Laparoscopic Vessel Sealing Technologies

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ABSTRACT

Laparoscopic vessel sealing devices have revolutionized modern laparoscopy. These devices fall into 2 major categories: advanced bipolar and ultrasonic instruments. The range of tissue effects available with these technologies is more limited than with conventional monopolar electrosurgery; however, both advanced bipolar and ultrasonic devices efficiently seal vessels (≤7-mm and ≤5-mm diameter, respectively), and most also have built-in tissue transection capabilities. These technologies have been the subject of a range of comparative studies on their relative advantages and disadvantages, and, to date, neither advanced bipolar or ultrasonic devices has been proven to be superior. Journal of Minimally Invasive Gynecology (2013) 20, 301–307 Crown Copyright © 2013 Published by Elsevier Inc. All rights reserved.

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DISCUSS

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Conventional monopolar electrosurgery remains a popular laparoscopic modality because of its low cost, general availability, and diverse range of available tissue effects. However, potential shortcomings of monopolar electrosurgery, including the need for a dispersive electrode, the relatively high power settings, the possibility of stray current injuries, and the inability to seal vessels larger than 1–2 mm diameter, led to the development of conventional bipolar electrosurgery to address these issues. More recently, ultrasonic energy sources were developed to limit the risks associated with electrosurgery, at the same time providing more efficient vessel sealing and tissue transection. Advanced bipolar technologies were subsequently introduced with optimized vessel compression and the delivery of electrical energy to provide even better vessel sealing capabilities. These new vessel sealing technologies are so successful that they have largely made the need for laparoscopic suturing of vascular pedicles redundant.

All electrosurgical devices achieve their tissue effects via the passage of electrical current through the target tissue, with the sequential conversion of electrical energy to mechanical energy to thermal energy. Ultrasonic devices also sequentially convert electrical energy to mechanical energy to thermal energy to facilitate vessel sealing but without the passage of electrical current through the tissue.

The tissue effects possible with monopolar electrosurgery include tissue vaporization and transection, fulguration, desiccation, and small vessel coaptation (Table 1) [1,2]. The tissue effects possible with advanced bipolar and ultrasonic technologies encompass a smaller subset of these tissue effects (Table 2). However, these new vessel sealing technologies have a significant advantage over monopolar electrosurgery in their ability to seal larger vessels (i.e., 5–7 mm diameter); with this, they have revolutionized modern laparoscopy. Furthermore, this vessel sealing capability is achieved without some of the risks inherent in monopolar electrosurgery. However, both advanced bipolar and ultrasonic technologies exert their surgical effects via the...
production of heat, and their use is not free of the risk of lateral thermal spread injury. This review focuses on the advanced bipolar and ultrasonic devices that seal vessels via analogous thermal processes, resulting in tissue desiccation, protein coagulation, and vessel coaptation.

**Advanced Bipolar Devices**

In reality, all electrosurgery is “bipolar” inasmuch as there needs to be 1 electrode from which the electrical current enters tissues and another electrode through which the current leaves the patient and returns to the electrosurgical unit (ESU) [1,3]. By convention, monopolar electrosurgery refers to the arrangement of a single small electrode contained within the surgical instrument that delivers focused alternating electrical current to the target tissue to impart the desired surgical effect. The second electrode is placed on the patient at a site remote from the surgical site to complete the electrical circuit; it is relatively large in size and is designed to disperse current (and prevent tissue heating) as it leaves the patient on its way back to the ESU. The tissue effects available with monopolar electrosurgery are achieved using either contact (“closed circuit”) or noncontact (“open circuit”) modes, with either continuous (ESU “cut” setting) or interrupted (ESU “coag” setting) current waveforms (Table 1).

In bipolar electrosurgery, both electrodes are contained within the surgical device, with current passing from 1 electrode to another. Current passes through tissue grasped between the electrodes to achieve the desired surgical effect. There are significant advantages to this arrangement over monopolar electrosurgery, mostly relating to the fact that the electrical current in bipolar electrosurgery does not have to take pathways through the patient to complete the circuit with the ESU. For example, power settings are typically lower, there is no need for a remote return electrode attached to the patient (eliminating the risk of return electrode injury), and there is no generation of capacitance-coupling current (eliminating the risk of capacitive coupling injury) [1,3]. Bipolar electrosurgery uses alternating current so the orientation of the “active” and “return” electrodes also rapidly alternates, resulting in an even distribution of thermal effects on the tissue grasped between the electrodes. In addition, because a continuous current waveform is used, the voltage is less for a given power setting and the tissue temperature rise to achieve the desired surgical effect is less. With prolonged activation, an interrupted current waveform may result in tissue temperatures exceeding 200°C with resultant carbon deposition and the adherence of tissue to the instrument jaws [2,3].

Bipolar electrosurgery is a modality in which there is minimal ability to vary the operational parameters; the electrical current is only delivered in a “closed circuit” (both electrodes are in contact with the target tissue), a continuous current waveform is standard, and both electrodes are the same size (for a given instrument) and have a relatively large surface area to maximize contact with the tissues. In contrast, monopolar electrosurgery offers more flexibility in that many of the operational parameters can be varied, which accounts for the range of available tissue effects (Table 1) [2]. It should be noted that when a monopolar forceps is activated whilst grasping tissue between the jaws (or, analogously, if a nonactive forceps holding tissue is intentionally

<table>
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<th>Monopolar electrosurgery tissue effects</th>
<th>Tissue effect</th>
<th>Current waveform</th>
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<tr>
<td>Vaporization (tissue destruction and/or transection)</td>
<td>Continuous</td>
<td>Noncontact</td>
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<td>Fulguration (tissue destruction and small vessel hemostasis (≤ 1-mm diameter))</td>
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<td>Desiccation (tissue dehydration)</td>
<td>Continuous or interrupted</td>
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<td>Coagulation (protein denaturation and coagulum formation)</td>
<td>Continuous or interrupted</td>
<td>Contact</td>
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<td>Continuous or interrupted</td>
<td>Contact (vessel compression)</td>
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<th>A comparison of the tissue effects with monopolar electrosurgery, bipolar electrosurgery, and ultrasonic devices</th>
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* With cutting mechanism incorporated into instrument tip.

* 7-mm diameter vessel sealing possible with advanced bipolar (less with conventional bipolar).
contacted by a monopolar electrosurgical instrument), the electrosurgical tissue effect is essentially the same as that obtained with bipolar forceps (desiccation, coagulation, and coaptation; Table 2). However, in this case, the electrical current must still pass back through the patient to a remote return electrode.

Both monopolar and bipolar electrosurgery achieve the respective range of tissue effects by the conversion of radio-frequency electrical energy into mechanical energy and thence into thermal energy [1]. With noncontact mode monopolar electrosurgery, tissue temperatures greater than 100°C and 200°C result from continuous and interrupted waveforms, respectively, yielding vaporization and fulguration tissue effects (Table 1) [2]. As mentioned previously, the tissue effects available with contact mode monopolar electrosurgery and bipolar electrosurgery are essentially the same (Table 2), and the tissue temperatures are lower, typically in the range of 60°C to 100°C. At these temperatures, cell membrane integrity is lost, and the loss of cytoplasm results in desiccation of the tissues. In addition, synchronous protein denaturation results as stabilizing hydrogen bonds are broken. As the tissue temperature subsequently decreases, hydrogen bonds reform but in a different configuration. This so-called “coagulum” is the “biological glue” that enables vessel walls to adhere to one another [3]. An essential requirement in achieving these tissue effects is the ability of the electrosurgical instrument to apply even contact to the tissue and with adequate compressive force. Compression of the vessel ensures that blood flow is interrupted and the potential heat sink effect of the moving liquid is removed. Furthermore, compression of the vessel brings the coagulum of the opposing vessel walls into close proximity so that hydrogen bonds can reform with resultant vessel sealing.

An awareness of the risk of lateral spread is essential, irrespective of the energy source used during laparoscopy, with the amount of lateral thermal spread proportional to the duration of instrument activation. Hence, lateral thermal spread will be detected at increasing distances from the primary surgical site for as long as the energy source is activated. Therefore, the specter of lateral thermal spread during conventional bipolar electrosurgery has been a quandary for the surgeon who must use personal experience and visual cues to estimate the time of device activation necessary for vessel sealing whilst being mindful of the risk of collateral tissue damage.

The delivery of electrical energy by advanced bipolar ESUs is highly pulsatile, allowing for tissue cooling during activation in an attempt to minimize lateral thermal spread. These proprietary ESUs also use computer-controlled tissue feedback response systems that monitor tissue impedance and/or temperature in order to continuously adjust the current and voltage generated by the unit. Hence, with graspers designed to enhance mechanical pressure delivery and electrosurgical energy optimized to improve the tissue effects at the lowest possible power settings, advanced bipolar technology combines optimal thermal and mechanical properties to seal vessels [4,5]. The advanced bipolar ESUs also either automatically switch off or alert the surgeon via an audio signal when the desired tissue effect has been achieved, thereby avoiding prolonged activation, increased tissue temperatures, excessive charring, and adherence of tissue to the instrument jaws and minimizing lateral thermal spread. However, despite promising laboratory and animal studies, it has yet to be shown in clinical trials that these safeguards actually result in a reduction in electrosurgical injury due to lateral thermal spread [6]. Nevertheless, the optimized mechanical force and electrical energy delivered to the tissues by advanced bipolar devices has been rewarded by the US Food and Drug Administration with approval to seal vessels up to 7 mm in diameter [7].

Currently available advanced bipolar technologies include LigaSure (Covidien, Mansfield, MD; Fig. 1), EnSeal (Ethicon Endo-Surgery, Cincinnati, OH; Fig. 2), and PlasmaKinetic System (PKS; Gyrus ACMI, Southborough, MA; Fig. 3). Each of these technologies is different although all are approved to seal vessels up to 7 mm in diameter. Each system also offers a range of devices that vary in aspects of their design. LigaSure, the first commercially available vessel sealing system (1998), has recently been improved with the introduction of the ForceTriad generator, which performs 4000 measurements of tissue impedance per second compared with 200 measurements per second for the conventional LigaSure to provide real-time adjustment control of the energy output with significantly improved mean burst pressures and shorter sealing times [8]. The electrical output between the EnSeal instrument jaws is autoregulated using a proprietary electrode that contains millions of nanometer-sized conductive particles embedded in a temperature-sensitive material, which...
Ultrasonic Devices

Not dissimilar in appearance to new-generation bipolar electrosurgical devices, ultrasonic laparoscopic energy sources are also able to seal vessels and transect tissues. Indeed, most of the tissue effects produced by ultrasonic devices are the same as those for bipolar devices (Table 2). However, these tissue effects are produced without the passage of electrical current through the patient or target tissue. Ultrasonic devices instead convert electrical energy to both mechanical and thermal energy via ultrasonic vibrations to achieve tissue transection and vessel sealing. Combining these 2 modalities into a single device helps to decrease “instrument traffic” (as for advanced bipolar devices), with potential economic advantages [9].

Ultrasonic devices produce tissue effects by generating mechanical vibrations at over 20,000 cycles per second (i.e., above the audible range). The ultrasonic generator delivers alternating electrical current to the handpiece transducer where excitation in piezoelectrodes interspersed between metal cylinders converts electrical energy into mechanical energy by vibrating the cylinders at frequencies ranging from 23 to 55 kHz [10]. The shaft of the instrument, the active component of the device, is in contact with the cylinders and oscillates linearly at the same frequency. The tip of the shaft forms the nonarticulating jaw of the ultrasonic shears. The articulating jaw of the instrument provides a mechanism for grasping and holding tissue against the active nonarticulating jaw so that the desired tissue effect can be achieved.

The ultrasonic generator varies the amount of mechanical energy applied to the tissue to achieve a particular effect. There are 2 generator settings available: “Max” and “Min.” The mechanical energy delivered to the tissue is greatest on the “Max” setting with larger oscillations of the shaft tip (fixed at 100 μm) and is suitable for rapid tissue transection; lateral thermal spread is less with this mode, but the hemostatic potential is poor. The oscillation distance of the ultrasonic shaft tip is smaller on the “Min” setting (adjustable down to 50 μm); the lower level of mechanical energy is ideal for vessel sealing, but there is an increased risk of lateral thermal spread with this mode.

Ultrasonic tissue transection occurs as a result of mechanical friction between the oscillating device shaft and the tissue. The surgeon has some control over this process, which is significantly shorter than for vessel sealing. For example, tissue transection will be more rapid (and less hemostatic) as the pressure applied by the articulating jaw is increased, due to greater resultant frictional and shearing forces. The application of pressure perpendicular to the tissue plane with the oscillating tip (e.g., lifting the pedicle) will similarly facilitate tissue transection. In addition to mechanical friction, cavitation may also facilitate tissue transection [11]. Cavitation is a phenomenon that occurs during tissue vaporization, which is the same process that is observed in electrosurgery when cells explosively rupture as the cytoplasm boils. Cavitation occurs when steam released from vaporized cells expands preexisting tissue planes, thereby assisting dissection. Because of the local environment created by the oscillating tip, cavitation may occur at lower temperatures with ultrasonic devices than in electrosurgery [11].

As with advanced bipolar devices, ultrasonic vessel sealing results from desiccation, coagulation, and coaptation.
However, the mechanism by which these effects are obtained is very different. With electrosurgery, the alternating current oscillates intracellular molecules as the polarity of the cell changes. Consequently, electrical energy is sequentially converted to mechanical energy to thermal energy via intracellular frictional effects to yield the desired tissue effects. With ultrasonic energy, electrical energy is likewise converted to mechanical energy to thermal energy as the frictional force exerted on the tissues by the oscillating shaft tip results in sequential extracellular heating followed by intracellular heating. So, for both bipolar and ultrasonic devices, thermal energy is responsible for the tissue desiccation, coagulation, and coaptation effects. The lateral thermal spread with ultrasonic devices is greatest during vessel sealing mode (i.e., desiccation and coagulation) and least with tissue transection mode (i.e., mechanical cutting and cavitation).

The laparoscopic “ultrasonic scalpel” was first described in 1993 by Amaral [12] with an ability to provide both vessel sealing and tissue transection. The Ultracision Harmonic Scalpel (Ethicon Endo-Surgery) was developed for commercial use and approved to seal vessels up to 3 mm in diameter [13]. The Harmonic ACE (Ethicon Endo-Surgery; Fig. 4) was subsequently developed; its “active” jaw oscillates at a frequency of 55,000 cycles per second, and it gained Food and Drug Administration approval to seal vessels up to 5 mm in diameter [7]. Other examples of currently available laparoscopic ultrasonic devices include the AutoSonix (Covidien), Sonocision (Covidien; Fig. 5), and SonoSurg (Olympus America, Center Valley, PA). These devices operate at similar frequencies to the Harmonic ACE and seal vessels up to 5 mm in diameter with similar mean burst pressures [14]. The AutoSonix, Harmonic ACE, and Sonocision are single-use disposable instruments, whereas SonoSurg is reusable and autoclavable. Sonocision is a newly released cordless ultrasonic device.

Purported advantages of ultrasonic vessel sealers included less tissue necrosis and charring, reduced lateral thermal spread, and less smoke generation compared with electrosurgery [15,16]. Because the tissue temperature resulting from ultrasonic vessel sealing (desiccation, coagulation, and coaptation) is less than 100°C, tissue charring will be much less than with the higher temperatures generated by noncontact continuous waveform (vaporization) or noncontact interrupted waveform (fulguration) monopolar electrosurgery (Tables 1 and 2). However, the tissue charring resulting from contact monopolar electrosurgery, conventional bipolar electrosurgery, and advanced bipolar electrosurgery (all producing desiccation, coagulation, and coaptation) is much less; the resultant tissue temperatures are similar to those for ultrasonic technologies [17]. In addition, the activation time for vessel sealing with ultrasonic devices is subjective (as for monopolar and conventional bipolar electrosurgery) because there is no tissue impedance/temperature cutoff or audio signal (available with advanced bipolar devices) to inform the surgeon when vessel sealing is complete. Hence, although the risk of lateral thermal spread may be low with ultrasonic devices, higher tissue temperatures (proportional to the increased time of activation) mean that lateral thermal spread injury remains a risk. Interestingly, the Harmonic ACE is associated with greater increases in tissue temperature compared with the Ultracision Harmonic Scalpel [13]. The newly available Harmonic ACE+ (Ethicon Endo-Surgery; Fig. 6) uses “adaptive tissue technology” to regulate energy delivery according to tissue conditions and provides the surgeon with an audio signal of energy output; it is yet to be proven that lateral thermal spread is decreased with this device compared to the Harmonic ACE. The smoke plume generated by ultrasonic vessel sealers is less than with other laparoscopic energy devices.
sources [11] although the smoke plume from these devices may still significantly obscure the surgeon’s view [18]. The tips of the Harmonic ACE are more effective for dissection than the Harmonic Scalpel but overall may have more limited dissection capability when compared with monopolar scissors and conventional bipolar forceps [13].

Comparison of Advanced Bipolar and Ultrasonic Vessel Sealing Technologies

The reasons for a surgeon’s preference for a particular laparoscopic energy source may be many and varied. A common reason for choosing a particular instrument is the surgeon’s own experience with that instrument that may have been preordained by a mentor during surgical training. Unfamiliar technologies often are not trialed. Surgeons are also subjected to marketing strategies and even inducements. Indeed, device manufacturers sponsor many of the studies on energy sources published in the medical literature. To complicate matters further, it is generally not possible to compare vessel sealing data from different studies because study conditions may vary widely. Hence, it is difficult for surgeons to make an objective, informed decision about the relative merits of different laparoscopic energy sources.

The relative merits of advanced bipolar and ultrasonic devices are summarized in Table 3. These data are from recent studies that compared at least 1 of the advanced bipolar devices with an ultrasonic vessel sealer. Both bipolar and ultrasonic devices are effective at sealing vessels up to 5 mm in diameter, but only bipolar devices are approved to seal vessels 6–7 mm in diameter [7,16,19–21]. There are conflicting data on the “time to seal.” No firm conclusion can be drawn as to which class of device is the faster vessel sealer [16,19]. For all laparoscopic energy sources (monopolar [contact mode], bipolar [conventional and advanced], and ultrasonic [vessel sealing mode]), the amount of lateral thermal spread and the risk of collateral tissue damage are proportional to the length of time of activation of the instrument. In general, lateral thermal spread generally seems to be less with ultrasonic devices [20,21] although the time of activation with this technology, and the resultant amount of lateral spread, are operator dependent. Interestingly, the residual temperature of the instrument tip after activation is less with bipolar devices [22]. As a general principle, tissue should not be grasped with any energy source immediately after activation. Particulate formation is less with ultrasonic devices although all laparoscopic energy sources produce a plume of smoke or steam [16]. In summary, there is insufficient evidence for one vessel sealing technology to be considered superior to the other. A detailed critical evaluation of comparative clinical, laboratory, and animal studies of all classes of laparoscopic energy sources is available elsewhere [6].

Devices have recently been developed that combine bipolar vessel sealing and bipolar tissue transection (PKS Omni, Gyrus ACMI), monopolar and bipolar electrosurgery (LigaSure Advance, Covidien; Fig. 7), and ultrasonic and bipolar technologies (Thunderbeat, Olympus America; Fig. 8) into a single instrument. Although it is desirable to incorporate multiple functionalities into 1 handpiece so that “instrument traffic” can be minimized, it is important not to compromise the functionality of individual technologies for the sake of efficiency. A single laparoscopic energy source that can produce all the tissue effects available with individual energy sources may become a reality for the future laparoscopic surgeon. Along with ultrasonic and electrosurgical modalities, the “ideal laparoscopic energy source” would also possess the capabilities of

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<th>Parameter</th>
<th>Advanced bipolar</th>
<th>Ultrasonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel sealing: maximum vessel diameter</td>
<td>Superior (7 mm)</td>
<td>Inferior (5 mm)</td>
</tr>
<tr>
<td>Vessel sealing: time to seal</td>
<td>Equal</td>
<td>Equal</td>
</tr>
<tr>
<td>Lateral thermal spread*</td>
<td>Inferior</td>
<td>Superior</td>
</tr>
<tr>
<td>Residual instrument tip temperature</td>
<td>Superior</td>
<td>Inferior</td>
</tr>
<tr>
<td>Smoke/vapor plume</td>
<td>Inferior</td>
<td>Superior</td>
</tr>
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</table>

* The time of activation for ultrasonic vessel sealing is operator-dependent so the degree of lateral thermal spread may vary.
fine tissue grasping and sharp tissue dissection. The dissecting abilities of various laparoscopic forceps have been reported previously [23], but the dissecting abilities of the newer-generation bipolar forceps and the ultrasonic shears have yet to be evaluated.

Conclusions

The development of laparoscopic vessel sealing devices has revolutionized modern laparoscopy. Despite these advances, the reliance on monopolar electrosurgery persists because of its wider range of tissue effects and dissection capabilities. At present, there is no clear evidence to support the use of either advanced bipolar or ultrasonic devices in preference to the other, although each technology has well-characterized advantages and disadvantages. It is likely that the surgeon will rely on 2 or more laparoscopic energy sources (or hybrid instruments incorporating multiple technologies) depending on the cost and availability of the devices (and their proprietary generator boxes), personal preference and experience, the surgical procedure to be performed, and the presence or absence of significant pathology in the surgical field.

References