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Application of electrosurgery in gastrointestinal endoscopy

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Highlights

- Proper parameter settings and mode selection are vital to minimize postoperative complications.
- Third Space Endoscopy offers innovative avenues beyond traditional methods for minimally invasive interventions.

Abstract

With the continuous advancement in medical device technology, minimally invasive surgery has become the cornerstone of modern surgical practices. At the forefront of this evolution is the fusion of medical endoscopes with high-frequency electrosurgical instruments, now a mainstream approach in minimally invasive surgeries, driving the development of innovative surgical procedures. This paper aims to provide an in-depth understanding of the principles of electrosurgical units, with a particular focus on standard procedures in gastrointestinal endoscopic electrosurgery. The goal of this review is to provide a more profound and comprehensive insight into endoscopic electrosurgery for medical practitioners and patients. Through the comprehensive study, it is anticipated to serve as a guide and reference for improving surgical outcomes, reducing patient discomfort, and simplifying the tasks of healthcare professionals.

Keywords: Electrosurgery, gastrointestinal endoscopy, clinical application

Introduction

High-frequency electric knife, with advantages such as rapid cutting speed, effective hemostasis, and convenient operation, notably simplifies surgical procedures for medical personnel and minimizes patient discomfort. Widely employed in various surgical disciplines, including general surgery, thoracic surgery, urology, otorhinolaryngology, cardiovascular surgery, gynecology, plastic surgery, orthopedics, and neurosurgery, the high-frequency electric knife has become an indispensable tool in surgical interventions. With the continuous progress of medical instruments, minimally invasive medicine has become pivotal in modern surgical practices. The integration of medical endoscopes with high-frequency electric knives, equipped with both cutting and coagulation capabilities, has become a prevalent approach in minimally invasive endoscopic surgeries, fostering the development of novel surgical techniques. However, many endoscopists lack comprehensive training and understanding of electrosurgical equipment. Therefore, this paper aims to enhance the knowledge and proficiency in managing electrosurgical units (ESUs) by introducing the principles of electrosurgery, associated equipment, and application of electrosurgery in gastrointestinal endoscopy.

Development of electrosurgery

The development of high-frequency electric knife is intricately linked with the discovery and evolution of electricity, as well as the profound exploration of electro-medicine by scholars throughout history. Goldwyn categorized the foundational epochs of electro-medicine into three significant historical periods leading up to

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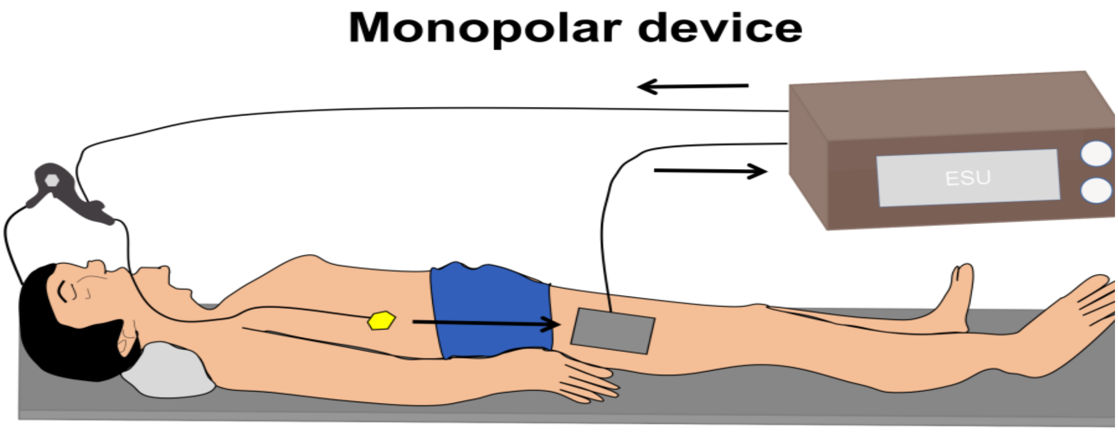

Figure 1. Monopolar device circuit. ESU, electrosurgical unit.

the introduction of the high-frequency electric knife [1]. The first epoch commenced with the discovery of static electricity, wherein static electricity was emerged as recognized as the only known form of electricity [2]. The second epoch, starting in 1786, was marked by Luigi Galvani's observation that frogs' legs spasm upon contact with different metals, introducing the concept of "animal electricity" [3]. In 1800, Volta et al. invented the "Voltaic pile", confirming that continuous electrical stimulation could induce sustained muscle contractions, laying the groundwork for electro-medicine [4]. The third epoch can be traced back to 1831, when Michael and Joseph independently discovered the phenomenon of "electromagnetic induction", a breakthrough that significantly accelerated development of electro-medicine [5].

The precursor to the high-frequency electric knife emerged in the late 19th and early 20th centuries. In 1891, Jacques discovered that high-frequency electrical currents above 100 kHz passing through the human body did not cause pain but elevated the temperature [6]. This breakthrough paved the way for electrosurgical technology. In 1900, Joseph, while treating a patient with high-frequency electric current, accidentally discovered that the electric arc generated by the electrode could coagulate the skin [7]. Subsequently, he successfully treated a patient with a hand ulcer using this electric arc current [7]. This event is considered the birth of electrosurgery. In 1926, Harvey performed the world's first electrosurgical procedure using an electric knife manufactured by William, ushering in the era of electrosurgery [8].

Early high-frequency electric knives primarily utilized spark gap discharge mechanisms, relying on capacitors, inductors, and adjustable spark electrodes. They generated arc sparks through high alternating current voltage, posing a significant risk of burn accidents and carrying substantial inherent risks [9]. With the development of semiconductor technology, high-frequency electric knife devices gradually transitioned to utilizing semiconductor technologies such as transistors and metal-oxide-semiconductor field-effect transistors, coupled with high-frequency sinusoidal waves with lower harmonic components as the output waveform. Simultaneously, high-performance microprocessors were employed for control, enhancing the precision and safety of equipment control [10, 11].

Today, high-frequency electric knives find widespread application across various surgical disciplines. With the deepening of the concept of minimally invasive surgery, high-frequency electric knives are also commonly used in endoscopic procedures. For example, VIO series electrosurgical devices manufactured by ERBE Elektromedizin GmbH utilize Hybrid Knife technology, enabling various digestive surgical procedures in conjunction with endoscopy [12]. In contrast to traditional open surgy for gastrointestinal disorders, which are characterized by minimal patient trauma, thorough curative outcomes, and lower treatment costs. These procedures have evolved into the primary therapeutic modality for early gastrointestinal diseases on an international scale in recent years.

Principles of electrosurgery

Electrosurgery utilizes electrical energy to generate heat effects for medical purposes, such as excision, incision, hemostasis, and inactivation of target tissues. The therapeutic foundation of all electrosurgical procedures lies at the cellular level, where heat effects are induced. When high frequency alternating current, generated by ESUs, flows through tissues along the circuit, it encounters resistance which generates heat [13]. Specifically, within

Table 1. The thermal effect of human tissue

Temperature	Effect
≤40 ℃	No effect.
40-50 ℃	Cell membrane and intracellular structures change depend on the duration of heating.
50-60 ℃	Coagulation (denaturation) of cellular proteins; Loss of viability.
60-80 ℃	Coagulation of extracellular collagen; Disruption of cell membrane.
80-100 ℃	Vaporization of tissue fluid; Desiccation and damage to cells; Tissue rupture resulting in incisions.
>150 ℃	Carbonization.
>300 ℃	Evaporation.

the circuit of high-frequency alternating current, the anions and cations within the tissue migrate towards positions near the positive and negative poles, respectively, based on the current-voltage direction. As the polarity rapidly changes, the movement direction of anions and cations within the tissue also changes swiftly. These particles oscillate rapidly within the cytoplasm, converting electrical energy into mechanical energy and, through friction, ultimately transforming into heat energy, resulting in a thermal effect [14]. These effects are primarily determined by the temperatures achieved, as outlined in **Table 1**. The most crucial effect of electrosurgical procedures is the denaturation of proteins, varying from coagulation at 60 °C to evaporation at 100 °C. The speed and extent of these processes depend on the heating rate and effective duration of temperature elevation [15].

ESUs, which generate electrosurgical energy, can be categorized into monopolar and bipolar devices, based on the current path. Monopolar technology is defined as high-frequency electric current flowing to the active electrode towards the target tissue, then returning through the body to the neutral grounding pad, ultimately forming a circuit, as shown in **Figure 1**. The current intensity (I) is defined as the ratio of the quantity of charge (q) through a conductor's cross-section to time (t), mathematically expressed as $I=q/t$. Current intensity is a physical quantity that describes the strength of the current at a specific point in an electrical circuit, representing the amount of current passing through a unit cross-sectional area. Current intensity is directly proportional to voltage (U) and inversely proportional to resistance (R). A higher working voltage leads to greater current intensity, while higher resistance results in lower current intensity [16]. Therefore, smaller tissue surfaces in contact with the active electrode generate higher current intensity, producing more significant thermal effects. In contrast, the contact area with the neutral grounding pad, which is well in contact with the body compared to the active electrode, has a larger surface area, making the thermal effects negligible. However, if there is poor contact with the neutral grounding pad, localized temperature elevation may occur, potentially causing skin burns. Thus, operators should be cautious in such cases. Bipolar technology involves high-frequency electric current emanating from one pole of the bipolar electrode, passing through nearby tissue to reach the other pole and then returning to the ESU, completing a circuit, as illustrated in **Figure 2**. The advantages of bipolar technology include the reduced travel distance of current within the body, limited thermal damage, and the ability to achieve similar effects with lower power, thereby reducing the risk of perforations [17]. Most ESUs used in digestive endoscopy support both monopolar and bipolar modes. However, monopolar mode is preferred due to its compatibility with a wider range of surgical instruments, facilitating both cutting and coagulation. On the other hand, bipolar mode instruments are generally less available and mainly designed for coagulation, with only a select few intended for cutting. Currently, despite the development of instruments suitable for bipolar mode, such as polypectomy snares, thermal biopsy forceps, sphincterotomes, IT knives and others, their widespread use remains limited [18-20]. This is partly due to their higher design and manufacturing costs compared to monopolar instruments. In summary, it is essential for endoscopists to have a thorough understanding of the characteristics of the instruments they choose to reduce the risk of accidents.

In addition to device types, the output waveform mode is also crucial. ESUs are designed to offer operators various output waveform modes labeled as "Cut", "Blend", "Coag" and others. It's important to note that these names are not standardized, and modes may vary with the same name between ESUs produced by different companies [21]. Endoscopists should

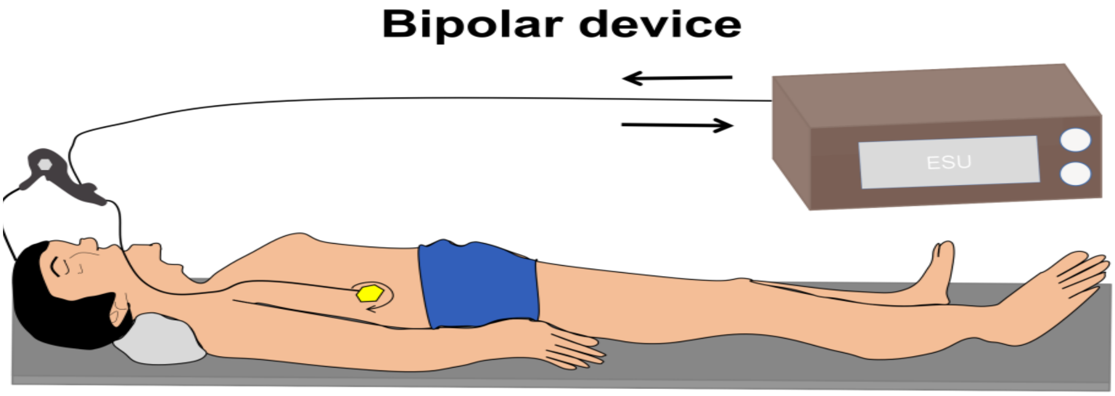

Figure 2. Bipolar device circuit. ESU, electrosurgical unit.

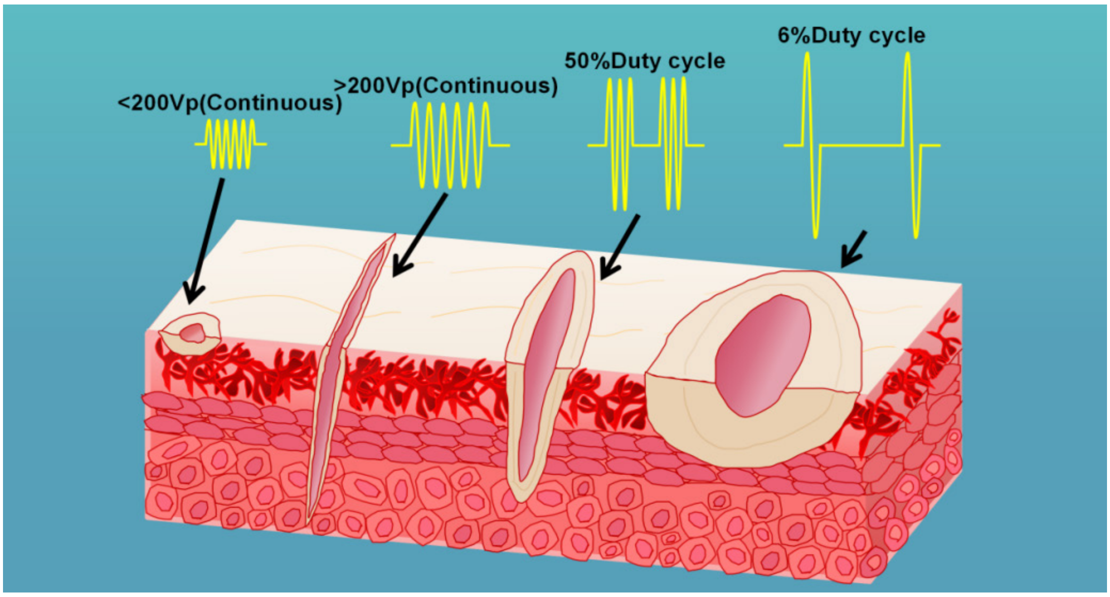

Figure 3. The effect of different waveforms.

carefully read the user manual of devices prior to operation. A profound understanding of the selected output waveform is crucial, as mode names can sometimes be misleading. For example, many outputs labeled as "Coag" can produce significant cutting capabilities. Pure coagulation effects can only be achieved with waveforms where the voltage peak does not exceed 200 V, commonly known as "Soft Coag" [22]. ESUs typically produce output ranging from continuous low-frequency sine waves to modulated interrupted higher-frequency sine waves, as illustrated in **Figure 3**. When the voltage peak of continuous waveforms exceeds 200 V, it rapidly generates high current density along the electrode, which creates a significant amount of heat, causing cell explosions, and results in a cutting effect. Cells farther from the electrode do not receive enough heat to explode, leading to coagulation. Even in modes labeled as "Pure Cut," there may be some coagulation along the cutting edge. Accurate "Pure Cut" is achieved only with cold-cutting instruments like surgical knives. When using an electrosurgical knife at voltages exceeding 200 V, the coagulation depth along the cutting-edge increases. However, it is impractical to endlessly boosting voltage for more coagulation, especially beyond about 600 V peak voltage due to excessive power [10]. The released heat (Q), calculated using Joule's law, is the product of power and time ($Q=W\times t$). By combining Ohm's law in this equation ($Q=V\times I\times t=I^2\times R\times t$), there is a risk of carbonization on cutting surfaces [22]. Intermittently halting the output allows tissue cooling, increasing the proportion of cells that dry without exploding. By adjusting the duty cycle and applying higher voltage peaks in the output, the coagulation edge of the tissue can be enhanced, achieving a deeper hemostatic effect. These modulated waveforms are termed "Blend" and "Coag." Typically, coagulation waveforms have a lower duty cycle, ranging between 6% and 12%, while blend waveforms have a duty cycle between 12% and 80% [23]. "Crest factor" is another concept when discussing waveforms and is often found in the ESU product manuals. It refers to the ratio of the current peak value to the effective current value on the load. For instance, the crest factor

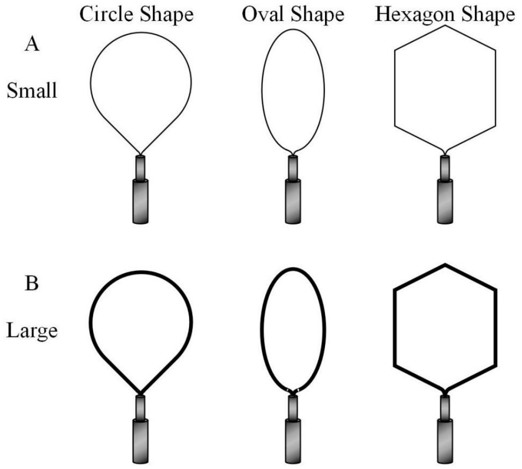

Figure 4. Different shapes and sizes of snares. (A) Small size snares; (B) Large size snares.

for a continuous sine wave is 1.4. Generally, cutting waveforms are characterized by crest factors less than 2, while blend waveforms have crest factors ranging between 2 and 5 and coagulation waveforms have crest factors ranging between 5 and 8 [22]. Endoscopists should understand the electrophysiological characteristics produced by different waveform modes and choose the most appropriate mode based on practical application scenarios.

Application of electrosurgery in gastrointestinal endoscopy

Endoscopic surgery has emerged as a safe and effective method for treating early gastrointestinal lesions, replacing traditional open surgery as a routine endoscopic treatment method [24]. The Paris endoscopic classification now plays a pivotal role in clinical practice, serving as the gold standard for endoscopic and visual assessment of gastrointestinal lesions [25]. In clinical practice, the Paris classification is widely employed to determine the type of lesion for subsequent selection of resection methods based on the size, location, and pathological diagnosis of the lesion. Gastrointestinal polyps are the most prevalent lesions encountered in clinical practice. Given the risk of malignancy associated with these lesions, early diagnosis and treatment are crucial. Endoscopic treatment for gastrointestinal polyps often employs various electrocautery techniques, such as hot snare polypectomy (HSP), argon plasma coagulation (APC), endoscopic mucosal resection (EMR), and endoscopic submucosal dissection (ESD). Additionally, the growing experience in endoscopic surgery and technological advancement has led to the development of a new technique that creates a submucosal tunnel, introducing a novel domain known as "third space endoscopy" for treating gastrointestinal ailments. One representative procedure of this frontier technology is peroral endoscopic myotomy (POEM) for esophageal sphincter myotomy.

HSP

Depending on the type of electrosurgical devices, polypectomy is divided into cold snare polypectomy (CSP) and HSP. CSP is generally effective for polyps measuring 3-5mm in diameter [26, 27]. It offers a shorter operating time and lower risk of thermal injury to the intestinal wall [28]. For polyps measuring 5-10mm, both methods have pros and cons, with CSP having a higher risk of incomplete resection [29]. For polyps of 10-19 mm, the European Society of Gastrointestinal Endoscopy recommends using HSP technology [30]. Compared to CSP, the cauterization effect of HSP may extend to the submucosal layer, making it more suitable for deep and complete removal of larger polyps. Submucosal preventive injection of normal saline, adrenaline, or other mixtures is recommended before HSP to reduce the risk of bleeding and prevent deep colonic mucosal thermal injury [30-32]. The HSP procedure involves positioning the hot snare into the biopsy channel, completely snaring the polyp, gradually tightening the snare, and subsequently connecting the electrosurgical energy-generating device to the snare for complete resection. Doctors need to choose the appropriate snare instrument based on the size and shape of the lesion. Commonly used snare instruments include circular, oval, hexagonal, etc., as illustrated in **Figure 4**. It's crucial to recognize that the choice of snare affects the current density and the nature of the cut: a thinner-edged snare yields a higher current density for precise cutting, whereas a thicker-edged snare offers lower current density, favoring coagulation. Currently, the Blend mode is the preferred option during the HSP process. A pure cutting mode may elevate the risk of transient bleeding with limited hemostatic effects. In contrast, a coagulation mode may increase the potential for transmural damage to the intestinal wall due to its deeper action, leading to electrosurgical syndrome [33]. Therefore, the Blend mode, which has a cutting effect at the excision site and a coagulation effect at the excision edge, represents the most suitable choice.

APC

APC is a non-contact tissue coagulation technique that utilizes argon gas discharge under atmospheric pressure to coagulate tissue without requiring the tissue to adhere to the electrode. Its application in electrosurgery is

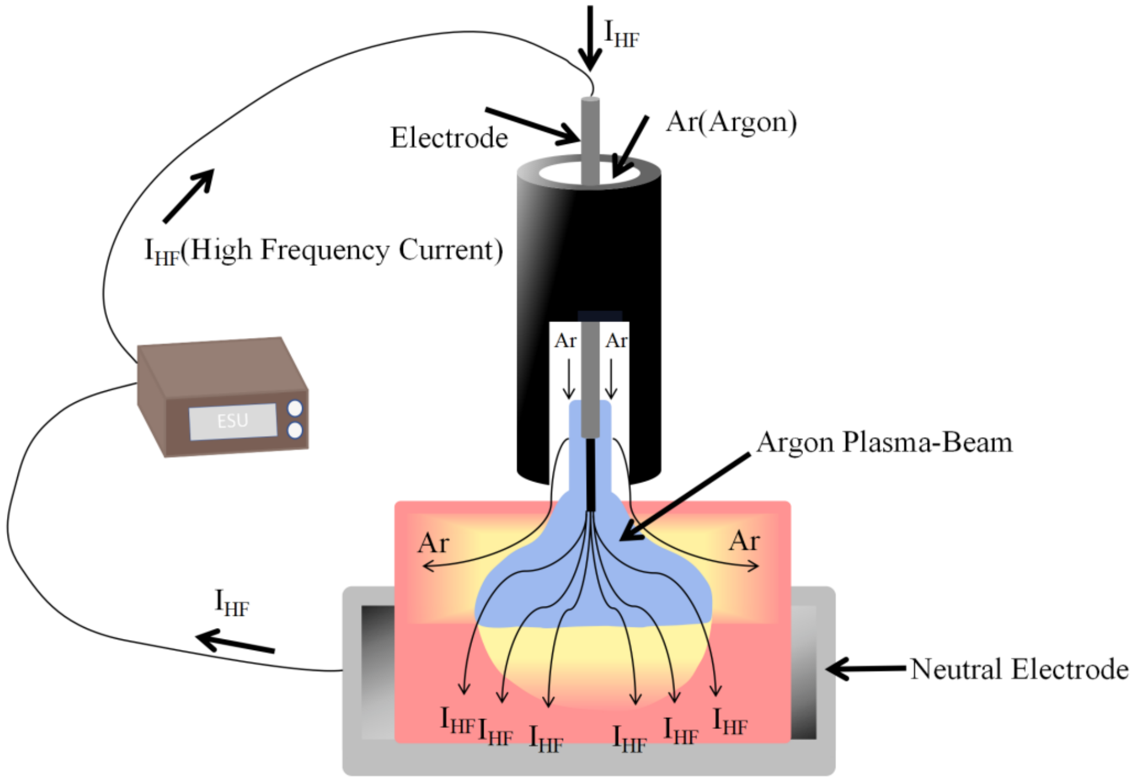

Figure 5. The fundamental working process of argon plasma coagulation.

widespread. Initially introduced in open surgical procedures in the late 1970s, APC found its endoscopic application in 1991, quickly becoming the preferred endoscopic coagulation technique [34, 35]. Argon gas was chosen due to its biochemical inertness, low breakdown voltage, and relatively low cost [36]. The principle of operation involves the transmission of electrical energy to the target tissue through an ionized argon plasma jet. The basic working process is illustrated in **Figure 5**. As tissue conductivity decreases and resistance increases, the argon plasma will automatically shift from the high resistance zone to the low resistance zone. The penetration depth of coagulation is limited to a few millimeters. Compared to other endoscopic thermal coagulation methods, APC provides quick hemostasis, minimal bleeding, and reduced scab formation. Typically, APC can be used as an adjunctive treatment for gastrointestinal polyps, effectively reducing postoperative residual tissue. Brooker et al. evaluated the role of APC in preventing recurrence at the polypectomy sites and confirmed its safety and effectiveness [37]. In addition, this technique is also suitable for treating erosion, ulcers, polyps, tumors, and other superficial lesions of the digestive mucosa by halting bleeding, relieving pain, and mitigating inflammation. Hybrid APC is a relatively new technology in this field. It combines traditional APC with prior submucosal injection using water jet-assisted submucosal dissection, representing a development of APC technology [38]. Compared to standard APC, submucosal injection serves as a heat sink to disperse energy, ensuring that the underlying intrinsic muscle layer remains unaffected and only the intact mucosal layer is coagulated, providing better safety [39].

EMR

EMR is a minimally invasive endoscopic surgery developed by Japanese experts in the 1980s [40]. It aims to completely remove pathological mucosa by submucosal dissection. EMR surgery is mainly suitable for early cancer surgery and can also be extended to removal of polyps and resection of partial precancerous lesions, typically those smaller than 20 mm. The most used techniques can be further categorized as injection-assisted EMR, as shown in **Figure 6**, cap-assisted EMR, as shown in **Figure 7**, and ligation-assisted EMR, as shown in **Figure 8**.

Injection-assisted EMR

The initial step of this technique involves injecting a solution into the mucosa to lift it, making it easier to capture the lesion. The common injection substances include physiological saline, a combination of fibrinogen, sodium hyaluronate, hydroxypropyl methylcellulose, glycerol, or hydroxyethyl starch. This injection serves as a buffer zone between the lesion and normal tissue, minimizing damage to the deeper layers of gastrointestinal wall during electro-surgery. Staining agents can be mixed into the injection

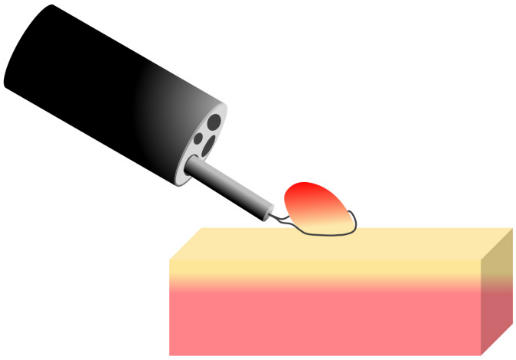

Figure 6. Injection-assisted endoscopic mucosal resection.

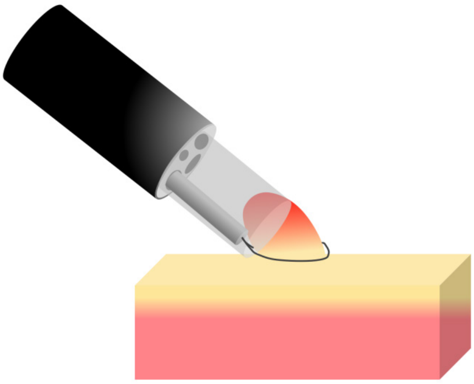

Figure 7. Cap-assisted endoscopic mucosal resection.

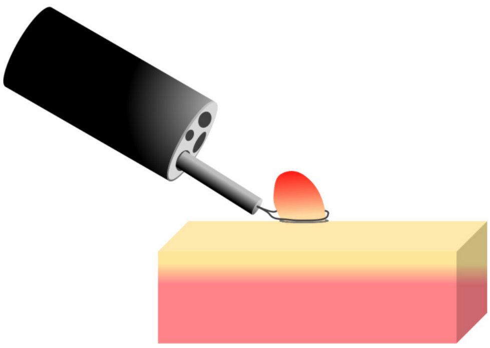

Figure 8. Ligation-assisted endoscopic mucosal resection.

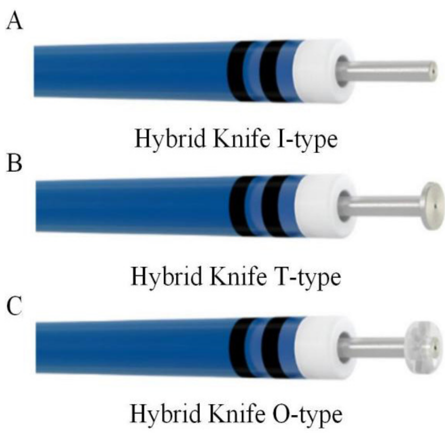

Figure 9. Hybrid Knife. (A) I-type; (B) T-type; (C) O-type. This figure was cited from the official website of Hybrid Knife (ERBE Elektromedizin GmbH).

material to identify the boundaries of the lesion more clearly [41]. Current research indicates that using autologous blood or adrenaline as injection materials can more effectively reduce the risk of bleeding and perforation [42, 43]. If the lesion cannot be effectively raised during injection, it may indicate deeper tissue invasion, and EMR should not be used for excision in such cases.

Cap-assisted EMR

This technique does not require submucosal injection. It involves using a cap-fitted endoscope to aspirate the lesion tissue, followed by excision using the electric surgery snare technique. The cap is typically made of transparent plastic, usually in a straight cylindrical shape or with an oblique pointed end. It can be either soft or hard, chosen based on the specific surgical site. Soft caps are commonly used in EMR procedures as they can reduce mucosal damage during surgery [44]. For gastric lesion surgeries, a straight cap is often used, while for esophageal lesion resection procedures, an oblique cap is commonly employed to compensate for the position and angle of the endoscope relative to the esophageal wall [45].

Ligation-assisted EMR

This technique does not require submucosal injection. Instead, it involves placing a variceal ligation band on the lesion tissue. Using suction, the lesion is pulled into the ligator. The contracting force squeezes the mucosa and submucosal layers without capturing the intrinsic muscle layer. Subsequently, the ligator is removed, and the lesion is excised using the electric surgery snare either above or below the ligated band [45].

ESD

ESD is an advanced technique for the endoscopic removal of mucosal lesions, offering a minimally invasive treatment for early gastrointestinal cancer lesions. Originating in Japan in the late 1990s as a treatment for early gastric cancer, ESD's applicability has expanded to include esophagus and colon lesions [46]. ESD offers advantages over EMR: notably its ability to excise larger lesions irrespective of their size, bringing about higher cure rates, lower recurrence rates, and precise histopathological analysis [47]. However, research indicates that EMR may be more advantageous for lesions (<10 mm) in size [48]. Currently, ESD has largely replaced EMR as the preferred surgical approach for early cancer surgeries worldwide, due to its growing prevalence and effective [49, 50]. The core steps of ESD involve lesion marking, submucosal injection to lift the lesion, dissecting, and achieving hemostasis. The technique employs a variety of specialized surgical knives, including the Dual Knife (Olympus), Flex Knife (Olympus), Flush Knife (Fujifilm), Hook Knife (Olympus), Triangle Tip Knife (Olympus), Hybrid Knife (ERBE Elektromedizin GmbH) and so on. Each knife has its own advantages, allowing for a rational selection based on lesion location and structural characteristics [51]. The Hybrid Knife from ERBE Elektromedizin GmbH is particularly advantageous as a multifunctional tool suitable for marking, excision, and submucosal injection. It significantly reduces the need for frequent instrument changes during surgery, thereby improving operational efficiency. Its integrated central capillary tube, when used in conjunction with the ERBEJET 2 system, can generate a 120 μm water jet for submucosal injection. The Hybrid Knife is available in three models: I-type, T-type, and O-type, as shown in **Figure 9**, offering greater flexibility in selection. **Figure 9** was cited from the official website of Hybrid Knife (ERBE Elektromedizin GmbH). Common ESU devices used in clinical endoscopic treatment include the ERBE VIO200S, VIO200D, VIO300S, and VIO300D series. Many other companies also offer similar ESU devices suitable for endoscopic treatment. However, regardless of the choice for ESU or knife, it is essential to adjust parameter settings flexibly based on the actual cutting and coagulation needs during surgery, in accordance with the clinician's experience, to achieve safe and effective surgery. Despite the absence of specific guidance on ESU settings for ESD surgery, a study by Masamichi Arao et al. regarding the use of the ENDO CUT mode and FORCED COAG mode of the VIO300D in pig esophageal endoscopic submucosal dissection demonstrated that the ENDO CUT mode significantly reduced the stricture rate and fibrosis degree compared to the FORCED COAG mode [52]. Additionally, Tonai et al. used the VIO300D to assess the effects of various modes on fibrosis and stricture in pig muscle layers after ESD, and found that among all ESU modes, the ENDO CUT mode exhibited the lowest stricture and fibrosis [53] . Therefore, it is recommended to minimize the use of the coagulation mode in regions prone to stricture formation, such as the esophagus, to reduce the occurrence of postoperative stricture-related complications.

POEM

In 1957, Hirschowitz developed the fiber optic scope, laying the groundwork for the invention of a stomach camera equipped with this technology that was subsequently widely adopted in Japan [54]. This innovation paved the way for endoscopy in the colon, esophagus, and duodenum [55]. The traditional endoscopic examination process, known as the first-space endoscopy, was conducted within the natural cavity of the gastrointestinal tract. In 2004, Kalloo et al. performed transoral intraperitoneal endoscopy in a porcine model, introducing the concept of second-space endoscopy [56]. In 2007, Sumiyama et al. first described the technique of using a mucosal flap valve to safely breach the gastrointestinal wall in a porcine model, known as submucosal tunneling technology [57]. Pasricha et al. further used this technique to successfully implement submucosal endoscopic myotomy in a porcine model [58]. Finally, in 2008, Inoue et al. performed the first case of POEM to treat achalasia, ushering in a new approach for third-space endoscopy treatment [59].

POEM, the first successful innovative technique in third-space endoscopy, has emerged as the preferred treatment for achalasia and other esophageal spastic disorders [60, 61]. The procedure involves several key steps: mucosal incision, submucosal dissection, myotomy, and mucosal closure [62]. When establishing the submucosal tunnel, it is essential to perform a thorough submucosal injection to ensure an excellent surgical field. Close attention should be paid to the condition of submucosal vessels to minimize bleeding. Prompt coagulation is necessary to maintain a clear view in case of bleeding. During POEM, a strong coagulation mode with high pressure and low duty cycle is typically used for small vessels or large capillaries. In contrast, a soft coagulation mode with <200 Vp continuous is used for significant vessels [63]. It is essential to wait for complete hemostasis before resuming cutting to ensure a clear surgical field. So far, there is limited data on the optimal mode and power settings of electrosurgical devices for endoscopic tunneling techniques, and research on this topic is still lacking. Parameter settings are mainly based on the equipment's actual conditions and endoscopists' personal experience, with common modes and power settings similar to those used in EMR and ESD [64].

Conclusions

Over the past 40 years, high-frequency electrosurgical technology has evolved and wide applied in digestive endoscopic examinations. In electrosurgical procedures, high-frequency electric current generates heat within tissues.

The various parameters of electrosurgical energy-generating devices, including current waveform, power, electrode type, and the specific device used, are closely associated with the occurrence of surgical complications. The parameter settings may vary significantly depending on the type of procedures. Therefore, it is essential for endoscopists to have an in-depth understanding of electrosurgical devices and their settings, which is critical to optimizing the safety and efficacy of a wide range of surgical interventions.

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