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$^{13}CO_2$ Isotopic Laser Used Through the Operating Channel of Laser Laparoscopes: A Comparative Study of Power and Energy Density Losses

G. DAVID ADAMSON, MD, HARRY REICH, MD, AND DAVID TROST, MS

***Objective*: To evaluate the power transmission, spot size, power density, and energy density of a new isotopic carbon dioxide ($^{13}CO_2$) laser compared with a conventional CO_2 laser.**

***Methods*: Experiments were performed in a laboratory using a conventional CO_2 laser and an isotopic $^{13}CO_2$ laser. Two laparoscopes with 5-mm and 7.5-mm operating channels were connected to a standard coupler and to each of the lasers. Standardized measurements were made of power transmission and spot size using both nitrogen purge gas and CO_2 purge gas at rates of 1–20 L/minute. Power density and energy density were calculated for continuous mode and ultrapulse mode transmission, respectively.**

***Results*: The isotopic $^{13}CO_2$ laser power transmission was higher and proportional to input power, while spot size was smaller compared with the conventional laser and was insensitive to power level or purge rate. Power density and energy density were markedly higher with the isotopic $^{13}CO_2$ laser, reaching the threshold for complete ablation, and were much more predictable. The 7.5-mm operating channel generally had superior operating results compared with the 5-mm channel because of the smaller spot size and higher power transmission.**

***Conclusions*: The isotopic $^{13}CO_2$ laser is associated with much higher power density and energy density capabilities than are conventional CO_2 lasers. At surgery, we have noted less thermal injury, faster ablation, more precise and predictable tissue effects, and greater control of tissue effect with the isotopic $^{13}CO_2$ laser than with other CO_2 lasers. These results are attributed to the improved beam propagation through CO_2 insufflation gas measured in the laboratory. Thermal injury can be varied according to the required surgical situation and can be kept to an absolute minimum at high-pulse energy.** *(Obstet Gynecol 1994;83:717–24)*

The underlying physical principle that makes laser action possible, stimulated emission of photons of light, was first proposed by Einstein[1] to help explain the properties of hot glowing objects. The application of this principle to infrared and visible lasers occurred nearly a half century later with the work of Schawlow and Townes in 1958.[2] The first report of successful laser operation was by Maiman in 1960.[3] The CO_2 laser, first reported by Patel in 1964,[4] remains one of the most efficient and widely used high-power lasers in a broad variety of fields. In 1979, Bruhat et al[5] reported the first use of the CO_2 laser through the laparoscope.

Since the early work of Bruhat et al,[5] CO_2 laser laparoscopy has achieved widespread use. It is customary to insufflate the peritoneum with CO_2 gas to distend the cavity and carry away smoke and debris. Carbon dioxide gas has become universally accepted as the medium for insufflation because of its favorable physiologic properties. It has been shown that if the probability for stimulated emission is high (a condition necessary for laser action), then the probability for absorption of the stimulated light in another sample of the same gas is also high.[6] Thus, CO_2 laser light is strongly absorbed in CO_2 insufflation gas. Reich et al[7] reported that laser-induced heating of the insufflation gas led to statistically significant loss of laser power delivered to the tissue as well as dramatic thermal blooming, causing the diameter of the laser beam at the tissue to grow as large as the full diameter of the operating lumen of the laparoscope. In the systems they tested, it was not possible to propagate more than

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From Fertility Physicians of Northern California, Palo Alto, Stanford University School of Medicine, Stanford, and the University of California at San Francisco, San Francisco, California; Wyoming Valley Gynecological Associates, Kingston, Nesbitt Memorial Hospital, Kingston, and The Graduate Hospital, Philadelphia, Pennsylvania; and Coherent, Inc., Palo Alto, California.

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40 W of laser power through the laparoscope regardless of input power (up to 100 W). Similarly, because of power loss and beam size increase, it was not possible to achieve power density at the tissue greater than approximately 800 W/cm^2.

A new surgical CO_2 laser has since been designed specifically to circumvent this difficulty. This laser (Ultrapulse 5000L; Coherent, Inc., Palo Alto, CA) uses a rare isotope of carbon, ^{13}C, in its CO_2 gas mix rather than the dominant, naturally occurring isotope ^{12}C. The result is a small wavelength shift from 10.6 to 11.1 μ. This shifted wavelength is not absorbed in the $^{12}CO_2$ insufflation gas, so the absorption problem is eliminated. Because both wavelengths are strongly absorbed by water, they interact with tissue identically through the mode of vaporization of water in the tissue.

The use of rare isotopes in CO_2 laser gas was first reported in 1966 by Wieder and McCurdy,[8] only 2 years after Patel's first report[4] of the CO_2 laser. It has since been used extensively in spectroscopy and laser radar.[9] Medical applications of the isotopic CO_2 laser are just now being developed.

Materials and Methods

In the laboratory, we performed a series of side-by-side tests of two lasers identical in every respect except that one contained a $^{12}CO_2$ laser gas mix (conventional CO_2 laser) and the other contained a $^{13}CO_2$ laser gas mix (isotopic $^{13}CO_2$ laser). The conventional CO_2 laser (Coherent Ultrapulse 5000; Coherent, Inc.) and the isotopic $^{13}CO_2$ laser (Coherent Ultrapulse 5000L) were verified to be performing to full factory specifications. Two laparoscopes (Karl Storz, GmBH, Tuttlingen, Germany) were used in testing each laser: One had a 5-mm operating channel and a 10.5-mm outer diameter (Storz 26036A), and the other a 7.5-mm lumen and an 11.5-mm outer diameter (Storz 26075A). The lasers were coupled to the laparoscopes with a Coherent/Nezhat coupler (Coherent, Inc.). Medical-grade CO_2 was used for insufflation gas, and the flow rate was measured with a flow meter (Porter Industries, Hatfield, PA). Laser power was measured with a Coherent power meter. The experiment was performed in an open environment on a laboratory bench. The CO_2 insufflation gas was run through the lumen of the laparoscope through which the laser was transmitted. The open environment of the laboratory bench was selected over a closed vessel to separate unambiguously the effect of insufflation gas in the lumen of the laparoscope from smoke in an enclosed chamber. For each laparoscope size, 48 data points were taken, and each data point consisted of two measurements: transmitted power and spot size. Each data point represents a different insufflation gas and/or flow rate. Therefore, we obtained a total of 96 data points, consisting of 192 separate measurements. Each data point was taken once. No data were discarded.

Measurement of spot diameter received special attention. An accurate measure of spot diameter is essential because power density and energy density (fluence) are related inversely to the square of the spot diameter. To circumvent errors, all beam-diameter measurements were made with a Modemaster beam propagation analyzer (Coherent, Inc.) to a specified accuracy of ±2%.

Power transmission measurements were made by first measuring the power at the end of the articulated arm. The coupler and laparoscope were then connected, and the power output was measured within 2 cm of the distal end of the laparoscope. Measurements were made over a broad range of laser power, with CO_2 insufflation gas at flow rates ranging from 1–20 L/minute. Control tests were also performed using nitrogen purge gas. All measurements were made in duplicate on the conventional CO_2 and isotopic $^{13}CO_2$ lasers for both continuous-wave mode and pulsed mode. The 7.5-mm operating channel was tested at 50 mJ per pulse for both lasers, and the 5-mm operating channel at 125 mJ per pulse because this level was required to exceed the single-pulse ablation threshold. To maximize the clinical usefulness of the reduced data, we paid special attention to comparisons of experimentally determined power density and energy density with known threshold values that determine the effect of the laser on tissue. For continuous-wave laser operation, the ablation threshold (the power density at or above which cutting and ablation are achieved with minimal thermal damage) is 5000 W/cm^2.[10] For pulsed laser operation, the single-pulse ablation threshold producing minimal thermal damage is 2.8 J/cm^2.[11]

Results

Detailed results are reported only for the more commonly used operating laparoscope with the 5-mm operating channel. When nitrogen insufflation gas was used, the power loss was 30% in both the conventional CO_2 laser and the isotopic $^{13}CO_2$ laser. This power loss was due to beam clipping resulting from the circumference of the lumen of the laparoscope and coupler shaving off the outside edges of the incoming gaussian laser beam. When CO_2 insufflation gas was used, the power loss for the conventional CO_2 laser was highly variable, peaking at 79%. With the isotopic $^{13}CO_2$ laser, the presence of CO_2 insufflation gas and the flow rate

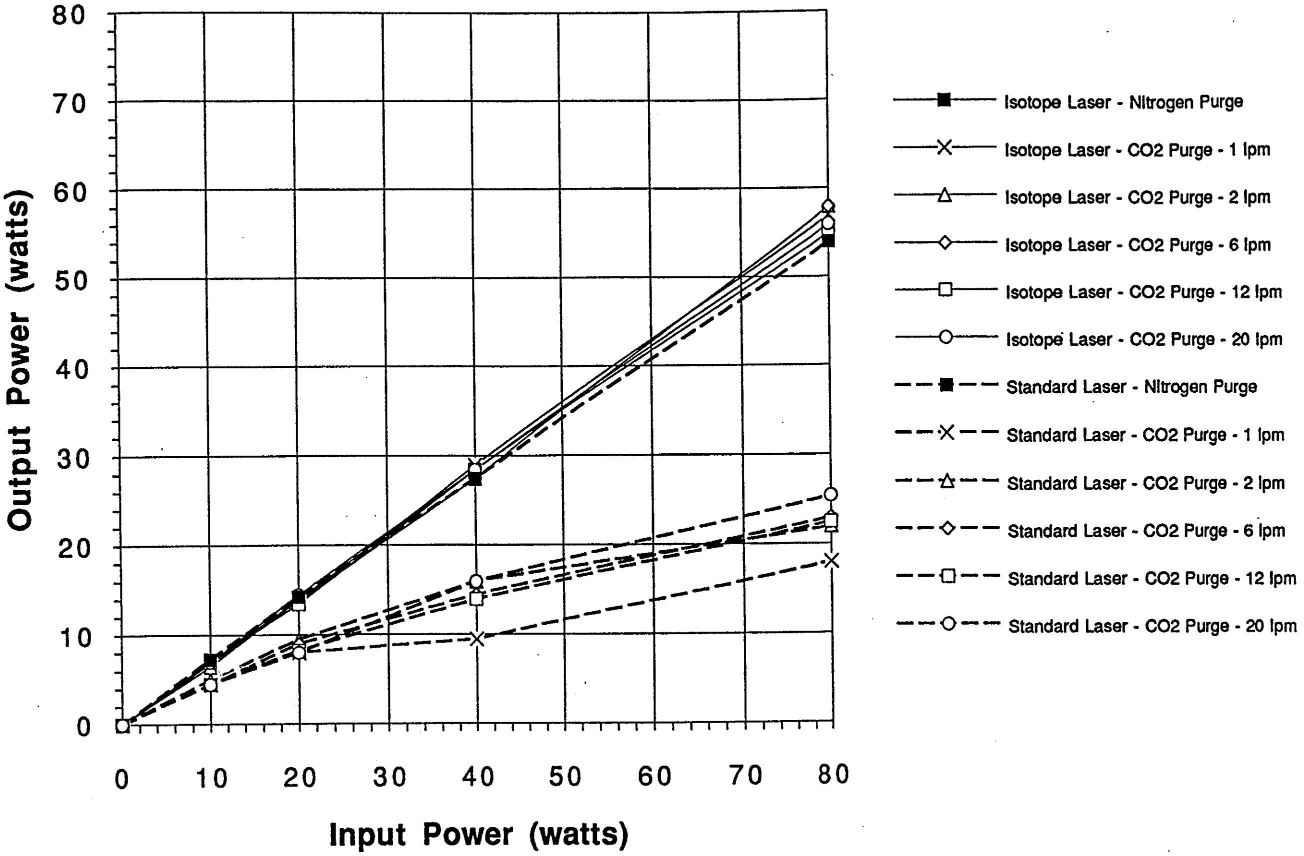

Figure 1. Output power through the 5-mm operating channel. Lpm = L/minute.

had no measurable effect on transmitted power (Figure 1).

Figure 2 illustrates the results of spot size measurements for the two laparoscopes. The conventional CO_2 laser laparoscope with 5.0-mm operating channel purged with nitrogen gas had a spot size of approximately 2 mm. When purged with CO_2 gas, the spot size became enlarged (bloomed) up to as much as 5 mm. Spot size was strongly dependent on both power input and insufflation rate. At an insufflation rate of 20 L/minute, no significant increase in spot size was noted. The spot size produced with the isotopic $^{13}CO_2$ laser was 1.6 mm when purged with nitrogen, but did not increase when CO_2 purge gas was used, and remained essentially unchanged at all power inputs and insufflation rates (Figure 2).

Power density data were computed by dividing the measured power (Figure 1) by the area of the laser beam cross-section, calculated from the measured spot diameters (Figure 2). With a conventional CO_2 laser and CO_2 purge gas (Figure 3), the power density increased with increasing input power at a less than linear rate. This was true at all insufflation rates, including 20 L/minute. At an input power level between 10–40 W (the actual value dependent on purge rate), the power density leveled off and failed to increase further with increasing input power. It was not possible to achieve power density greater than 1500 W/cm^2 at any input power up to 100 W. It was not possible even to approach the ablation threshold for minimal thermal damage of 5000 W/cm^2 using any combination of input power and purge rate.

Power density computation from data taken with the isotopic $^{13}CO_2$ laser increased linearly with increasing input power over the full range tested (10–80 W). The maximum power density was approximately 3000 W/cm^2 at an input power of 80 W (Figure 3). At high power settings approaching 80 W, we noted a small dependence of power density on purge rate. At purge rates of 1–2 L/minute, the power density was a maximum of 35% below that measured with the same input power and a purge rate in excess of 6 L/minute. Under these worst-case conditions and using identical input and purge rates, the power density with the isotopic $^{13}CO_2$ laser was tenfold higher than that of the conventional CO_2 laser.

With the 5-mm operating channel laparoscope, it was not possible to achieve the single-pulse ablation threshold of 2.8 J/cm^2 with an input pulse energy of 50 mJ. Although conventional superpulse lasers are

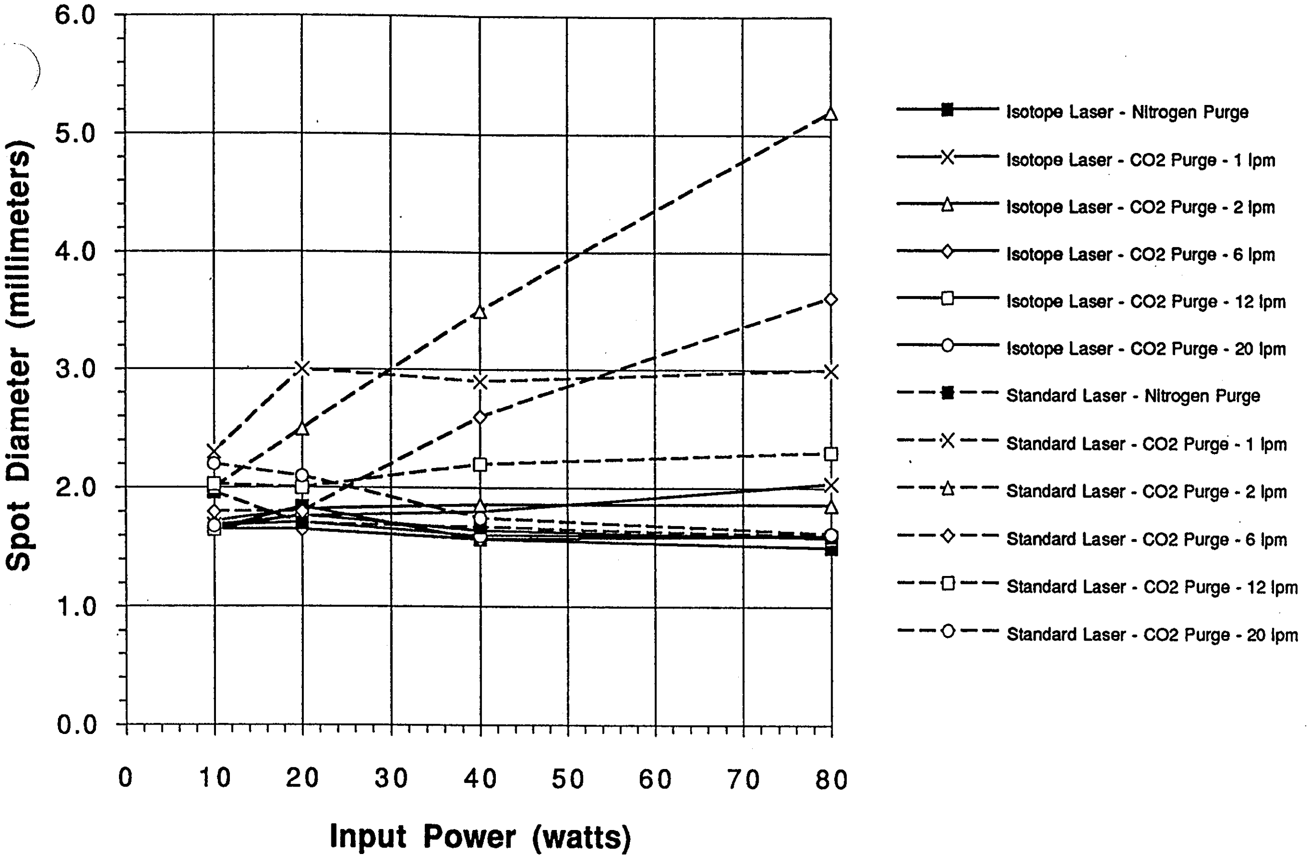

Figure 2. Spot diameter through the 5-mm operating channel. Lpm = L/minute.

limited to pulse energy of approximately 50 mJ, the isotopic $^{13}CO_2$ laser allows for selectable pulse energy up to 200 mJ. To achieve the single-pulse ablation threshold, a pulse energy of 125 mJ was selected.

The energy density through the 5.0-mm operating channel laparoscope at 125 mJ per pulse (Figure 4) achieved with the conventional laser was well below the single-pulse ablation threshold at all power settings and CO_2 insufflation rates. The $^{13}CO_2$ isotopic laser operating at 125 mJ per pulse achieved energy densities above the single-pulse ablation threshold at every power setting and every insufflation rate. Similar to the power density measured in the continuous-wave mode, the $^{13}CO_2$ isotope laser in the ultrapulse mode produced up to a 20-fold increase in energy density over the conventional pulsed laser under exactly the same operating conditions.

Results with the 7.5-mm operating channel were at least as favorable as those with the 5.0-mm operating channel. Power loss through the laparoscope with nitrogen insufflation averaged 15% with the 7.5-mm operating channel, compared to 30% with the 5.0-mm channel. This power loss was due to clipping of the beam by the lumen (aperture) of the laparoscope. Power loss with CO_2 insufflation averaged 66% with the conventional CO_2 laser and only 15% with the isotopic $^{13}CO_2$ laser. The spot size was 1.25 mm when purged with nitrogen gas in both laparoscopes. With CO_2 purge, the spot size bloomed to a maximum of 5 mm with the conventional CO_2 laser but remained constant with the isotopic $^{13}CO_2$ laser. Power density with CO_2 gas purge never exceeded 1400 W/cm^2 with the conventional CO_2 laser but increased linearly with power to 5000 W/cm^2 with the isotopic $^{13}CO_2$ laser. Energy density with CO_2 gas purge and 50 mJ per pulse varied at 0.1–2.8 J/cm^2 for the conventional CO_2 laser, and was always above 2.8 J/cm^2 for the isotopic $^{13}CO_2$ laser (Figure 5).

Discussion

The use of a laparoscopic coupler reduced power transmission in all laser systems. When CO_2 was used as an insufflation gas, conventional CO_2 laser power loss was up to 79% in a 5-mm channel. The isotopic $^{13}CO_2$ laser showed markedly superior laparoscopic power transmission, with a 30% fixed loss that did not increase at higher power (Figure 1). These results occurred in continuous mode and the pulsed mode, in which the average power was simply the sum of the

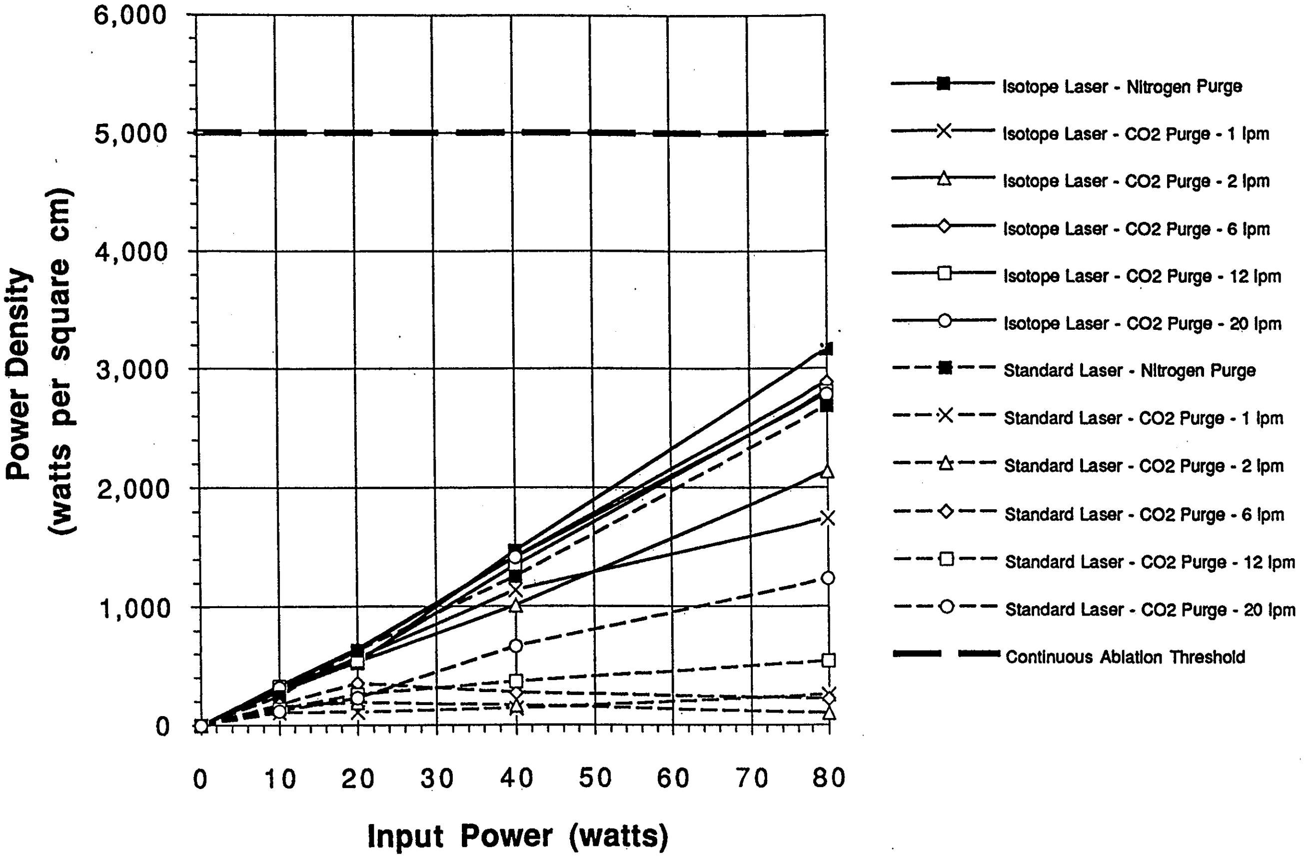

Figure 3. Power density through the 5-mm operating channel. Lpm = L/minute.

energy of all the pulses delivered in 1 second. The conventional CO_2 laser transmitted power indistinguishably from the isotopic $^{13}CO_2$ laser when the purge gas was nitrogen. However, power transmission fell dramatically with CO_2 purge gas, with a slight reduction in transmission loss with increasing CO_2 gas purge rates. With the isotopic $^{13}CO_2$ laser, purge gas type or rate had no apparent effect on output power.

The spot diameter with the conventional CO_2 laser purged with nitrogen gas stayed essentially constant with purge rate and power changes. However, the spot size increased up to 5 mm with CO_2 purge gas. Spot diameter depended strongly on both input power and purge rate. In general, a high power and low purge rate led to the largest spot diameter. This "blooming" occurred because the CO_2 laser beam absorbed by the CO_2 insufflation gas in the operating channel heated the gas, resulting in a thermally induced lensing action that caused the beam to diverge when it exited the laparoscope.[7] The spot diameter with the conventional CO_2 laser depended on, but was not predictably related to, the CO_2 gas insufflation rate (Figure 2). This is highly undesirable because the normal changes in insufflation rate that occur with aspiration or with routine automatic cycling of the insufflation system can lead to large and unpredictable changes in spot size. In marked contrast, the spot size produced by the isotopic $^{13}CO_2$ laser showed no dependence on power or on purge gas type or rate. The 7.5-mm operating channel produced a consistent spot size of approximately 1.25 mm, whereas the 5-mm working channel produced a consistent spot size of approximately 1.6 mm. This difference resulted from the diffraction limit, a result of physical optics that describes the limiting focus spot diameter that can be achieved at the end of an opaque tube of given length and diameter, and has little dependence on the laser except for the wavelength.[12] The diffraction-limited spot size measured at the distal end of the laparoscope results from the clipping of the beam to the diameter of the lumen at the proximal end of the laparoscope.

When a laser is used in the continuous-wave (nonpulsed) mode, the most important predictor of thermal damage is power density at the tissue. It is generally accepted that for continuous-wave CO_2 lasers, the nature of the tissue interaction changes gradually as the power density crosses through a threshold at about 5000 W/cm^2.[10] At or above this threshold, cutting and ablation are achieved with minimal thermal damage; below this threshold, more thermal damage is pro-

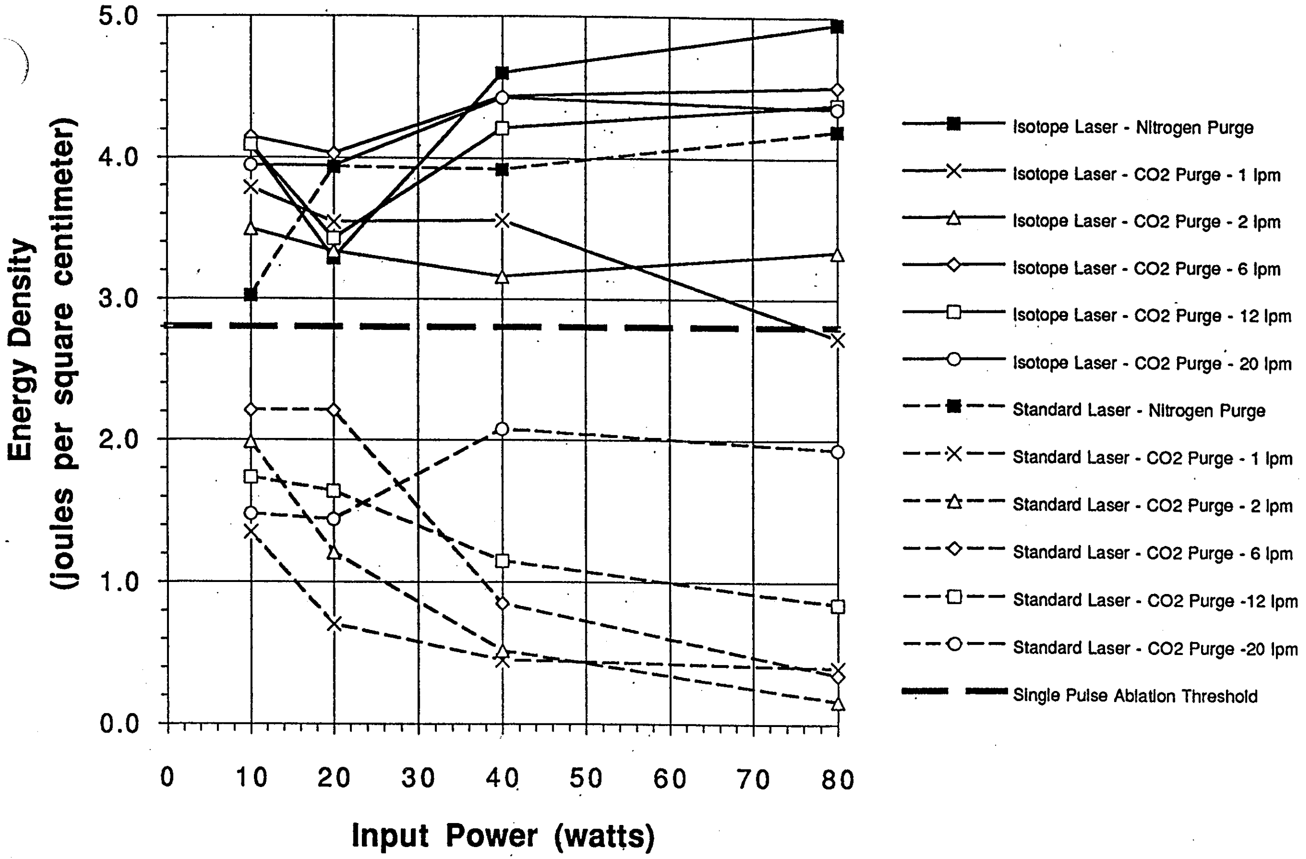

Figure 4. Energy density through the 5-mm operating channel (ultrapulse mode, 125 mJ per pulse). Lpm = L/minute.

duced. Figure 3 shows the power density at the distal end of the laparoscopes. With the conventional CO_2 laser and CO_2 purge gas, it was not possible to produce power density greater than 1500 W/cm^2, even at 80 W and a 20-L/minute purge rate. At the more common purge rate of 6 L/minute in the 5-mm working channel, the power density did not exceed 400 W/cm^2, more than an order of magnitude below the ablation threshold. With the isotopic $^{13}CO_2$ laser, a power density of 3000 W/cm^2 could be reached with the 5-mm working channel at an input power of 80 W, independent of purge gas or purge rate. The two- to threefold increase in power density with the 7.5-mm operating channel laparoscope was due primarily to the smaller spot size, resulting from reduced diffraction and, to a lesser degree, to the higher transmitted power.

Recent experimental work with pulsed CO_2 lasers has highlighted the importance of high energy density (fluence), short-duration laser pulses on the effectiveness of the laser as a surgical tool.[11,13] It has been shown that at an energy density threshold value of 2.8 J/cm^2, the laser-tissue interaction undergoes a change similar to that described above for continuous (non-pulsed) lasers.[11] These pulsed lasers are a breakthrough in laser development, making it possible to work above the thermal damage threshold (single-pulse ablation threshold), but at a low power setting. This results in better precision and control of surgical pace.

Concurrent advances in laser technology have increased the available energy in short-duration pulses from approximately 50 mJ, produced by conventional superpulse lasers, to 250 mJ, produced by ultrapulse lasers. Figure 5 shows the energy density measured at the distal end of a 7.5-mm operating channel with 50-mJ input pulses. It is clear that conventional CO_2 superpulse lasers, when used with a laparoscope and CO_2 insufflation gas, do not yield sufficiently high energy density at the tissue to exceed the single-pulse ablation threshold. Although superpulse lasers have been in use for a number of years, they have not achieved widespread use and acceptance among laparoscopic surgeons. These data suggest that one reason could be their inability to deliver sufficient energy density to the tissue to exceed the single-pulse ablation threshold. Therefore, until now, they have provided no real benefit over continuous-wave lasers when used in laparoscopy. With the isotopic $^{13}CO_2$ laser, also operating at 50-mJ pulse energy, energy density above

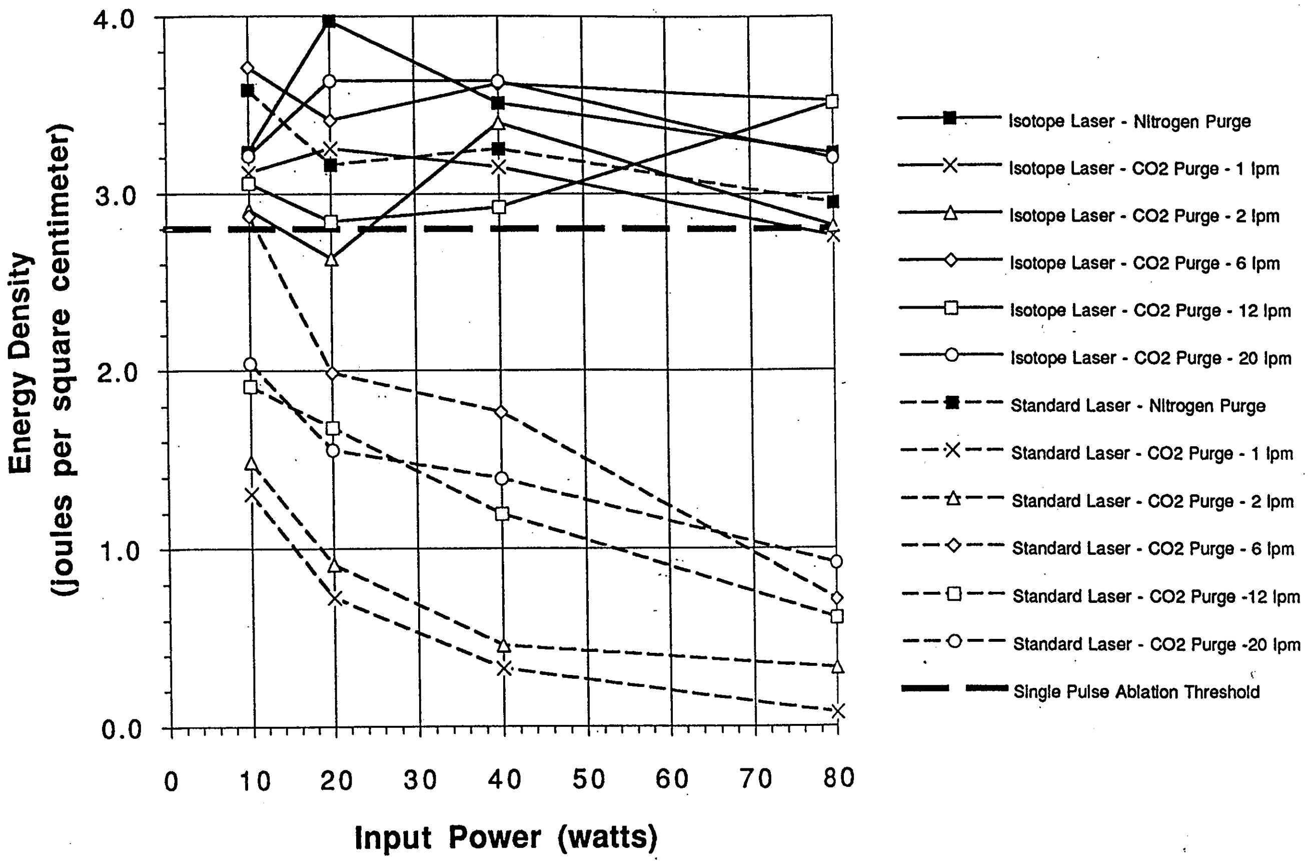

Figure 5. Energy density through the 7.5-mm operating channel (ultrapulse mode, 50 mJ per pulse). Lpm = L/minute.

the threshold value may be achieved at any power setting and any insufflation rate (Figure 5).

When using a 5-mm operating channel, 50 mJ of pulse energy was not sufficient to exceed the single-pulse ablation threshold, even with the isotopic $^{13}CO_2$ laser, because of the larger spot size (Figure 4). However, the isotopic $^{13}CO_2$ laser has the unique ability to produce higher energy pulses than superpulse lasers, and this pulse energy is adjustable from the control panel. The pulse energy was set at 125 mJ, which is 2.5 times that which can be achieved by currently available conventional superpulse CO_2 lasers. Once again, it was possible to exceed the single-pulse ablation threshold independent of power or insufflation rates.

These unique properties of the isotopic $^{13}CO_2$ laser should result in substantial clinical advantage. The very large reserve of deliverable power should allow the surgeon to operate at any speed with no limitations imposed by the laser, resulting in shorter operating times in experienced hands. Two of the authors (GDA and HR) have performed hundreds of operations with both conventional lasers and the $^{13}CO_2$ laser. They believe that these potential surgical advantages do occur with the $^{13}CO_2$ laser, although randomized trials are required to confirm these impressions. The surgeon can vary not only the power but also the energy per pulse to obtain the desired speed and tissue effect independently. At 200 mJ per pulse, essentially no thermal effect occurs. This could occasionally result in more bleeding in highly vascular areas. At 25 mJ per pulse, substantial thermal effect appears to be achieved, resulting in coagulation or desiccation. The surgeon's capability to control energy density and depth of coagulation directly from the laser control panel allows many different surgical techniques. That this control of thermal injury can be exercised reliably and independently of power and operating speed is especially important. For example, the isotopic $^{13}CO_2$ laser can deliver power as low as 50 mW and pulse energy as low as 1 mJ. This flexibility appears to be very useful when performing salpingostomy with the technique of Bruhat et al.[14] The capability to operate at 125 mJ per pulse and higher also appears to result in rapid tissue ablation without charring.

The constant spot size associated with the long focal length from the laparoscopic delivery system results in a constant tissue effect and hence greater surgical precision. In addition, because the laser energy produced by the ^{13}C isotope is not absorbed in the insufflation gas, there is no significant heating of the laparoscope. There are no variations in the beam characteristics with varying insufflation rates, as can occur with the conventional CO_2 laser because of intermittent automatic insufflation, and no subsequent variation of temperature of the CO_2 gas within the laparoscope's operating channel. The surgeon can operate at any distance from the tissue without the significant changes in spot size that occur with conventional superpulse CO_2 lasers. This should produce great flexibility in selection of magnification and operating technique, with predictable and constant tissue effect for a given laser setting.

The isotopic $^{13}CO_2$ laser reliably performs single-pulse ablation in the laboratory and appears to function similarly in the operating room, using standard instrumentation and standard procedures under any normal conditions. Clinical evidence for single-pulse ablation is the consistent lack of char observed when using the isotopic $^{13}CO_2$ laser in the operating room. When conventional CO_2 lasers are used under the same conditions, coagulation and tissue damage, rather than ablation, inevitably occur. The isotopic $^{13}CO_2$ laser overcomes limitations of conventional CO_2 lasers.

The isotopic laser under test was the Coherent Ultrapulse 5000L. This laser is identical to earlier Coherent Ultrapulse lasers except for the isotopic gas-filled laser tube. Because modern laser tubes are sealed at the factory, it is not practical to change the gas in the tube at a user site. However, Coherent maintains a policy of changing laser tubes at the user site so that the earlier Ultrapulse laser may be upgraded to full Ultrapulse 5000L specifications, at a cost that is a fraction of that of a new isotopic laser.

References

1. Einstein A. Zur quantentheorie der strahlung. Phys Zeitschr 1917;18:121–8.
2. Schawlow AL, Townes CH. Infrared and optical masers. Phys Rev 1958;112:1940–9.
3. Maiman TH. Stimulated optical radiation in ruby. Nature 1960; 187:493–4.
4. Patel CKN. Continuous wave laser action on vibrational transitions of CO_2. Phys Rev 1964;136:1118–93.
5. Bruhat MA, Mage G, Manhes H. Use of CO_2 laser via laparoscopy. In: Kaplan I, ed. Laser surgery III. Jerusalem: Academic Press, 1979:275–6.
6. Milonni P, Eberly JH. Lasers. New York: Wiley, 1988:211–41.
7. Reich H, MacGregor TS, Vancaillie TG. CO_2 laser used through the operating channel of laser laparoscopes: In vitro study of power and power density losses. Obstet Gynecol 1991;77:40–7.
8. Wieder I, McCurdy GB. Isotope shifts and the role of fermi resonance in the CO_2 infrared maser. Phys Rev Let 1966;16:565–7.
9. Freed C. Status of CO_2 isotope lasers and their applications to tunable laser spectroscopy. IEEE J Quantum Electron 1982;QE–18:1220–8.
10. McKenzie AL. A three zone model of soft tissue damage by a CO_2 laser. Phys Med Biol 1986;31:967–83.
11. Green HA, Domankevitz Y, Nishioka NS. Pulsed carbon dioxide laser ablation of burned skin. Lasers Surg Med 1990;10:476–84.
12. Buck AL. The radiation pattern of a truncated gaussian aperture pattern. Proc IEEE, March 1967;448–50.
13. Walsh JT, Flotte TJ, Anderson RR, Deutsch TF. Pulsed CO_2 laser ablation. Lasers Surg Med 1988;8:108–18.
14. Bruhat MA, Wattiez A, Mage G, Pouly JL, Canis M. CO_2 laser laparoscopy. Baillieres Clin Obstet Gynecol 1989;3:487–97.

Address reprint requests to:
G. David Adamson, MD
Fertility Physicians of Northern California
540 University Avenue
Suite 200
Palo Alto, CA 94301

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