

Laparoscopic Surgery with a New Tuned High-Energy Pulsed CO₂ Laser

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ABSTRACT

Although CO₂ lasers have gained popularity in operative laparoscopy, it has been suggested that they do not deliver sufficiently high power density at the distal end of a laparoscope. Heating of the insufflation gas inside the laparoscope by absorption of some of the laser power causes the gas density to change and creates distortion and defocusing, resulting in lower power density at the tissue as the laser power is increased. A new laser uses the carbon-13 isotope in the laser gas mix instead of the carbon-12 isotope, which is used in both conventional lasers and CO₂ insufflation gas. The new laser was found to have no noticeable effect on tissue attributed to distortion or power loss from absorption in the insufflation gas, and it allowed the surgeon to work with minimal thermal side effects, such as the formation of charred tissue. The laser was fitted with separate controls for adjusting pulse energy and average power, allowing the surgeon to control the laser-tissue response at different operating speeds. (J GYNECOL SURG 8:251, 1992)

INTRODUCTION

USE OF THE LAPAROSCOPE in conjunction with the video monitor,¹ electrosurgery, and lasers has revolutionized intraabdominal surgery. Since the first reported use of the CO₂ laser in conjunction with a laparoscope,^{2,3} it has become an increasingly common method to treat intraabdominal gynecologic disorders.

The CO₂ laser's short absorption length by water results in highly controlled tissue vaporization. This also allows the CO₂ laser to be used in conjunction with fluids for increased protection of underlying critical tissue (hydrodissection).⁴ Additionally, the CO₂ laser is able to coagulate small blood vessels as it cuts.

A drawback to cutting with the CO₂ laser is char formation. Char results from slow, inefficient vaporization of tissue. If left inside the body, char can cause a foreign body reaction and may be a contributing factor in adhesion formation.⁵ Continuous wave (CW) CO₂ lasers used at low powers produce the greatest amount of char and thermal damage.^{6,7}

Advances in CO₂ technology leading to superpulsed CO₂ lasers, which deliver laser energy in discrete pulses,^{6,7} have reduced the incidence of char formation. Superpulsed lasers act on the tissue in a time period too brief to allow significant thermal conduction to surrounding tissue.⁸ Concentrating the laser energy into a small spot results in sufficient energy to vaporize the tissue in a single pulse, leaving little residual heat in surrounding tissue. Using short pulses and a small laser spot significantly improves tissue response in open procedures. Using the CO₂ laser through the operative channel of the laparoscope has several advantages. It acts as a long knife that is always sharp, it eliminates the need for an additional incision, and it does not obstruct the surgeon's view. Unfortunately, the efficacy of the superpulsed laser in laparoscopic procedures is

compromised by three phenomena⁹: absorption of the CO₂ laser beam energy by the CO₂ insufflation gas, thermal blooming, which is the defocusing and distortion of the laser beam due to heating and density changes of the insufflation gas by the absorbed laser energy, and clipping of laser beam energy by the optics and by the wall of the laparoscope bore when the laser beam is defocused by the heated insufflation gas (Fig. 1).

The CO₂ molecules in the insufflation gas absorb light of the same frequencies that the CO₂ molecules in the laser emit, since identical molecules absorb light at the same frequencies that they emit light. This is resonant absorption. If the isotope ¹³C is used instead of ¹²C in the laser gas mix, the emitted frequencies of the ¹³CO₂ molecules in the laser are shifted enough so that they will not be absorbed by the ¹²CO₂ molecules in the insufflation gas.

A recently introduced CO₂ laser (Ultrapulse 5000L, Coherent Inc., Palo Alto, CA) produces laser energy that is frequency shifted, by using the isotope ¹³CO₂, just enough to miss the resonant absorption peaks of the ¹²CO₂ insufflation gas. In addition, the laser produces pulses with up to 200 millijoules of energy in less than a millisecond. There is no observable absorption or defocusing of the laser beam in the laparoscope so that the laser delivers high enough power densities and energy fluences to minimize char formation and thermal damage to surrounding tissue.

MATERIALS AND METHODS

We investigated a new surgical laser on 365 patients to treat a variety of conditions, including endometriosis, myomas, adhesions, hysterectomy, and oophorectomy with no intraoperative or postoperative complications. The laser uses a ¹³CO₂ gas mixture and produces pulses with energies of up to 200 millijoules in less than a millisecond.

The lasers have separate, independent controls for setting energy per pulse from 1 to 200 mJ and average power from 1 to 80 W. This allowed the surgeon to select the pulse energy for the optimal tissue effect and the average power for the preferred operating speeds for the individual procedures performed during this investigation.

Preliminary spot size measurements at different laser powers were performed on acrylic targets. The lasers were set to 150 mJ per pulse, which is above the ablation threshold for the nominal spot size of about 1.5 mm from a laparoscope with 3 lpm flow rate of insufflation gas. Laser burns were made in the acrylic at 10, 20, 30, 40, 50, 60, 70, and 80 W of average power. Exposures were timed to 0.1 sec, and the diameters of the burns were measured.

RESULTS

The results of the acrylic burn measurements are illustrated in Figure 2. The spot size for a conventional ¹²CO₂ laser increases with increasing laser power. Assuming that similar conditions occur in tissue, the

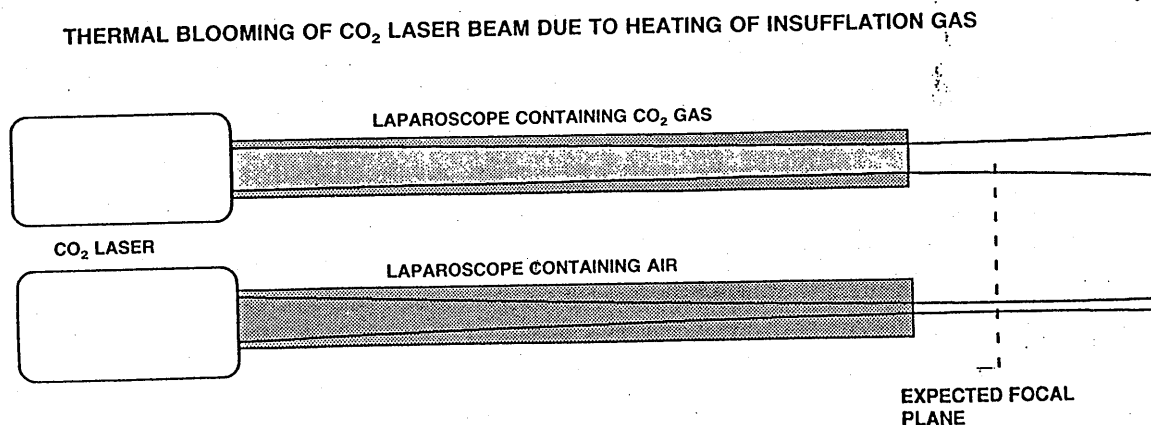


FIG. 1. CO₂ insufflation gas absorbs power and is differentially heated. Warmer gas in center of lumen is less dense than gas near lumen walls. The density gradient forms a thermal lens increasing the laser spot size at the focal plane.

SPOT SIZE COMPARISON OF CO₂ LASERS THROUGH A LAPAROSCOPE

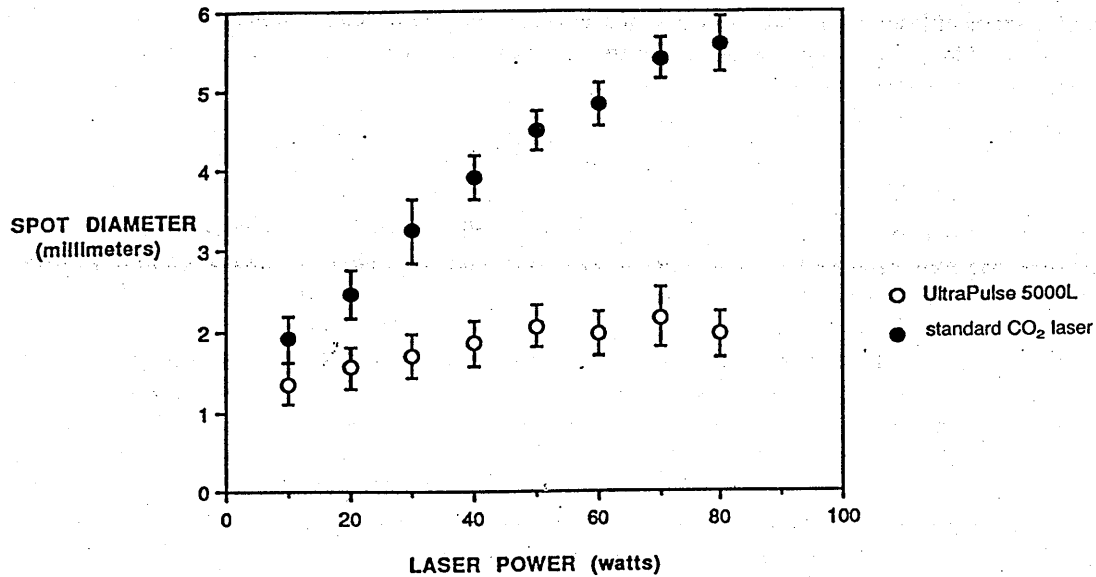


FIG. 2. Measurements of laser spot sizes with 3 lpm CO₂ insufflation gas.

expected fluence of energy at the tissue will decrease with increasing power. Fluence is the laser energy per unit area incident on the tissue. The expected fluence to the tissue from the laparoscope was determined from the results of the acrylic burn measurements and are illustrated in Figure 3. It has been shown that the fluence of a pulsed CO₂ laser should be between 3 J/cm² and 19 J/cm² in less than a millisecond to achieve minimal thermal damage when vaporizing or ablating tissue.^{8,10} As seen in Figure 3, this threshold is achieved at only very low average powers when using conventional lasers.

However, the patients treated with the new laser show a significant decrease in the incidence of char formation during treatment. When used through a laparoscope, the pulse energy of the laser can be adjusted so that cutting, vaporization, or ablation of tissue can be achieved with no visible char. The conventional laser

CO₂ LASER PULSE ENERGY FLUENCE THROUGH A LAPAROSCOPE

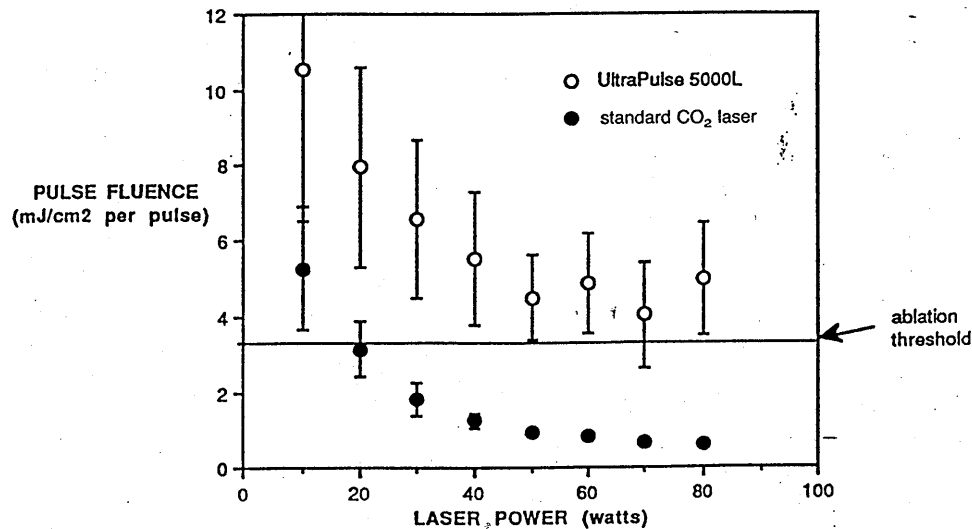


FIG. 3. Calculated pulse energy fluence with 3 lpm insufflation rate and 150 millijoules per pulse.

always shows varying degrees of visible char formation for average powers over 10 W. Adjusting the pulse energy of the conventional laser has some effect on char formation, but spot size blooming is the predominant factor in char formation. Thermal blooming and the resultant char formation are illustrated in Figure 4. The figure shows a series of laser burns taken at different average powers, with a conventional laser and with the new laser. Thermal blooming at higher average powers is readily apparent and is consistent with the results of the test managements in acrylic.

DISCUSSION

The CO₂ laser cuts tissue by vaporizing its water content. When sufficient CO₂ laser light energy is absorbed by the target tissue, the absorbed energy vaporizes the aqueous content of the cells, and the entire mass is carried away with the vapor plume. The vaporized water in the plume carries away much of the heat energy that was deposited by the laser. The remaining heat tends to cause thermal damage of adjacent tissue by conduction. Laser light heats tissue almost instantaneously while conduction spreads heat and thermal damage further into adjacent tissue with the passing of time. If conduction dissipates too much of the laser's energy or if the laser does not have adequate power, the laser gradually heats the tissue instead of instantly vaporizing it. This slow heat desiccates the tissue until it is finally burned into char. After char has formed, it tends to increase the rate at which heat is conducted into the tissue because the char absorbs laser energy and functions as a heat reservoir, continually heating the surrounding tissue. The key to minimizing thermal damage is to deliver enough energy with each pulse to vaporize the illuminated target tissue before conduction can carry the heat energy to the adjacent areas. The pulse duration must be less than the time required for significant thermal conduction to spread to adjacent tissue. The heat is then carried away in the vapor plume. This process requires a laser that can produce very short duration, high-energy pulses.

The critical factor in the interaction between laser and tissue is the pulse energy density, defined as the pulse energy divided by the area of the spot and the depth of laser energy penetration into the tissue. The depth of penetration is the same for all CO₂ lasers, so it is the pulse energy divided by the spot size, called the pulse energy fluence, which is the critical factor for comparing different CO₂ laser-tissue interactions. Minimal thermal damage when vaporizing or ablating tissue with a pulsed CO₂ laser occurs with a fluence of between 3 J/cm² and 19 J/cm² in less than a millisecond. This corresponds to about 75 mJ per pulse for the smallest spot sizes typical of laparoscope delivery systems.

A high-energy fluence pulse produces clean, char-free ablation with minimal damage to surrounding structures. Low-pulse energy fluence or low CW power density produces coagulation and char. In an open procedure, a superpulse laser delivering its maximum energy per pulse of about 75 mJ would be sufficient to

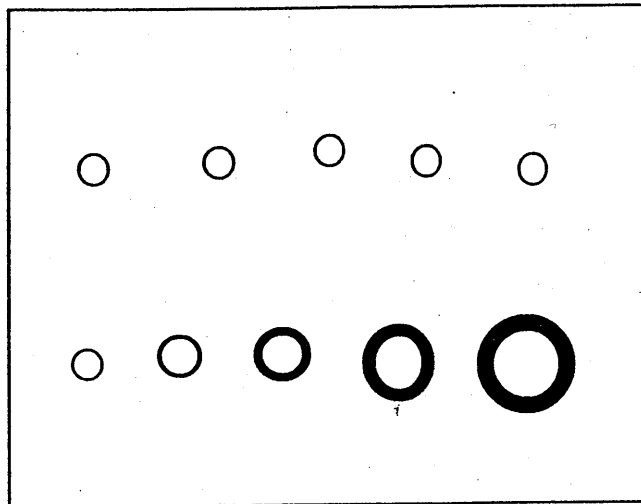


FIG. 4. The figure shows laser defects produced at powers between 10 and 80 watts, left to right, delivered through a laparoscope on to a uterus. The upper row was produced by the new laser and shows a consistent spot size at all power levels. The lower row shows blooming and resultant char for a conventional laser used under the same conditions.

produce single pulse ablation in spots with diameters up to 1.2 mm. When used with a laparoscope, it is impossible for conventional superpulsed lasers to deliver the energy density required to produce clean, single pulse ablation. This is due to the energy losses resulting from absorption, thermal blooming, and clipping associated with laparoscopic delivery. Spot sizes up to 3 mm and laser power density reductions of 50% produced by a variety of laparoscopes at average power settings above 50 W have been reported.⁹ For a pulsed laser, however, it is pulse energy fluence that is the determining factor in tissue response and char formation. The energy per unit area of tissue is shown to be compromised in laser laparoscopy because of CO₂ insufflation gas. This situation has been corrected with the new laser, which can deliver up to 200 mJ pulses without resonant absorption of laser energy by CO₂ insufflation gas. As the average power is increased, the spot size does not change because no thermal blooming occurs.

CONCLUSION

Because the pulse energy reaching the tissue remains constant at different average power settings, the new laser can produce char-free tissue ablation in laparoscopy at the slow working speeds that accompany low average power and at the high working speeds that accompany high average power. This gives the surgeon a new level of control that has not been available previously.

Surgeons typically can use a lower energy density if more coagulation is required to control bleeding. A lower energy density leaves more heat in the tissue, resulting in deeper coagulation. At any given average power setting, the pulse energy can be varied from 200 mJ down to 1 mJ, providing continuous control over energy density unaffected by average power levels in the insufflation gas. The independent control of pulse energy and average power and the elimination of pulse energy dependence on average power level make it possible for the first time to control the depth of coagulation at any average power or speed of operation.

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