Energy Sources for Laparoscopic Endometriosis Treatment: Reconsidering the CO_2 Laser

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Case Introduction

Endometriosis is an inflammatory disorder defined by the presence of endometrial glandular and/or stromal cells outside the uterine cavity, primarily on the pelvic peritoneum and ovaries[1,3]. An estimated 10% of reproductive-aged women worldwide are affected by the disease, with highest incidence between the ages of 25-29 years[1,4].
Clinical symptoms range from fatigue, dysmenorrhoea, pain at ovulation, and dyspareunia, to chronic severe pelvic pain and infertility[2,5]. The goals of endometriosis treatment are to alleviate symptoms by reducing or removing endometriotic tissue, and to improve or preserve fertility for women who desire pregnancy[4].

Medical treatments for endometriosis create an unfavorable milieu for growth and maintenance of endometrial tissue through hormonal manipulation of the menstrual cycle in an attempt to produce pseudo-pregnancy, pseudo-menopause, or sustained anovulation[6,7]. However, in patients with more extensive disease (revised American Fertility Society (rAFS) classification grade III or IV[8]), hormonal modulation rarely yields satisfactory longterm results as pelvic pain associated with fibrotic alterations and scar tissue may be refractive to medical therapy[6]. There is no role for drug therapy in treatment of endometriosis-related infertility[7]. Surgical removal of endometrial tissue is the most effective treatment for improving fertility, relieving moderate to severe pain, and removing deep infiltrating endometriosis (DIE), i.e., endometriosis infiltrating deeper than 5-6 mm beyond the peritoneum (Figure 1)[4,9,10]. Surgical treatment has been reported to be associated with significant improvements in quality of life (QOL), and low rates of recurrence[1,11-16]. Within 1 year of initial diagnosis, as many as 65% of patients undergo some type of surgical procedure for endometriosis, most commonly therapeutic laparoscopy[1,4]. Indeed, it has become standard practice to remove endometrial tissue and endometriomas at the same time as laparoscopic diagnosis to reduce the need for additional surgery[4,17].

Surgical objectives are to remove all endometrial lesions and restore normal pelvic anatomy. Electric current and laser light are used to desiccate, coagulate, cut, and vaporize tissue. The choice of energy source for removal of endometrial tissue depends on the type, extent, and location of the lesions. Surgeons are familiar and comfortable with electrosurgical instruments, and most are less costly than laser technology, but they can cause injury to surrounding tissue and other organs from unnoticed electrical energy burns[18]. Laser surgery is not associated with many of the complications seen with electrosurgery. Several types of surgical lasers are commercially available. They are usually named for the atomic medium that is being stimulated to produce the single-wavelength photons. Carbondioxide (CO_2) lasers are the most widely used for gynecologic surgery[19]. Compared with all available energy sources, CO_2 lasers are especially well suited for excision and ablation of endometrial tissue in the pelvic cavity because they are precise, have a very short depth of tissue penetration (0.1 mm), can coagulate small blood vessels, and produce the least thermal spread compared with electrosurgical instruments and other laser types[10,17].

The complexity of laparoscopic procedures aimed at treating various fertility-related disorders, including endometriosis and adhesions, has increased substantially over the years with a clear trend for more aggressive, multidisciplinary treatment modalities[16,20]. Removal of DIE can pose a tremendous surgical challenge, as in many cases pathology is multifocal and located in tight proximity with important intraabdominal structures such as the bowel, ureters, urinary bladder, and major blood vessels. Electrocautery-based treatment carries a higher risk of causing transmural thermal injury than the CO_2 laser[17,22]. Thermal injury to the bowel (e.g. perforation or abrasion) during laparoscopic gynecologic surgery often goes undetected, causing serious postoperative complications including sepsis and death[21]. In a series of 12 laparoscopic bowel complications, 50% were attributed to thermal injury from electrocautery devices[21]. The CO_2 laser is more precise than electrocautery and does not cause thermal injury away from the site of impact[17,22].

Despite its many potential benefits, ergonomic challenges to operating early CO_2 laser technology may have limited its use to specialists in endometriosis referral centers. Technical advancements and refinements made based on clinical experience have improved the operational and functional capabilities of current CO_2 lasers to an extent that supports more mainstream use of the lasers for endometriosis surgery.

Figure 1. Endometriosis diagnostic and treatment algorithm (from Hoffman et al[3])

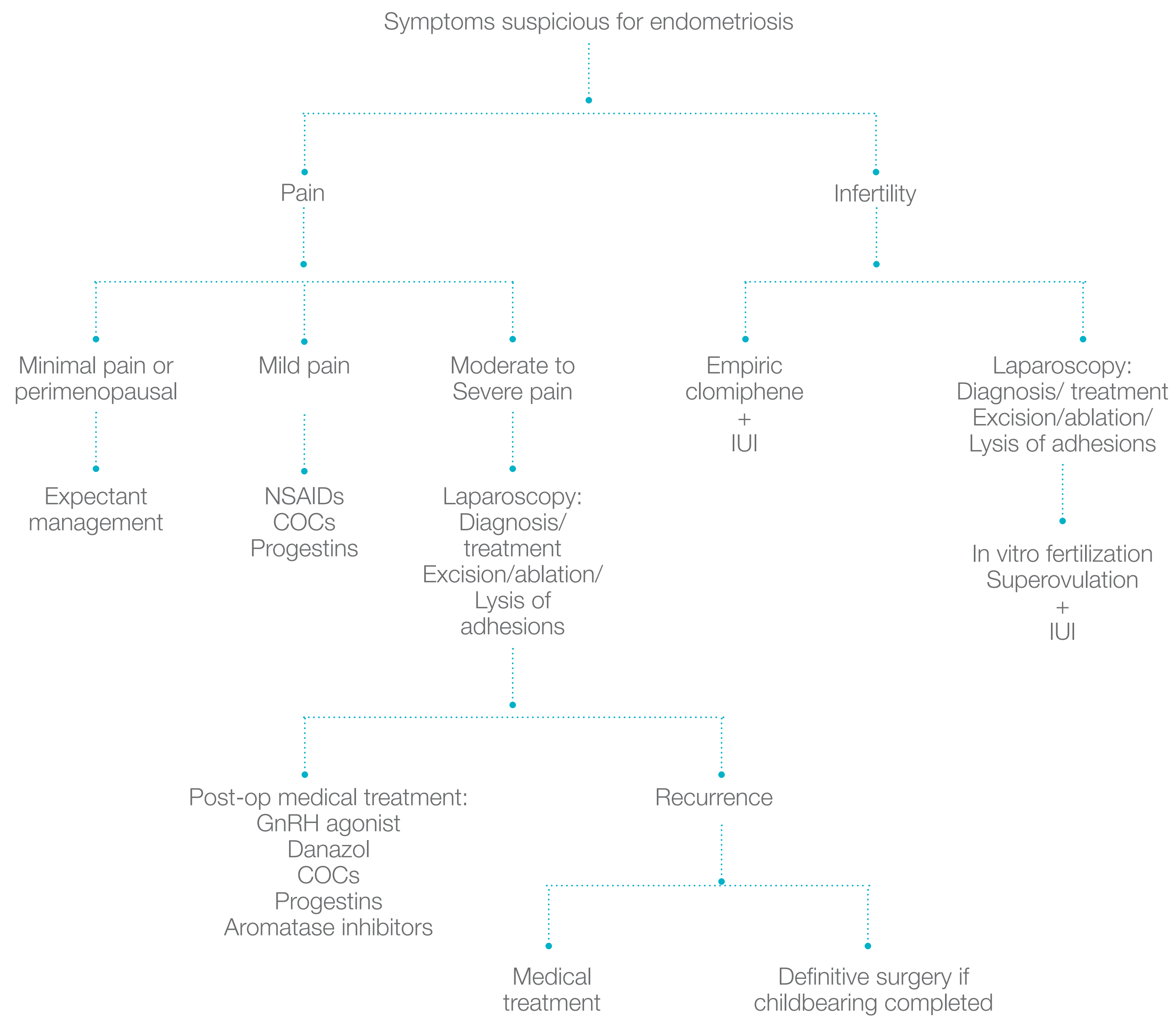

Figure 1. Diagnostic and treatment algorithm for women with presumptive or proven endometriosis. COCs = Combination Oral Contraceptives; GnRH = Gonadotropin Releasing Hormone; IUI = Intrauterine Insemination; NSAIDs = Nonsteroidal Anti-inflammatory Drugs

Surgical Techniques and Tools for Removing Endometrial Tissue

No matter what energy modality is employed, intracellular and parenchymal events depend on the rate of temperature rise in tissue, which is determined by how highly concentrated the energy applied to a given tissue volume is, and on the duration of temperature elevation[23]. Delivery of lower temperatures for longer durations produces coagulation. As intracellular water is heated toward 100°C, liquid is vaporized to steam. If heat diffusion across cell membranes outpaces the formation of intracellular water vapor (i.e., at temperatures below 100°C), tissue eventually becomes coagulated, either superficially (fulguration) or deeply (desiccation)[18]. Conversely, if formation of water vapor outpaces heat diffusion, increasing atmospheric pressure from steam causes a burst of cellular components into a plume of water vapor and tissue fragments, resulting in excision or vaporization. Excision and vaporization need not be mutually exclusive; Thermal Excision by Linear Vaporization (TEL-V) is a common technique. During vaporization, transfer of heat to adjacent tissue is minimal because of the rapid cellular disruption and ventilation provided by emissive steam.

Electrical Energy

Monopolar and bipolar electrosurgical instruments utilize high-frequency radio waves to provide electric current. With monopolar instruments, heat is generated in tissue via transmission of the electron flow through a conductive medium (electric cable) and through the patient to a grounding pad. The conductance or resistance of the tissue determines the flow of current toward ground to complete the circuit[23]. With sufficient voltage (at least 200 volts), electrosurgical instruments cut or vaporize tissue via an electric arc[23].

Alternately, contact between the electrode and tissue reduces current density and tissue is heated more slowly leading to desiccation and coagulation at the surgical site. The argon beam coagulator is a monopolar electrosurgical device that uses a flow of argon gas through an electrode canula to form a bridge of highly modulated electric arcs to produce fulguration[23].

Bipolar electrosurgery uses two small electrodes of the same size, one is active and the other serves as a return electrode. With bipolar instruments, the flow of current is restricted to the tissue between the two poles rather than through the patient, making it safer for the patient than monopolar electrosurgery.

Standard bipolar instruments deliver lower power than monopolar devices and are typically reserved for coagulation and removal of superficial endometrial lesions[23,24]. The LigaSure (Covidien, Boulder, Colorado, USA) is a proprietary bipolar device with integrated impedance and/or temperature monitoring primarily designed for vessel sealing and tissue coagulation. The LigaSure device has been associated with reduced-but not negligible-thermal spread, blood loss, and surgical time compared with conventional electrosurgical instruments[25,26].

The risk of complications from electrosurgery has decreased over the last few decades, but the potential for unintended thermal injury to surrounding tissue or far from the surgical site remains[23]. The potential for collateral thermal damage is greatest with monopolar surgical instruments because electricity can arc to nontarget tissue (e.g., the bowel), and insulation failure, direct coupling (current is diverted from the instrument to another metal instrument), or capacitive coupling (current transfer without direct contact) can cause electrical burns to surrounding organs that may go unnoticed during surgery[10]. At high temperatures, tissue can adhere to the electrode surface of monopolar and bipolar instruments, forming carbon deposits and char, which direct energy away from the target tissue. With bipolar surgical devices, there is less risk of thermal injury to surrounding tissue and hemorrhage is reduced. Because bipolar instruments require tissue displacement by forceps, visibility can be compromised at the surgical site[23]. Visibility of pelvic structures may be further compromised by the smoke generated by electrosurgical instruments, rendering it difficult to distinguish the plane between the endometrial lesion and healthy tissue. The smoke produced during electrosurgery can be cytotoxic, genotoxic, and have mutagenic properties, making it an environmental hazard to the surgical team[27,28].

Less smoke is produced by the argon beam coagulator because there is a lower depth of tissue damage. However, a potential danger of using the argon beam coagulator for endometriosis surgery is that the high-flow infusion of argon gas can cause a rise in intraabdominal pressure and predispose the patient to life-threatening gas embolism[27]. A drawback to the LigaSure device is that the sophisticated impedance/temperature feedback mechanism makes LigaSure more fragile and subject to damage than standard electrocautery devices. Generic monopolar and bipolar electrosurgical tools are typically reusable and relatively inexpensive, whereas the LigaSure is a single-use device that requires a proprietary electrosurgical generator for power, making it much more costly[29].

Ultrasonic Energy

Ultrasonic devices such as the Harmonic Scalpel (Ethicon Endo-Surgery, Inc., Cincinnati, OH) operate by converting electric energy into mechanical vibrations, thereby disrupting hydrogen bonds and forming a coagulum[18]. Such devices are well suited for dividing and sealing small to medium blood vessels (up to a diameter of 3 mm) at the same time. The frequency, 55.5 kilohertz (kHz), is in a range that will denature collagen molecules, vaporize cells, and provide both coagulation and cutting[18]. These instruments operate in a lower temperature range than electrosurgical tools, and cause less lateral thermal damage than the monopolar or bipolar electrosurgical instruments[18,30]. Nevertheless, they can still cause significant tissue damage, particularly if the instrument tip is used for tissue handling when still hot[28]. The Harmonic Scalpel destroys tissue by vaporization instead of carbonization, which causes less smoke. However, the steam produced by the harmonic scalpel can create a humid operative environment and frequent fogging of the laparoscope, and because it requires direct contact with tissue, visibility may be suboptimal at smaller surgical targets.

Laser Energy

Laser is an acronym for Light Amplification by Stimulated Emission of Radiation. Lasers emit single or narrow bands of wavelengths of intense light energy.

Tissue Chromophores and Laser-Tissue Interactions

Human tissue contains three useful chromophores-water, melanin, and oxyhemoglobin-that selectively reflect, transmit, absorb, or scatter specific wavelengths in the electromagnetic spectrum. Laser energy must be absorbed to have an effect. The absorption coefficients for water, melanin, and oxyhemoglobin determine how a particular laser wavelength will affect tissue. If the tissue surface reflects light or if the light is transmitted through tissue without the associated chromophore, there will be little to no effect, reflecting a low absorption coefficient. Conversely, if the tissue chromophore has a high affinity for a specific wavelength, i.e., a high absorption coefficient, laser energy can be confined to the tissue chromophore, thereby minimizing effects on adjacent tissue. In contrast, if the laser energy scatters before it is absorbed, the amount of surrounding tissue affected by the energy will be greater. For each chromophore, the absorption efficiency of various energy wavelengths is shown in Figure 2. CO_2 laser energy (10,600 nm), which is selectively absorbed by water, is ideal for use in soft-tissue where water is ubiquitous. Argon and potassium-titanyl-phosphate (KTP) laser energy, and neodymium yttriumaluminum- garnet (Nd:YAG; 1064nm) laser energy, are preferentially absorbed

Table 1. Wavelength, chromophores, and penetration depths of lasers used in endometriosis surgery

Laser Type	Wavelength Microns (µm)10-6	Region	Chromophore	Depth of penetration (mm)
Argon	0.532-0.514	Visible	Melanin, hemoglobin	0.8
KTP	0.532	Visible	Melanin, hemoglobin	1-2
Nd:YAG	1.064	Infrared	Melanin, proteins	4.2
CO_2	10.6	Far Infrared	Water	0.1

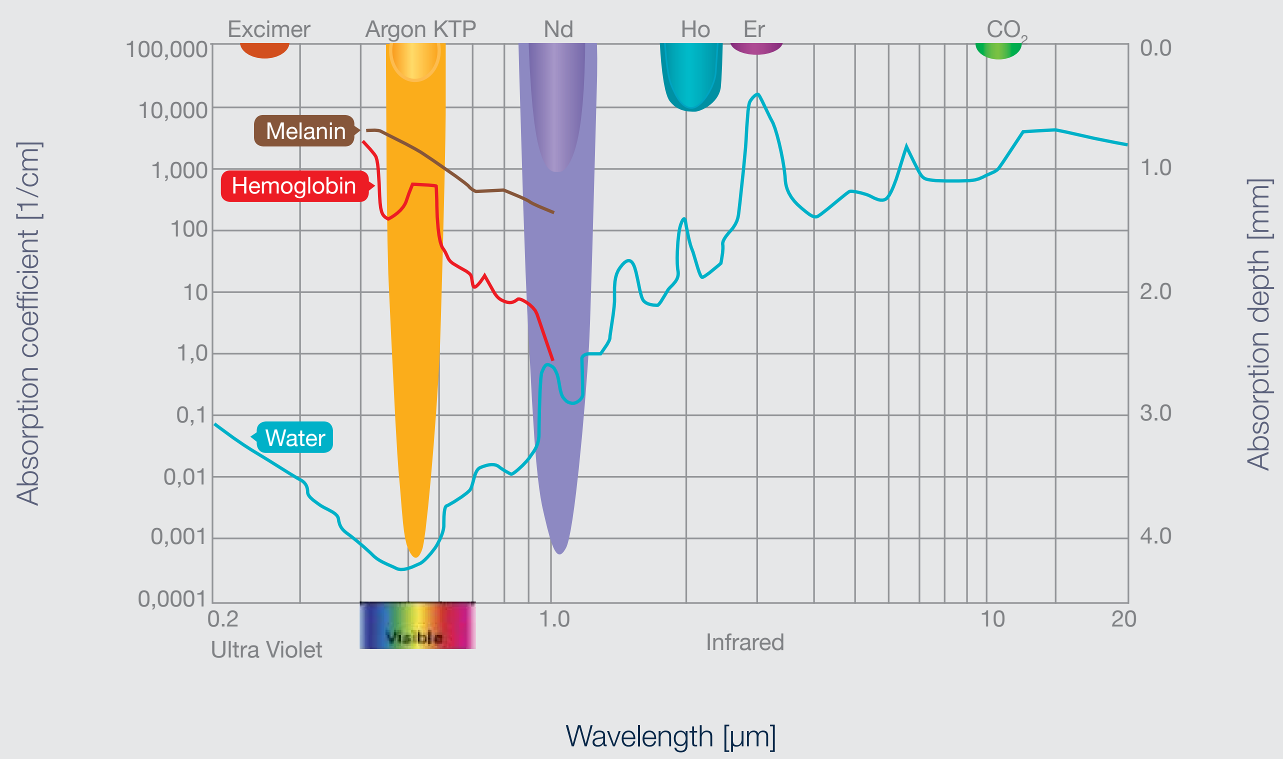

Figure 2. Laser absorption and tissue penetration

by oxyhemoglobin and melanin, making them good choices for vascular applications and aesthetic surgical procedures.

An important factor in tissue-laser interactions is the depth of laser energy penetration in tissue. Laser energy will penetrate tissue to different extents on depending several variables, including wavelength (Figure 2), absorption coefficient, the composition of the receiving tissue, power density of the beam, and application method (e.g., non-contact, light contact, or contact with firm pressure)[31]. The smaller the cutting depth, the lower the thermal spread.

Due to preferential absorption by water, 90% of CO_2 laser energy is superficially absorbed by an approximate 0.1 mm layer of soft tissue.

The KTP laser has a wavelength of 532 nm and penetrates deep into tissue until absorption by melanin or by oxyhemoglobin in blood vessels. Similarly, diode lasers with varied wavelengths (e.g., 830 nm, 940 nm, 980 nm) penetrate several millimeters into tissue and produce diffuse coagulative effects. Nd:YAG laser energy scatters in tissue and thermal effects can spread several millimeters beneath the tissue surface. Because of their relatively poor precision, Nd:YAG lasers are better suited for coagulation than excision[32]. Coagulation may be appropriate for removing superficial lesions; however, the appearance of coagulated tissue can make it difficult to gauge whether all of the endometrial tissue has been destroyed or how deeply the tissue is coagulated. The risk of unintended thermal damage due to light scattering and/or deep penetration of energy from KTP, diode, and Nd:YAG lasers makes them less suitable than CO_2 lasers for highly selective removal of endometrial implants.

Selective Photothermolysis

The basis for precise cutting and vaporization by laser is selective photothermolysis ("selective" refers to the use of the appropriate wavelength for the target chromophore, "photo" refers to the absorption of laser light in the chromophore, "thermo" refers to the transformation from light to heat, and "lysis" refers to the heat-induced destruction of the target tissue). In addition to choosing the best target chromophore for the job at hand and selecting a preferentially absorbed wavelength, selective photothermolysis requires selection of two additional conditions: time and fluence. Thermal Relaxation Time (TRT) refers to the maximum length of time laser energy can be applied, beyond which heat will build up and spread to adjacent tissues. Thermal effects can be confined to the irradiated three-dimensional target by limiting the dwell time of laser energy to less than the TRT, which can vary according to tissue type. Fluence refers to the concentration of laser energy (Joules) per unit area (energy density) and the conventional denotation is Joules (J)/cm_2.

To minimize dwell time and still efficiently vaporize tissue, the energy fluence must be sufficiently high. By delivering very high fluence, it is possible to make any laser wavelength vaporize tissue regardless of the available tissue chromophores, but the laser-tissue interaction could be nonselective and non-target tissue may be destroyed. The Thermal Ablation Threshold describes the minimum laser fluence necessary to vaporize soft-tissue.

Thus, administering laser energy beneath the Thermal Ablation Threshold will heat rather than ablate the tissue. For the laser to perform selective photothermolysis in soft-tissue, the requirements for TRT and Thermal Ablation Threshold must be met. Continuous Wave (CW) CO_2 laser energy emits from the laser cavity in a steady stream at constant power wattage. When using CW mode, heat builds up in tissue because the physical characteristics of the mode make it difficult to attain both requirements for TRT and Thermal Ablation Threshold. However, heat buildup in tissue is sometimes desirable, particularly when greater hemostasis is wanted. Pulsing laser energy makes it easier to satisfy the requirements for TRT and Thermal Ablation Threshold. Pulsed laser energy emits at very short intervals (msec) with low to very high peak power. The display panel on the laser shows average power, based on peak power and duration of intermittent exposures. Pulsed power modes are used when less thermal spread is desired for greater treatment precision. Pulsed power settings on many lasers can be manipulated to accommodate surgeon preference, as tissue effects produced by various pulsed modes can differ greatly.

CO_2 Lasers

Since the 1980s, CO_2 lasers have been used successfully for endometriosis removal[33]. Laparoscopic treatment of mild to severe endometriosis using a CO_2 laser results in high fertility rates, low recurrence rates, and minimal complications[12,14-16,34-38]. CO_2 lasers are more precise and cause less thermal injury than electrosurgical instruments, the Harmonic Scalpel, and other types of lasers[17,22,39-41]. Their high precision and capacity for simultaneous coagulation allows for controlled and virtually bloodless ablation of endometrial implants[36,42]. In addition to its precise cutting characteristics specialists in surgical removal of endometriosis cite other advantages of the CO_2 laser: It does not touch the target tissue allowing continuous visualization of the section plane between healthy and diseased tissue, and the low thermal impact of CO_2 lasers minimizes adverse healing responses and adhesion formation[16,36,39].

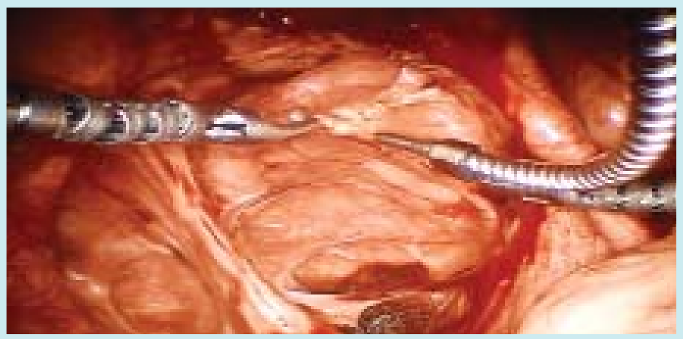

Figure 3. Fiber Delivery with Robotic Drop-in Guide

A comparative study assessing the macroand microscopic characteristics of the most commonly used energy sources applied on the ureter, bladder, and bowel in a laparoscopic setting (in vivo porcine model) showed that CO_2 laser energy was associated with the lowest incidence (0/12 specimens) of urothelial or epithelial damage[22]. In contrast, 9/12 specimens from all three organs showed urothelial or epithelial damage (presenting as coagulative denaturation of collagen bundles, resulting in eosinophilic homogenization of tissue) when either monopolar or bipolar cautery was used for surgery; as did 5/12 ureter and rectum specimens when an ultrasonic scalpel was used.

CO_2 lasers have strictly localized therapeutic effects and because of its preferential absorption by water, 90% of CO_2 laser energy is superficially absorbed by an approximate 0.1 mm layer of soft tissue[32,41]. The short absorption length results in highly controlled tissue vaporization and vision is enhanced because of concurrent microvascular hemostasis[43]. The surgeon can “shave” (vaporize) deep infiltrating endometriosis tissue layer-by-layer while the appearance of remaining tissue is unchanged, thus allowing for accurate assessment of the progress of surgical treatment[33]. This feature makes the CO_2 laser especially suited for precise work around the bowel, ureters and other critical structures.17

Endometriosis on the bowel affects between 3% and 37% of patients[6]. Donnez and Squifflet[12] conducted a prospective controlled study of 500 patients with deep rectovaginal endometriotic nodules, using the shaving technique (debulking surgery) with a CO_2 laser and no rectal resection. This technique preserved organs, nerves, and vascular blood supply. This surgical technique resulted in high postoperative pregnancy rates (84% of patients who wished to conceive, over a median of 3.1 years follow-up) and low complication and recurrence (7.8%) rates[12]. Adhesions often involve the bowel and adhesiolysis is a challenge because adhesions are thick and vascular[10]. The CO_2 laser may also be preferred for adhesiolysis of dense adhesions because of its limited thermal spread and a small depth of penetration[10,44].

For many lasers, maximum average power is lower in pulsed modes than in CW mode. The UltraPulse® CO_2 laser (Lumenis Surgical, Yokneam, Israel) can provide the same level of average power in both pulsed and CW laser modes. The UltraPulse laser provides high power for rapid dissection, and the ability to vary power level and coagulating effect make it well-suited for work around delicate structures[17]. TEL-V is a good approach for removing endometrial lesions that are not located on vital structures. Subsequently, ablative vaporization with a CO_2 laser can be used to remove endometrial implants located on vital structures[16].

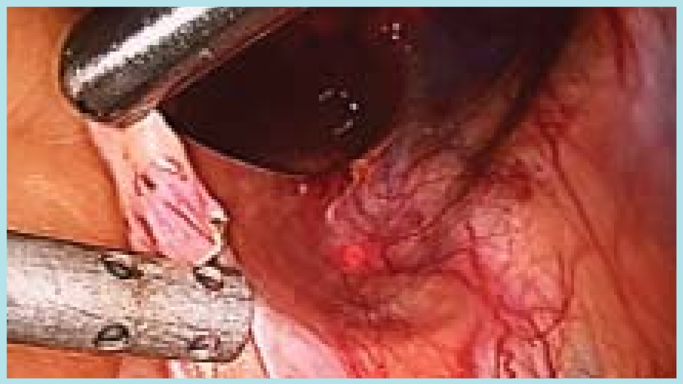

Figure 4. Free Beam Delivery. Precision tissue targeting with an aiming beam.

Excision by CO_2 laser of large endometriotic nodules is a preferred technique because it is quicker than vaporization and avoids bleeding, and excising deep infiltrating endometriomas may reduce their recurrence compared with ablation or coagulation[24]. Meuleman et al. reported clinical outcomes from three studies (2 retrospective[15,16], 1 prospective[14].) in subjects with (mostly recurrent) deep infiltrating endometriosis, with or without colorectal wall invasion in which all visible endometriosis lesions were removed by laparoscopic radical excision with CO_2 laser (Compact 40C[16], or 40W[14,15]. CO_2 laser, Lumenis Inc., USA)[14-16]. Surgery was performed with or without segmental bowel resection and reanastomosis. The surgeons excised all visible endometriosis lesions using very low power density (15 watts Super Pulse) to prevent thermal damage to surrounding tissue and minimize risk of adhesion formation, to work effectively at the border of healthy and diseased tissue, and to avoid complications with the ureters, bladder, or bowel[15]. Median follow-up in the 3 studies ranged from 1.7 to 2.4 years.

Results showed low postoperative complication rates (0-5%), cumulative reintervention (5-11%) and recurrence rates (4-7%); high fertility rates (46-51%); and significantly improved QOL [14-16,20].

Discussion

In the OR setting, the CO_2 laser offers a set of attributes that make it a safer and more precise tool than all other energy-based solutions for endometriosis and fertility surgery. Compared with all available energy sources, CO_2 lasers are optimally suited for excision and ablation of soft tissue in the pelvic cavity because they allow precise and highly controlled excision and vaporization, can simultaneously coagulate small blood vessels, and produce the least thermal spread reducing the risk of damage to surrounding tissue and structures[10]. The benefits of CO_2 lasers are appreciated by gynecologic surgeons in specialty referral centers and those who specialize in endometriosis. Certain problems with early CO_2 lasers, however, may have limited their widespread use. The long CO_2 wavelength (10,600 nm) prevents transmission via the flexible fiber optic cables used in other types of lasers, and bulky articulating arms with mirrors were required to transmit sufficient energy in a direct line to the surgical site, restricting freedom of movement[29]. Even though the early CO_2 laser was known to be more precise than lasers with other wavelengths, surgeons used them because of their more convenient fiber optic systems. Contemporary CO_2 lasers transmit light using a hollow optical fiber lined with an interior omnidirectional dielectric mirror making them more flexible and removing this ergonomic barrier to wider application in endometriosis surgery. The relatively cumbersome early equipment contributed to a steep “learning curve” for surgeons.

The flexibility of current instruments has reduced some of the rigorous training required to control the CO_2 beam; nevertheless, a learning curve for the safe use of lasers remains. Misused, they can injure the patient and/or the operator. To promote safety and efficacy of laser operation, the Society for Laser Medicine and Surgery ASLMS) provides recommendations for training and credentialing, which are part of the American National Standards Institute (ANSI) consensus standards[45].

The expense of laser technology and accessories and increased operative time have been suggested to be disadvantages of lasers in general[46]. According to my experience, CO_2 laser technology CO_2 laser technology has the potential to lower the total cost of endometriosis treatment, given the reduced risk of collateral thermal injury compared with other surgical tools, and low rates of recurrence and reintervention. CO_2 laser instrumentation costs may be justified by the direct benefits provided to the patient through their use. Procedural “speed” changes over time, and the length of a procedure will diminish as the surgeon becomes more experienced and adept at the techniques and technology used to safely and effectively remove endometriotic lesions. If greater access to CO_2 laser surgery improves the lives of even some of the ~176 million women affected by endometriosis worldwide[47], the associated training time and expense are well worth the investment.

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Risk Information

CO_2 lasers (10.6 µm wavelength) are intended solely for use by trained physicians. Incorrect treatment settings or misuse of the technology can present risk of serious injury to patient and operating personnel.
The use of Lumenis CO_2 laser is contraindicated where a clinical procedure is limited by anesthesia requirements, site access, or other general operative considerations. Risks may include excessive thermal injury and infection. Read and understand the CO_2 systems and accessories operator manuals for a complete list of intended use, contraindications and risks.

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