The Carbon Dioxide Laser for the Surgical Management of Endometriosis-A Treasure in the Armamentarium of the Gynecological Surgeon

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Case Introduction

The use of laser technology in gynecology became widespread since the carbon dioxide (CO\textsubscript{2}) laser was first utilized by Kaplan and his colleagues in 1973 for the treatment of cervical erosions [1]. Over the next ten years, the CO\textsubscript{2} laser was used during basic laparoscopic procedures [2], and from the early 1980’s to 1990’s, the Nezhat Brothers in USA had optimized its use for laparoscopic treatment of extensive endometriosis involving multiple organs [3-8].

The CO\textsubscript{2} laser has several features that make it suitable for performing multiple surgical functions. It can be used for both excision and vaporization with homeostatic capability on small vessels. There are several advantages in utilizing the CO\textsubscript{2} laser in gynecological procedures. High precision and capacity for simultaneous coagulation allows for controlled and virtually bloodless ablation of endometrial implants. Compared with all available energy sources, such as electrosurgical instruments and other types of lasers, the CO\textsubscript{2} laser is precise, has minimal depth of tissue penetration (0.1 mm), can coagulate small blood vessels, and produces the least thermal spread [9-14]. In addition to its precise cutting characteristics, this laser is used in a non-contact mode, thus does not touch the target lesion, allowing continuous visualization of the section plane between healthy and diseased tissue [15]. Finally, the low thermal impact of CO\textsubscript{2} lasers minimizes adverse healing responses and adhesion formation [15].

Despite the advantages of the CO\textsubscript{2} laser, in the past, ergonomic challenges associated with the free beam CO\textsubscript{2} laser delivery mode, which requires significant training and above average eye-hand coordination, as well as the ability to handle complex assembly and operation, made its use available to only limited number of experts from around the world. However, many new innovations have occurred since the CO\textsubscript{2} laser was first introduced, that maximize precision, safety, ease of use, and delivery to target tissue. Also, the new generation of surgeons is well versed in operative endoscopy with ample ambidexterity and eye-hand coordination. This paper reviews the CO\textsubscript{2} laser as an energy source, discusses the new developments in laser technology as well as highlights its applications for minimally invasive gynecological surgery in comparison with alternative energy sources.
Physics of the CO2 Laser making it suitable for gynecological endoscopic surgery

The CO2 laser has a long wavelength (10.6 μm) that is able to produce excitation and rotational energy in the tissue, resulting in vaporization of cell contents [16, 17]. The depth of penetration of the CO2 laser is limited to a precise area less than 0.1 mm [16, 17]. This high energy impact produces steam that explodes the intracellular water within a cell. The resulting cellular debris is carried off as plume. Depending on the power density, the CO2 laser can be used for vaporization, excision, or incision of tissue. Bleeding is limited with the use of the CO2 laser because its coagulation ability seals small vessels as it cuts.

Tissue Selectivity

In order for laser energy to be effectively absorbed, it must be absorbed by chromophores in the tissue. Human tissue contains three useful chromophores (water, melanin, and oxyhemoglobin) that selectively reflect, transmit, absorb, or scatter specific wavelengths in the electromagnetic spectrum. The absorption coefficients of these chromophores, and their distribution in a specific tissue determines how a particular laser wavelength will affect the tissue [16, 17]. If the tissue surface either reflects or transmits laser energy, the CO2 laser is unlikely to have adequate penetration to induce a therapeutic effect.

In contrast, the argon laser, potassium-titanyl-phosphate (KTP), and the neodymium ytrium-aluminum-garnet (Nd:YAG) laser energy, are preferentially absorbed by oxyhemoglobin and/or melanin, thus making them good choices for vascular excision, or incision of tissue. Bleeding is limited with the use of the CO2 laser because its coagulation ability seals small vessels as it cuts.

Table 1: Types of lasers and their properties

<table>
<thead>
<tr>
<th>Type of Laser</th>
<th>Wavelength (nm)</th>
<th>Region</th>
<th>Chromophore</th>
<th>Depth of Penetration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argon</td>
<td>488-512</td>
<td>Visible</td>
<td>Melanin, Hemoglobin</td>
<td>0.5-0.8</td>
</tr>
<tr>
<td>KTP</td>
<td>532</td>
<td>Visible</td>
<td>Melanin, Hemoglobin</td>
<td>1-2</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>1064</td>
<td>Infrared</td>
<td>Melanin</td>
<td>3-4</td>
</tr>
<tr>
<td>CO2</td>
<td>10,600</td>
<td>Far Infrared</td>
<td>Water</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Limited Depth of Penetration and Lateral Spread

An important factor in tissue-laser interactions is the depth of laser energy penetration. Laser energy will penetrate tissue to different extents depending on several variables. These factors include: wavelength of the laser, the absorption coefficient, the composition of the receiving tissue, the power density of the beam, and the application method (e.g., non-contact, light contact, or contact with firm pressure) [18]. Since the CO2 laser is not pigment seeking (i.e. oxyhemoglobin, melanin), its depth of penetration is strictly limited, and is virtually independent of tissue type. Due to preferential absorption by water, 90% of CO2 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 it is absorbed by melanin or by oxyhemoglobin in blood vessels [19]. Similarly, diode lasers with varied wavelengths (λ = 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. Therefore, the risk of unintended thermal damage produced by non-visible deeper necrosis caused by light scattering and/or deep penetration of energy from potassium-titanyl-phosphate (KTP), diode, and Nd:YAG lasers makes them less suitable than CO2 lasers for highly selective ablation of endometrial implants [18, 19].
Delivery Modes
Historically, CO2 lasers used to be fixed to rigid instruments leading to ergonomic difficulties, thus limiting their use. However, newer technologies have allowed for a flexible fiber delivery systems for the CO2 laser in gynecology. These systems feature several characteristics that have the potential to foster the adoption of this energy form by the wider community of gynecologic-surgeons. Flexible CO2 laser fibers, such as the FiberLase Flexible CO2 Laser Fiber (Lumenis Surgical) utilized either on the AquaPulse DUC, or UltraPulse DUO systems, overcome past ergonomic challenges by providing flexibility, durability, and ease of use. The hollow fibers feature controlled beam divergence, and intuitive method which allows the surgeon to control the area of laser-tissue interaction simply by moving the beam slightly away from the tissue. A smaller area concentrates the energy to produce a cutting effect, while a larger area allows for broad deposition of energy contributing to hemostasis or superficial ablation. The addition of the aiming beam is a significant contributor to the ease of use and the ability to target the desired tissue. Flexible delivery systems can easily be introduced through a side port, an operative channel of the laparoscope, or used in robotic assisted laparoscopic surgery (RALS).

Other Energy Sources
Electrosurgical Techniques
Before the advent of laser, the only method available for the endoscopic removal of endometriosis was by laparoscopic scissors, heating the endometrial implants with an endocoagulator.

Monopolar and bipolar electrosurgical instruments utilize high-frequency radio waves to provide electric current. With monopolar instruments, heat is generated in tissue. This occurs by transmission of the electric flow through a conductive medium (electric cable) that passes through the patient and exits via a grounding pad. The conductance or resistance of the tissue determines the flow of current towards the area around to complete the circuit. If sufficient voltage (at least 200 volts) is applied, electrosurgical instruments cut or vaporize the tissue via an electric arc [19]. Alternately, contact between the electrode and tissue reduces current density and tissue is destroyed by mechanical vibrational energy, thereby disrupting hydrogen molecules, vaporize cells, and provide both coagulation and minimal destruction of surrounding normal tissue, minimal bleeding, as well as minimal scar formation.

Ultrasonic Instruments
Ultrasound devices operate by converting electrical energy into mechanical vibrational energy, thereby disrupting hydrogen bonds and forming a coagulum [16]. The frequency, 55.5 kilohertz (kHz), is in a range that will denature collagen molecules, vaporize cells, and provide both coagulation and cutting capabilities [16]. These instruments operate in a lower temperature range than electrosurgical tools and cause less lateral thermal damage than the monopolar or bipolar electrosurgical instruments [16]. Nevertheless, they can still cause significant tissue damage, particularly if the instrument tip is used for tissue handling while still hot [22].

Ultrasonic energy devices are well suited for dividing and sealing small to medium sized blood vessels and tissue during certain gynecological procedures, such as laparoscopic hysterectomy [23]. Ultrasonic devices lack the fine precision of the CO2 laser, and are not able to vaporize superficial tissue implants with limited depth of coagulation. Theoretical concerns are of importance when attempting to vaporize or excise endometriosis tissue near delicate structures. In addition, there is no data with respect to safety, efficacy, recurrence, and future fertility rates that support the use of ultrasonic devices over other techniques for the surgical management of endometriosis.

A recent study [24] has compared flexible CO2 laser fiber with ultrasonic harmonic scalpel during robotic myomectomy and demonstrated similar mean operative times and blood loss with both instruments. However, the CO2 laser group had 87% reduced odds of staying in hospital for more than 1 day, compared with those who underwent the same operation with the ultrasonic scalpel [19]. More specifically, 45% of patients in the ultrasonic scalpel group were admitted for more than 1 day as opposed to only 14.2% of those in the CO2 laser group, a statistically significant difference [24]. As complication rates were similar between groups, the authors attributed this difference to decreased post-operative pain in the CO2 laser group. In five animal as well as human cadaver studies, the CO2 laser has been shown to cause less thermal tissue damage in comparison to the harmonic scalpel [14,25], also a superior wound-healing effect on the uterus compared with electrosurgical instruments. [26]

CO2 Laser for Treatment of Endometriosis
Laparoscopy has been shown to be the gold standard in the management of endometriosis. Removal or destruction of lesions, eradication of symptoms, and preventing them from spreading to other critical structures such as the ureter and bowel are among the more common laparoscopic procedures applied as surgical treatment. The CO2 laser has been shown to be a well-suited instrument for reproductive surgeons with several benefits for patients, including precision of application, minimal destruction of surrounding normal tissue, minimal bleeding, and as minimal scar formation. The CO2 laser is more precise and causes less thermal injury compared to other electrosurgical or ultrasonic instruments. The cutting action of the CO2 laser is analogous to what occurs when increased mechanical energy is applied to a water droplet. The physical vaporization of water is greater than the incision depth but not greater width (lateral spread) [27]. A comparative study assessed the gross and histologic effects of bipolar cautery, monopolar cautery, ultrasonic scalpel, and the CO2 laser on porcine ureter, bladder, and rectum demonstrated CO2 laser energy was associated with the lowest incidence (0/12 specimens) of urothelial or epithelial damage [14]. In contrast, 9/12 specimens from all three organs showed urothelial or epithelial damage (presenting as coagulative denaturation of collagen bundles, resulting in exfoliation homogenization of tissue) when either monopolar or bipolar cautery were used for surgery; as did 5/12 ureter and rectum specimens when an ultrasonic scalpel was used. Monopolar caused the most lateral spread of thermal energy. The CO2 laser caused the least deep-tissue injury of all the energy sources tested. Similarly, another animal study by Bailey et al. showed monopolar electrosurgery, in both cut and coagulation modes, damaged uterine tissue significantly more than the CO2 laser delivered via fiber [27].

Clinical Benefits to CO2 Laser Laparoscopy for Endometriosis

Pain Control
Use of the CO2 laser for the treatment of endometriosis has shown good pain control and resolution of symptoms in endometriosis patients. In a prospective, randomized, double-blind, controlled trial of laparoscopic treatment of pelvic pain associated with minimal, mild, and moderate endometriosis, Sutton et al. demonstrated improved pain related outcomes in patients treated with CO2 laser laparoscopy [28]. In this study, use of CO2 laser laparoscopy resulted in statistically significant pain relief compared with expectant management at 6 months after surgery, with 62.5% of the patients in the CO2 laser reporting improvement or resolution of symptoms compared with 22% in the expectant management group [28]. This is supported by data from a prospective study by Cibula et al. that showed pain reduction in 40% of patients 18 months post CO2 laser ablation of peritoneal Stage II-III endometriosis [29].

Fertility Outcomes
The use of the CO2 laser for ablation of ovarian endometriomas is associated with good reproductive outcomes. Wyrs and Donnez measured MII stimulation parameters (number of gonadotrophin-ampoules, number of follicles and mature oocytes, maximum estradiol concentrations) in a group of 85 patients with an ovarian endometrioma treated by CO2 laser vaporization of the internal wall [30]. Ovarian stimulation parameters were not significantly different in patients managed by CO2 laser vaporization compared to control patients with tubal infertility (no ovarian procedure). The authors concluded that the theoretical risk of loss of ovarian cortex when treating endometriotic cysts can be eliminated by the technique of vaporization. In a separate study, Donnez and colleagues assessed MII outcomes after laser vaporization of endometriomas in comparison to controls with tubal infertility [31]. MII outcome was not compromised by laser vaporization of the internal cyst wall. The clinical pregnancy rate was 37.4% and 34.6% in the endometriosis group and the control group, respectively [31].
In addition to its ablative capabilities, the CO2 laser can also be used for more complex endometriosis cases requiring segmental bowel resection and reanastomosis after conventional laparoscopic colorectal/endometriosis surgery. Increased Cost

The CO2 laser is a valuable instrument in the armamentarium of gynecologic surgeons. Its increased cost compared to electrosurgical or ultrasonic instruments may not be a significant concern in centers performing the procedures, as the improved outcomes and reduced risk of collateral thermal injury compared with other surgical tools and lower rates of recurrence and revision. Improved IVF outcomes, fecundity, and pregnancy rates may impart a cost-saving advantage that warrants further assessment. Thus, the costs associated with the CO2 laser may be justified by the direct benefits provided to the patient through their use [45].

Myths Associated With the CO2 Laser

Ergonomic Disadvantage

The early generation of CO2 lasers posed certain problems that have since been overcome. Early CO2 lasers were rigid, which restricted freedom of movement [43]. Today, contemporary CO2 lasers transmit emission via the flexible fiber optic cables used by other types of lasers. These hollow fibers feature beam divergence, which allows the surgeon to increase the area of laser-tissue interaction simply by increasing the beam area or altering the tissue, thereby controlling the tissue effect [44]. This new generation of CO2 lasers can be used both for conventional video laparoscopy and robotic assisted laparoscopic surgery (RALS).

In addition, use of the CO2 laser by advanced surgeons has increased the number of patients admitted to the hospital overnight after surgery, which may be associated with higher healthcare costs.

Conclusion

The CO2 laser is appropriate for use in all other endometriosis cases that require the use of other lasers, either alone or in conjunction with each other. With its increased cost and toll on the healthcare system, this factor may also be associated with a cost-saving advantage. Certainly further prospective studies are needed to assess cost impact with use of the CO2 laser in these areas.

In addition, as demonstrated in the study described earlier by Chousen et al [44], patients undergoing myomectomy with a CO2 laser have a significantly lower chance of being admitted to the hospital overnight after surgery compared to those in whom an ultrasonic scalpel was used. Because overnight hospital admission is associated with an increased cost and toll on the healthcare system, this factor may also be associated with a cost-saving advantage. Certainly further prospective studies are needed to assess cost impact with use of the CO2 fiber laser in these areas.

References

Risk Information

CO₂ 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 CO₂ 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 CO₂ systems and accessories operator manuals for a complete list of intended use, contraindications and risks.

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