on well vascularized muscle tissue.

Table 1 Ways to avoid electrosurgical complications during operative laparoscopy

* Carefully inspect the instrument for insulation breaks.
* Use the lowest possible power setting necessary.
* Do not activate the electrode in an open circuit.
* Do not activate the instrument in close proximity or direct contact with another instrument.
* Keep instruments clean and smooth. Coagulum build-up can cause impedance and adhere instruments to undesired blood vessels or nerves.
* Use brief intermittent activation versus prolonged activation.
* Use bipolar electrosurgery when appropriate.
* Avoid using a hybrid system (metal and plastic components) to avoid capacitive coupling.
* Ideal power setting for coagulation use is 30–50 W.
* Ideal power setting for cutting use is 50–80 W.
* Consider using an active electrode monitoring system to decrease the risk of insulation failure and capacitive coupling.
* Do not bundle multiple cords together on the surgical field.
* When not in use, place the active electrode in an insulated holster rather than on the surgical field.

In an effort to avoid this type of injury, *contact quality monitoring systems* were introduced in 1981. This system inactivates the generator if a condition develops at the patient return electrode site that could result in a burn [4].

5.2. Alternate site burns

Prior to the development of the isolated generator system (where the return electrode is not connected or referenced to the ground), the accidental division of current and its resulting burns plagued electrosurgery. Due to the poor design of early electrosurgical units, stray currents would exit the patient from alternate grounded areas and cause burns if the current density was high enough or if the resistance was low enough. Although the return electrode was connected to the ground to reduce current passing through any other route, if there was a problem with the return electrode, then stray current would result in burns [1,4]. Additionally, the stray current could be intensified if the return electrode was distant from the operating site or if the grounded sites occurred in the path between the active and return electrode. In the case of ground-referenced electrosurgical units, even if the return electrode was disconnected, electrosurgery would continue with current finding alternative pathways to return to the ground. Electrocution of the patient under these circumstances was possible.

6. Pitfalls of monopolar electrosurgery during minimally invasive surgery

Although return electrode and alternate site burns are associated with the use of monopolar electrical currents in either open or endoscopic cases, three additional hazards exist with the use of monopolar devices specifically during minimally invasive surgery [4,9,12] (Table 1).

6.1. Direct coupling

Direct coupling occurs when the electrosurgical unit is accidentally activated while the active electrode is in close proximity to another metal instrument. Current from the active electrode flows through the adjacent instrument through the pathway of least resistance, and potentially damages adjacent structures or organs not within the visual field which are in direct contact with the secondary instrument [4]. Direct coupling can be prevented with visualization of the electrode in contact with the target tissue and avoiding contact with any other conductive instruments prior to activating the electrode [2].

6.2. Insulation failure

Insulation failure occurs when there is damage to the material covering the active electrode. Breaks in the insulation create alternate pathways for current to flow. With a high enough concentration of current, injury to adjacent organs is possible. This occurs primarily when a coagulation waveform is used due to its high voltage output. Two major causes of insulation failure include the use of high voltage currents and the frequent re-sterilization of instruments which can weaken and break the insulation. Extensive burns and operating room fires can occur from these current leaks with temperatures measured to be as high as 700 °C [9,13]. By lowering the concentration of the current used, coagulating with a cutting current, and using an active

Table 2 Comparison of energy modalities

	Monopolar	Traditional bipolar	Advanced bipolar	Ultrasonic
Tissue effect	Cutting, coagulation	Coagulation	Cutting, coagulation	Cutting, coagulation
Power setting	50–80 W	30–50 W	Default generator setting	55,000 Hz frequency
Thermal spread	Not well assessed (multiple variables)	2–6 mm	1–4 mm	1–4 mm
Maximum temperature	>100 °C	>100 °C	Not well assessed	<80 °C
Vessel sealing ability	Not applicable	Not applicable	Seal vessels ≤ 7 mm	Seal vessels ≤ 5 mm
Technique	Not applicable	Not applicable	Tension-free application	Tension-free application

electrode monitoring system, the risk of accidental burns caused by insulation failure can be reduced [4].

6.3. Capacitive coupling

A capacitor occurs when two conductive elements or instruments are separated by an insulator and form stored energy. An electrostatic field is created between the two conductors such that current through one conductor is transmitted to the second conductor once the net charge exceeds the insulator's capacity. This results in capacitive coupling. Because this phenomenon is a rare and often misunderstood complication of monopolar electrical current use during endoscopic surgery, it is an important concept to review. Although the most common example of a capacitor being created is the placement of an active electrode, surrounded by its insulation, down a metal trocar, this can also occur with plastic trocars. If an injury is to occur, it is often away from the surgeon's visual field and involves body structures. Ironically the use of metal trocars can actually reduce this risk by allowing the stored energy from a capacitor to dissipate over the large surface area of the patient's skin thereby making the electrical energy less concentrated and less dangerous. The use of an active electrode monitoring system and limiting the amount of time that a high voltage setting is used can also eliminate concerns about capacitive coupling [2,4,9,13].

7. Patient safety advancements and new technologies

7.1. Active electrode monitoring systems

In an effort to minimize the risks of insulation failure and capacitive coupling, active electrode monitoring systems now exist. When interfaced with electrosurgical units, these systems continuously monitor and shield against the occurrence of stray electrosurgical currents. Critical to the success of these systems are the integrated laparoscopic instruments which have a secondary conductor within the shaft that provides coaxial shielding.

7.2. Tissue response generators

Tissue response generators are the next step in the evolution of electrosurgical generators. By using a computer-controlled tissue feedback system that senses tissue impedance or resistance, a consistent electrosurgical clinical effect is obtained through all tissue types. This is accomplished by the generator's ability to automatically adjust the current and output voltage once tissue impedance is assessed. Improved performance can now be achieved at lower electrosurgical settings [4,14].

7.3. Vessel sealing technology

The most recent advancement in electrosurgery has been the introduction of vessel sealing technology. Core to this technology is the use of bipolar electrosurgery which relies on tissue response generators. This advanced electrical current is combined with optimal mechanical pressure delivery by the instruments in order to fuse vessel walls and create a seal. Specifically, high current and low voltage are delivered to the targeted tissue and denature the collagen and elastin in the vessel wall while the mechanical pressure from the instrument allows the denatured protein to form a coagulum [15]. Vessels up to 7 mm in diameter and large tissue bundles can now be surgically ligated. Seals have been shown to also withstand more than three times a normal systolic blood pressure. This is comparable to pressures that are withstood by vascular staples, titanium clips, and sutures as well as other energy-based technologies. Additionally, thermal spread appears to be reduced when compared to traditional bipolar electrosurgical systems. Unlike traditional electrosurgical instruments, these devices require a tension-free application to tissue bundles in order to successfully obtain the desired tissue effect. Valleylab, Gyrus ACMI, and SurgRx, Inc. are three companies which have developed devices for both open and laparoscopic applications [4,6,15–18].

7.4. Ultrasonic technology

Although ultrasonic instruments are not electrosurgical, they are worth mentioning as both an alternate energy source and to clear up the confusion often encountered when defining this technology. Ultrasonic instruments possess vibrating elements that cycle at 55,000 Hz. There is no electrosurgical current generated therefore this mechanical energy forms the mechanism by which these instruments cut and coagulate tissue. The combination of mechanical energy and the heat that is generated causes protein denaturation and formation of a coagulum that seals small blood vessels. Typically, this energy modality is effective for blood vessels between 2 and 3 mm, although a newer device has demonstrated the ability to coagulate blood vessels up to 5 mm in diameter with less heat, charring, and thermal injury to surrounding tissues [19–21]. The heat generated from the friction of tissue is typically less than 80 °C [22]. Similar to vessel sealing technology, these instruments also require a tension-free application to tissue bundles. When applied successfully, these devices are able to divide tissue at the time of coagulation with minimal blood loss and avoid electrical injury [3,22]. Disadvantages of this technology are the formation of aerosolized fatty droplets from the tissue being treated which can interfere with visualization through a laparoscope [15,23]. Also, unintended transaction of tissue bundles can occur with prolonged or repetitive application of the device. United States Surgical, Ethicon EndoSurgery, and Olympus are three companies which have developed devices for both open and laparoscopic applications.

8. Conclusion

The evolution of electrosurgery has been rapid and continues to improve upon itself. The ability of today's electrosurgical devices to minimize blood loss and decrease operative times has had a significant impact across all surgical specialties. Critical to obtaining optimal clinical effects and reducing potential complications is a thorough understanding of the proper use of each energy modality. Distinct differences and similarities exist between these energy sources as summarized in Table 2. This working knowledge of electrosurgery will allow surgeons, both in open and endoscopic cases, to address a more complex pathology in an efficient and minimally invasive fashion.

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