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A review of low thermal damage technologies in electrosurgery

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Highlights

- Comprehensive Technology Review – It systematically compares three major techniques for reducing thermal damage in electrosurgery.
- Balanced Evaluation Framework – Each method is evaluated across multiple dimensions, including effectiveness, applicability, complexity, and cost.
- Forward-Looking Insight – It discusses future trends such as AI integration and the development of advanced materials for smarter surgical systems.

Abstract

Electrosurgery is widely applied for precise tissue cutting and coagulation through high-frequency electrical energy, yet it carries the risk of collateral thermal injury. This review examines emerging strategies to mitigate such damage, including cooling systems, real-time temperature monitoring, pulsed cutting, and laser- or ultrasound-assisted techniques. By improving temperature regulation, enhancing feedback accuracy, and enabling adaptive power control, these innovations reduce heat diffusion and tissue charring, thereby enhancing surgical safety and outcomes.

Keywords: Electrosurgery, thermal damage, adaptive control

Introduction

In early surgical practice, tissue separation, tumor excision, and necrotic tissue removal were primarily performed with surgical blades. However, the sharpness of the blade often caused rupture of adjacent blood vessels, leading to bleeding that required hemostasis by manual pressure, ligation, or the use of hot cautery. With advances in medical technology and the discovery of electromagnetic induction, surgery gradually transitioned toward electronic methods. In the early 20th century, Walter reported that high-frequency currents could generate spark-like effects between electrodes and tissue at a short distance, which were applied to treat skin tumors [1]. In 1911, Clark employed very high voltage and extremely low current with a single electrode to destroy tissue, producing marked desiccation at the contact site [2]. Subsequently, with support from the Liebel-Flarsheim Company, Bovie developed the first electrosurgical instruments. By the mid-1980s, ionization devices using high-frequency alternating current to generate localized high heat with a single electrode were introduced, enabling both tissue cutting and coagulation [3]. Since then, electrosurgery has become a widely adopted clinical technique [4].

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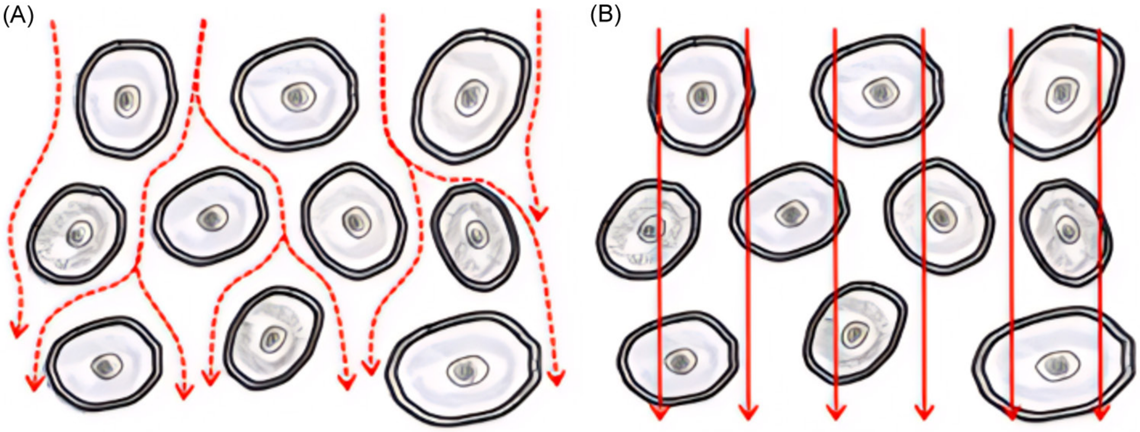

Figure 1. The internal current path of the organization at different frequencies. (A) Low-frequency current path within the tissue; (B) High-frequency current path within the tissue [8].

Electrosurgical devices broadly refer to instruments that utilize high-frequency electrical energy (typically 0.2-5 MHz) for tissue cutting, dissection, coagulation, and related procedures. These include monopolar and bipolar electrosurgical devices, radiofrequency knives, ion knives, argon plasma coagulators, and laser scalpels. A standard electrosurgical system consists of a high-frequency power source and return electrode pads. Current passes through the patient's body, and heat is generated at the tissue–electrode interface, enabling precise cutting and coagulation. With advances in material science and surgical technology, a variety of electrosurgical knives have been developed to meet the needs of different surgical scenarios. However, the high temperatures produced during cutting inevitably cause thermal diffusion, which can damage surrounding normal tissue and even result in charring or necrosis. Therefore, reducing thermal injury has become a major focus in the development of electrosurgical devices. This review will discuss the basic principles of high-frequency electrosurgery, mechanisms of thermal damage, and emerging technologies aimed at minimizing such effects.

Operating principle of electrosurgery

Electrosurgery applies high-frequency electrical energy to biological tissues, offering two key clinical advantages.

First, because biological tissues are composed of numerous cells with membranes that behave as capacitors, the current pathway is frequency-dependent [5]. Direct current is blocked, and low-frequency alternating current encounters high impedance, so current primarily flows through extracellular fluid (**Figure 1A**). In contrast, high-frequency alternating current can traverse both extracellular and intracellular fluids (**Figure 1B**). When the amplitude is sufficiently high, Joule heating raises the temperature of intracellular fluid to its boiling point. Vapor expansion induces microscopic cell rupture, producing the macroscopic cutting effect [6]. In an experiment conducted by Burcu Tunc, a sudden temperature drop of 0.5-18 °C was observed during the initial ablation phase, indirectly confirming gas formation during electrosurgical cutting and supporting this mechanism [7].

Second, the frequency range of electrosurgical currents (0.2-5 MHz) is far higher than physiological signals in the human body [8]. This minimizes interference with both the patient's and the surgeon's physiological functions during the procedure.

As shown in **Figure 2**, progressive heating leads to cellular dehydration above 80 °C, followed by vaporization above 100 °C. This sequence underlies the mechanism of tissue cutting in high-frequency electrosurgery [9].

Mechanisms of thermal effects in electrosurgery and analysis of tissue thermal damage

Definition and classification of thermal damage

Definition of thermal damage

Thermal damage refers to the structural and functional changes in cells or tissues caused

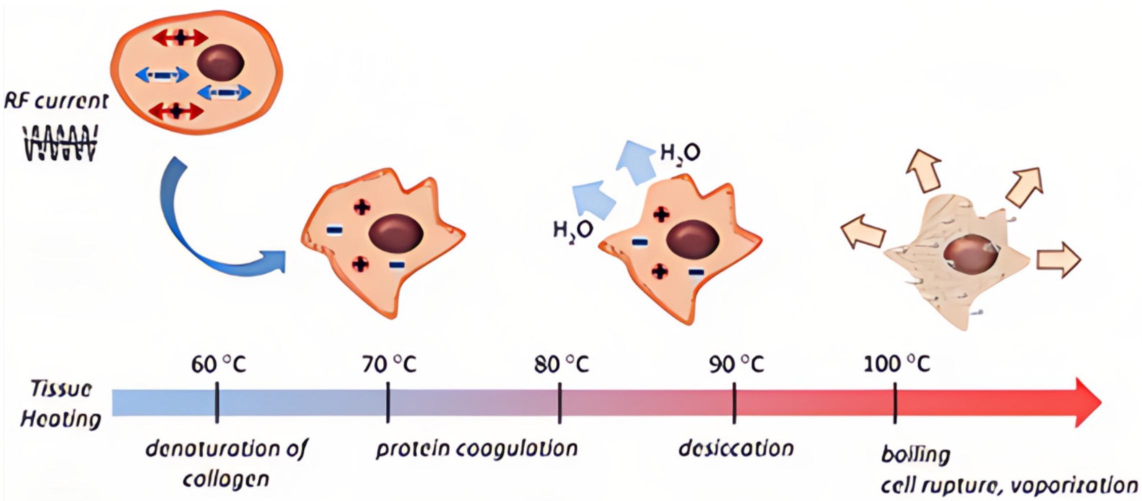

Figure 2. State changes of cells at different temperatures.

by exposure to excessive temperatures, leading to damage. High temperatures can cause water evaporation within tissues or protein denaturation, ultimately resulting in tissue death. Thermal damage typically occurs when tissues are exposed to temperatures exceeding their normal tolerance threshold [10].

Classification of thermal damage

Thermal damage is commonly classified based on temperature and exposure time. The primary classifications are as follows:

(1) Mild Thermal Damage (Low-Temperature Damage): This occurs when tissues are exposed to temperatures between 40 °C and 60 °C for short durations. Mild damage may result in temporary loss of cellular function, but tissue recovery is generally expected. This type of damage is often seen in localized high-temperature procedures, such as hot compresses or light electrosurgical cutting.

(2) Moderate Thermal Damage (Coagulation Damage): Damage occurs when tissues are exposed to temperatures between 60 °C and 80 °C for longer durations. In moderate thermal damage, cellular proteins begin to denature, leading to functional impairments. This damage can often be managed surgically, with the affected area typically showing signs of coagulation. The damaged cells may not recover.

(3) Severe Thermal Damage (Vaporization and Carbonization Damage): Exposure to temperatures above 80 °C for extended periods results in the evaporation of water, vaporization, carbonization, or complete charring of the tissue. Cellular death becomes irreversible, and the tissue cannot recover. Severe thermal damage is commonly observed with devices like high-frequency electrosurgical knives, and it is the primary mechanism behind the cutting action in electrosurgery.

Common mechanisms of thermal damage caused by high-frequency electrosurgical knives

Power and heat generation

Electrosurgery generates heat within tissue via high-frequency currents, causing rapid temperature increases at the point of contact. When electrosurgical power is too high, the current generates significant heat as it passes through the tissue. For a given current, higher power results in more heat generation and a faster temperature rise at the local tissue site. Excessive heat accumulation can surpass the tissue's tolerance threshold, leading to thermal damage.

During surgery, the electrosurgical power must be adjusted according to the specific requirements of the procedure. If the power is too high, heat may not dissipate quickly enough within the tissue, causing overheating. Conversely, if the power is too low, the desired cutting or coagulation effect may not be achieved, resulting in incomplete results. Therefore, precise power adjustment based on tissue types and surgical needs is crucial in clinical practice to avoid excessive heat accumulation.

Heat propagation and tissue thermal conductivity

Heat conduction refers to the transfer of heat from high-temperature regions to cooler areas through molecular vibration. Different tissues have varying thermal conductivities, which influence how heat is distributed within them. Tissues with higher water content, such as muscles and blood, generally have better thermal conductivity, allowing heat to spread quickly and reducing the risk of localized overheating. In contrast, tissues with lower water content, such as fat, have poor thermal conductivity, meaning heat spreads slowly and can accumulate, increasing the risk of thermal damage.

During electrosurgery, heat is generated as current passes through tissue. When power output is too high, tissue temperature rises rapidly. In low-conductivity tissues like fat, heat cannot dissipate efficiently, leading to heat accumulation and potentially severe damage such as charring. In contrast, tissues with higher conductivity, such as muscle, spread heat more effectively, which slows the rise in temperature and helps reduce the risk of damage.

The thermal conductivity of tissue is closely related to the power settings of the electrosurgery. When power is too high, heat accumulates rapidly, especially in low-conductivity tissues like fat, where heat dissipation is inefficient. This causes local temperatures to rise quickly, leading to protein denaturation, tissue necrosis, and even carbonization. On the other hand, in tissues with higher thermal conductivity, such as muscle, heat is spread more effectively, reducing the rate of temperature increase and lowering the risk of thermal damage. Therefore, adjusting the power settings based on tissue thermal conductivity is essential for minimizing thermal damage during surgery.

Common mechanisms of thermal damage caused by high-frequency electrosurgical knives

Thermal damage caused by high-frequency electrosurgical knives involves two primary mechanisms:

(1) Power Setting and Impedance Variability: When electrosurgery is used for cutting or coagulation, the impedance of the tissue it contacts varies depending on the type of tissue and its pathological state. Since the power setting is often fixed by the surgeon during the procedure, any imbalance between the power output and the tissue's impedance can result in inefficient energy transfer. If the power is too high, the heat generated by the current may exceed the tissue's capacity to dissipate it, causing heat to accumulate and leading to extensive and severe thermal damage. Conversely, if the power is too low, the tissue may not receive sufficient heat to achieve the desired effects, such as incomplete coagulation or inadequate cutting, resulting in suboptimal surgical outcomes.

(2) Thermal Injury to Surrounding Healthy Tissue: The fundamental operation of electrosurgery involves heating tissue to achieve cutting or coagulation. However, this process inevitably affects surrounding healthy tissues, causing "collateral damage". This is especially noticeable in tissues with low thermal conductivity, such as fat, where heat tends to concentrate in localized areas. These tissues' inability to dissipate heat efficiently increases the risk of thermal damage. Even with precise control of the electrosurgery's power, heat will still propagate and affect surrounding healthy tissues. Therefore, careful management of both power settings and tissue characteristics is critical to minimizing this risk during surgery.

Technologies for reducing thermal damage

While high-frequency electrosurgical knives are widely used in surgical procedures, thermal damage to surrounding tissues due to their high temperatures remains a significant concern. In recent years, several technical strategies have been developed to address this issue. These strategies can be broadly classified into three categories: real-time feedback systems for intelligent power regulation, physical cooling mechanisms to actively reduce temperature at the surgical site, and waveform modulation techniques to interrupt continuous heat delivery. This section discusses representative techniques from each category, along with their respective mechanisms, advantages, and challenges.

Temperature feedback and intelligent power control

The first approach focuses on controlling heat generation at the source through intelligent power regulation based on real-time feedback. Among various feedback signals, temperature and impedance are commonly used to assess tissue conditions and adjust power output accordingly.

With advancements in electrosurgical equipment and its application by surgeons, numerous methods have emerged to evaluate the performance of electrosurgical devices, including power exposure, accuracy, and more [10]. Initially, these methods were used only for evaluation, but later, researchers proposed using the numerical indicators obtained from these evaluations as feedback to the electrosurgical device for intelligent cutting. Devices capable of such intelligent cutting are referred to as adaptive electrosurgical knives, and the algorithm that processes the feedback information and adjusts the electrosurgery's power output in real-time is called the adaptive algorithm (also referred to as intelligent power control).

In the implementation of adaptive algorithms, key reference indicators include tissue surface temperature and impedance. Temperature directly reflects the tissue's damage state, while tissue impedance indirectly indicates the tissue type and whether the heat exposure is within the normal range. This section uses temperature feedback as an example to explain the implementation of power adaptive algorithms.

A real-time temperature monitoring system can continuously track both the electrode tip's and surrounding tissue's temperature during high-frequency electrosurgery. Using temperature sensors, the surgeon remains informed about the temperature changes in the tissue, helping avoid thermal damage caused by excessive heat [11]. For example, infrared temperature sensors detect infrared radiation to measure tissue surface temperature, allowing rapid feedback. These sensors offer the advantage of non-contact measurement, making them suitable for dynamic adjustments during surgery. Alternatively, thermocouple sensors, typically in the form of miniature probes, directly contact the tissue for precise temperature measurements. These sensors are ideal for high-precision monitoring, ensuring optimal cutting results while minimizing thermal damage to surrounding tissues.

By integrating these feedback mechanisms, adaptive electrosurgical knives can adjust their power output in real-time, improving cutting accuracy and reducing thermal damage to healthy tissues.

Figure 3 illustrates the use of a traditional monopolar electrosurgery system based on real-time temperature monitorin [12]. The current-sensing transformer and voltage-sensing transformer are represented by CT (Current Transformer) and PT (Power Transformer), respectively. The high-frequency transformer (T) increases the output voltage. The tissue is placed between the electrosurgical electrode (ES) and the return pad, with the tissue surface temperature being monitored in real-time via an infrared thermography system.

The primary advantage of real-time temperature monitoring is its ability to provide early warnings when temperatures rise excessively. The adaptive algorithm helps the surgeon take corrective actions, such as reducing power or temporarily halting the procedure. This monitoring approach specifically addresses the first mechanism of damage discussed in Chapter 2, ensuring that the electrosurgical power output remains within a safe range by precisely controlling temperature. This is particularly beneficial for lengthy surgeries and temperature-sensitive tissues, as it significantly reduces the risk of thermal damage. Additionally, the high accuracy of the temperature monitoring system, coupled with the power adaptation algorithm, minimizes collateral damage, making it an effective strategy for improving surgical outcomes.

However, the implementation of temperature-feedback-based adaptive algorithms still faces several challenges. First, real-time temperature acquisition requires highly sensitive, fast-response sensors that do not interfere with surgical operations. Second, from an algorithmic perspective, modeling the relationship between temperature and power regulation is difficult due to the complex and variable nature of tissue types and surgical environments. Finally, from a mechanical standpoint, integrating sensors seamlessly into electrosurgical equipment

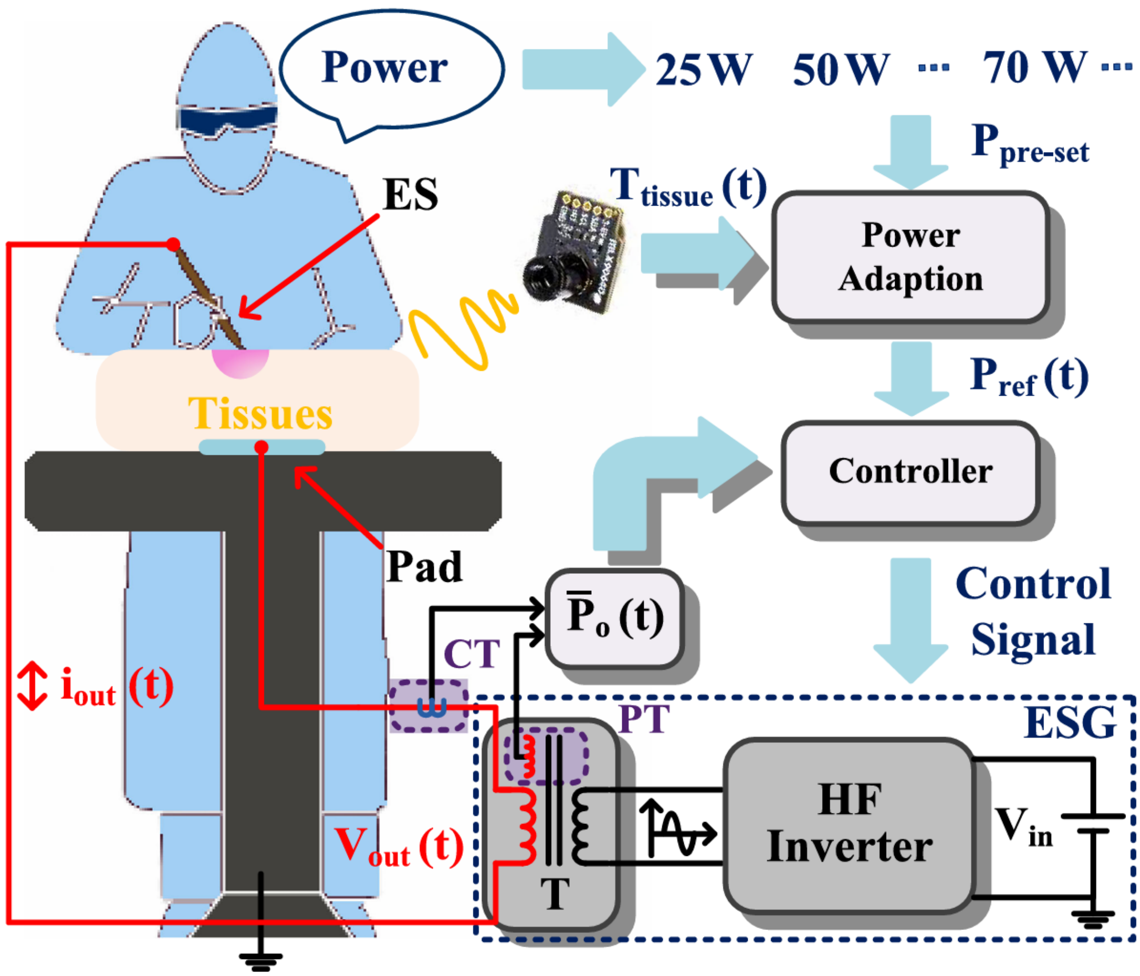

Figure 3. Flowchart of adaptive electrosurgery operation based on real-time temperature monitoring [12].

without compromising ergonomics or functionality remains a significant technical challenge.

Moreover, most current systems employing this technology can only detect surface tissue temperatures or rely on impedance feedback, which fails to accurately reflect temperature variations in deeper tissues. Additionally, sensor latency or measurement errors may cause delayed power adjustments, undermining thermal control. Furthermore, most control algorithms are heuristic in nature and struggle to adapt to the rapidly changing conditions encountered during surgery.

The future development of this technology will largely depend on advancements in temperature sensors. High-precision, interference-resistant miniature sensors are essential, and the lack of such devices is a major limitation preventing this technology from reaching its full potential. Previous studies have also demonstrated that optimizing electrode geometry can significantly minimize lateral thermal spread during radiofrequency procedures [13]. Additionally, Yang et al. designed and simulated a multi-functional radiofrequency electrode structure, enabling integration of temperature feedback with structural optimization [14]. The integration of artificial intelligence (AI) and machine learning can enhance the responsiveness of cutting algorithms. Once these algorithms mature, standardized feedback parameters will be crucial for their consistent implementation.

Active cooling system

Beyond regulating the power source, another strategy to reduce thermal damage involves actively removing heat from the electrosurgical knife or surrounding tissues. This approach is particularly crucial in extended procedures where thermal buildup is unavoidable.

Cooling systems are widely used to reduce thermal damage caused by high-frequency electrosurgical knives, especially in long or large-scale surgeries where the knife tip temperature continuously rises, leading to overheating and unnecessary tissue damage. The cooling system works by lowering the electrosurgical knife tip's temperature, reducing heat accumulation and effectively preventing thermal damage. For instance, Qian et al. achieved precision cooling during radiofrequency ablation under real-time temperature monitoring, with both simulation and experimental results confirming significant temperature reduction [15].

The water cooling system is the most commonly used method. It circulates cooling water through the electrosurgical knife handle and tip, removing excess heat and maintaining the knife tip temperature within an acceptable range. Research has shown that water cooling systems can significantly reduce the temperature of high-frequency electrosurgical knives and mitigate heat diffusion [16].

The air cooling system uses cool air or carbon dioxide (CO_2) to cool the knife tip and surrounding tissue. This method offers a fast response time and does not interfere with the surgical field of view, making it suitable for short-term procedures or small-scale cuts. In the air cooling system, controlling the flow rate and temperature of the gas is crucial for efficiently reducing temperature without disrupting the surgical operation.

In summary, cooling systems primarily address the second thermal damage mechanism discussed in Chapter 2. By providing additional cooling, these systems help dissipate excess heat rapidly, reducing heat exposure to surrounding healthy tissue. Not only do cooling systems significantly reduce the risk of thermal damage, but they also provide a more stable working environment for surgeons, ensuring optimal cutting and coagulation performance.

The main challenges faced by active cooling systems include the integration of the cooling mechanism into electrosurgical devices, ensuring the stability of the cooling effect, and preventing the surgical field from being obstructed by smoke or vapor produced during the cooling process. Additionally, as temperature changes dynamically, fluctuations in the cooling channel's flow rate can pose potential safety concerns that need to be addressed.

Furthermore, incorporating a cooling system increases the structural complexity and weight of the device, which may reduce the surgeon's operational sensitivity. Cooling systems may also lead to overcooling or condensation, potentially impairing tissue visibility or causing cold-related tissue injury.

To address these challenges, future cooling systems should incorporate artificial intelligence technologies to dynamically adjust the cooling intensity based on real-time temperature readings from the electrode tip. Additionally, passive or compact cooling technologies, such as phase-change materials or thermoelectric components, should be explored further.

Pulsed cutting technology

A recent development in electrosurgery is waveform modulation, specifically pulsed cutting technology. Unlike continuous high-frequency current, this technique delivers energy in short bursts, allowing tissues to cool between pulses.

Pulsed cutting technology replaces continuous high-frequency current with intermittent pulse currents, providing cooling periods during which the tissue can dissipate heat naturally. The principle of this technology is to achieve tissue cutting through short, high-frequency pulses, while the gaps between pulses allow for heat dissipation. By adjusting pulse duration, output voltage, and power can be dynamically controlled in real-time.

This method not only minimizes thermal damage to surrounding tissues but also improves cutting precision, as the tissue remains cooler during the procedure. It is especially beneficial for surgeries where maintaining tissue integrity and reducing thermal damage are crucial.

Firstly, pulsed cutting reduces the average temperature, preventing tissue damage such as protein denaturation and necrosis, which result from prolonged exposure to high temperatures. Secondly, the intermittent current reduces the spread of heat to surrounding tissues, effec-

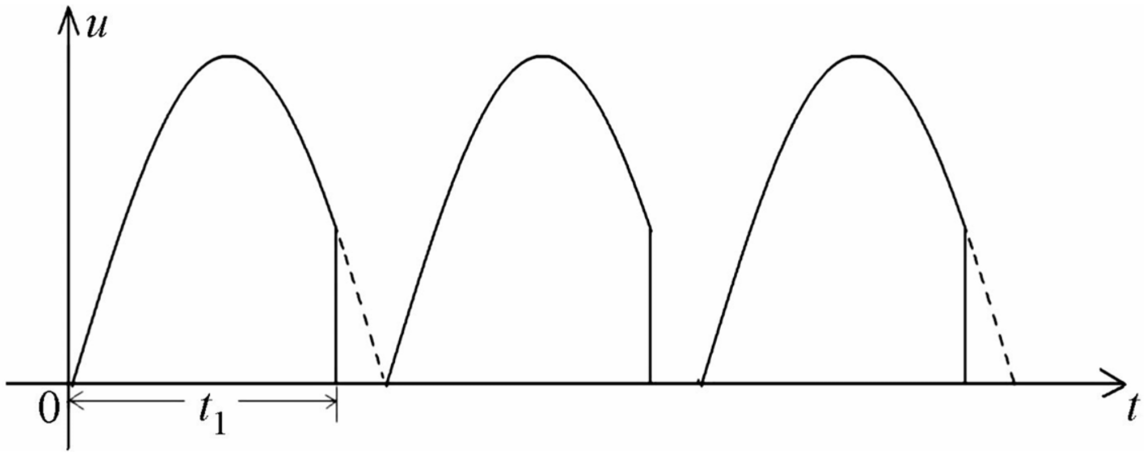

Figure 4. Schematic diagram of pulse cutting power control system output [17].

tively limiting the area affected by thermal damage.

Figure 4 illustrates pulsed cutting technology allows electrosurgical knives to maintain effective cutting performance while significantly reducing thermal damage, making it especially suitable for tissues sensitive to temperature changes. This technique has proven to be an effective, low-thermal-damage surgical method. Experimental results by Bao Congbo et al. demonstrated that without a blank period, widespread heat diffusion and noticeable carbonization occurred [17]. However, with intermittent current blank periods, heat diffusion was greatly minimized, and tissue carbonization was reduced.

Pulsed cutting technology addresses both thermal damage mechanisms discussed in Chapter 2. It achieves power control during electrosurgical output through adaptive algorithms and uses the pulsed method to control excessive heat, effectively reducing the risk of thermal damage.

While pulsed cutting technology is highly effective, its implementation requires precise control of pulse parameters—such as duration, duty cycle, and frequency—to balance efficient cutting with minimal thermal diffusion. Additionally, in regions of dense tissue, cutting efficiency may decrease, and different tissue types respond differently to pulsed energy, making uniform parameter settings difficult.

In summary, the three strategies—intelligent feedback control, active cooling, and pulsed waveform modulation—represent distinct but complementary approaches to minimizing thermal damage in electrosurgery. Their integration into unified, smart surgical platforms may define the next generation of safe and precise electrosurgical devices.

The future development of this technology lies in three main directions: first, the development of adaptive pulse modulation systems based on real-time tissue feedback; second, integrating pulsed cutting with intraoperative image-guided navigation to achieve precise energy targeting; and third, incorporating AI-driven control systems to dynamically adjust pulse output based on tissue response, thereby enhancing cutting precision and surgical safety.

Summary and future outlook

Since the introduction of high-frequency electrosurgical knives, they have revolutionized surgery with their efficient cutting and coagulation abilities. However, the widespread use of these devices has led to thermal damage, which limits their effectiveness. Thermal damage not only affects surgical outcomes and prolongs recovery times but can also lead to surgical failure. Thus, reducing thermal damage caused by high-frequency electrosurgical knives has become a key focus in surgical innovation.

Recent progress has been made in addressing this issue with various technological solutions, such as cooling systems, temperature feedback control, and pulsed cutting modes. Cooling systems effectively lower the knife tip temperature, reducing thermal diffusion from the source. The

Table 1. Comprehensive comparison of three technologies

Evaluation Dimension	Adaptive Control	Active Cooling System	Pulsed Cutting Technology
Effectiveness	Maintains tissue temp <80 °C with real-time feedback	Lowers knife temp by >20 °C; mitigates lateral heat spread	Reduces heat accumulation; carbonization area down ~35%
Applicability	Suitable for most tissues; ideal for long or precise surgeries	Best for large-area or prolonged procedures; limited by structural setup	Ideal for thermally sensitive tissues; protects nerves and vessels
Operational Complexity	High – Requires sensor integration and algorithm control	High – Adds hardware bulk; requires fluid/gas control	Medium – Needs pulse generator and tuning
Cost Impact	+30-50% – Sensors and AI algorithm overhead	+40-60% – Cooling system cost and maintenance	~+10% – Can reuse existing power hardware
Quantitative Evidence	Charring reduced by ~40%; cutting temp stabilized ±2 °C [13]	Tip temp drop ~23 °C; lower lateral spread [12]	Carbonization reduced ~35%; avg temp lower by 10-15 °C [13]
Overall Evaluation	High precision, intelligent; higher threshold for implementation	Effective thermal risk control; best for specific cases	Mature and cost-efficient; suitable for broader adoption

combination of temperature feedback and intelligent power regulation technologies allows for real-time adjustments, minimizing thermal damage to surrounding tissues. Pulsed cutting technology mitigates heat accumulation through intermittent currents, improving the precision and safety of the cut.

These three technologies each have distinct advantages and disadvantages, addressing the reduction of thermal damage through both internal control and external intervention. The outcomes vary in effectiveness depending on the approach, as summarized in **Table 1**.

Despite these advancements, further improvements are still needed, particularly in device complexity, ease of operation, and real-time feedback mechanisms during surgery. Additionally, refining thermal management strategies to accommodate different surgical types, tissue characteristics, and patient variations remains a key focus for future research. The future development of reducing thermal damage in high-frequency electrosurgical knives will likely center around three key areas:

(1) Intelligent Adaptive Control: With the advancement of artificial intelligence (AI) and machine learning, future electrosurgery systems will not only be tools but intelligent assistants [18-20]. By analyzing large amounts of surgical data (such as temperature, impedance, and tissue type), AI will help surgeons adjust the knife's output parameters in real-time, accurately controlling temperature changes during cutting and minimizing thermal damage. For example, deep learning algorithms will allow electrosurgery systems to automatically adjust power, frequency, and pulse modes according to the tissue's real-time status, ensuring optimal cutting and coagulation effects while minimizing thermal damage. Future electrosurgical systems may incorporate additional sensors (e.g., infrared sensors, micro thermocouples, pressure sensors) to monitor multiple data dimensions such as tissue temperature, pressure, and elasticity [20]. Combined with AI for multi-level data analysis, the system could automatically adjust output and issue warnings when tissue temperature nears safety thresholds, ensuring more precise operations and reducing thermal risks.

(2) Higher Precision Temperature Monitoring and Feedback Systems: To further improve cutting precision and reduce thermal damage, future temperature monitoring systems will focus on miniaturization, real-time capabilities, and accuracy. Current temperature sensors (such as infrared or thermocouples) often suffer from large size and slow response times [21]. Future miniaturized sensors will offer more accurate monitoring of small temperature changes in tissue, providing real-time feedback to the electrosurgical system, enabling timely intervention. For example, implantable temperature sensors can be placed directly in the surgical area to monitor temperature changes continuously, providing more accurate data than external sensors. These sensors could wirelessly connect to the surgical equipment, providing

"zero error" temperature feedback and helping avoid tissue damage due to overheating.

(3) Introduction of Innovative Materials with Good Thermal Conductivity and Biocompatibility: Beyond thermal management, innovative surgical materials such as biodegradable staples have been explored for synergistic safety improvement in gastrointestinal anastomosis [22]. With the development of materials science, future high-frequency electrosurgical knives may utilize nanocoating electrodes or biocompatible materials (e.g., the Ti-SS304 layered composite material discovered by Harasani I et al.) to reduce thermal damage [23]. These new electrodes not only improve heat dissipation but also enhance tissue-contact efficiency, reducing carbonization and thermal damage. For example, carbon nanotube coatings can improve electrode thermal conductivity and biocompatibility, stabilizing the electrosurgery during high-temperature cutting and reducing the risk of overheating. Additionally, these materials reduce electrode wear and corrosion, extending the lifespan of the equipment.

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