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Incision properties and thermal effects of three CO_2 lasers in soft tissue

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Objectives. It was the aim of this study to determine thermal and histologic events resulting from soft tissue incision with three CO_2 lasers: one emitting light energy via a hollow waveguide at 9.3 μm; the others emitting light energy at 10.6 μm, one via a hollow waveguide, the other through an articulated arm delivery system.
Study design. Thirty standardized incisions were made in the oral mucosa of pig's mandibles with three different lasers at actual power levels of 1,4, and 12 W. Thermal events were recorded with thermocouples, and a histologic examination was performed to determine vertical and horizontal tissue damage as well as incision depth and width.
Results. Thermal and histologic results were related to parameters and beam characteristics rather than wavelength.
Conclusion. In addition to wavelength, many variables can contribute to the surgical characteristics of a laser.
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Carbon dioxide (CO_2) lasers have been used successfully for soft tissue surgery in the head and neck region for over 25 years. Clinical and laboratory investigations have consistently confirmed the advantages of this tool: precision, minimal intraoperative hemorrhage, sterilization of the surgical area, healing with minimal scarring, and decreased postoperative pain and swelling.[1-5] Areas of routine laser use include frenectomies, periodontal surgery, tumor resections, and excision of lesions such as hyperplasia, papillomas, hemangiomas, lymphangiomas, and mucoceles.

The CO_2 laser emits light energy that is strongly absorbed by water and therefore also by tissues with a high water content, such as the oral soft tissues. The absorbed energy causes vaporization of the intra- and extracellular fluid and destruction of the cell membranes.[6, 7]

The exact nature and extent of the laser effect on soft tissue is governed by several factors. These include the total amount of energy delivered to the tissues over the entire period of irradiation (measured in Joules) as well as power levels (Watts), that is, energy delivered per second. A unit of energy delivered over a very short period of time will have a greater effect than that same unit of energy delivered over a long time period. Spot size of the light beam used is also important. A unit of power or energy delivered over a large area by a large spot size will have milder effects than the same power or energy focused into a small spot size.

Structures directly adjacent to the area of vaporization demonstrate a range of thermal effects, depending on their proximity to the irradiation site and their optical properties. These marginal thermal interactions can range from mere transient heating to protein denaturation, water evaporation, or even carbonization and burning.

One characteristic difference between a laser and a scalpel cut is the generation of a coagulated tissue layer along the walls of the laser incision. This zone of thermal damage to adjacent structures should ideally be kept to a minimum, as it may impede wound healing, graft take, and reduce tensile strength, especially if it is extensive. Furthermore, deeply penetrating laser-induced temperature increases can threaten the vitality of adjoining structures such as teeth, pulp, or periodontium.

In the CO_2 lasers traditionally available to clinical dentistry, light at 10.6 μm is delivered by means of an articulated arm and a handpiece to the surgical site. As the articulated arm configuration consisting of hollow rigid tubes linked by joints can be cumbersome when working intraorally, various alternative delivery systems, usually in the form of hollow waveguides, are now becoming available. Hollow waveguides, flexible or semiflexible fibers used to conduct the laser beam, often provide better maneuverability of the delivery

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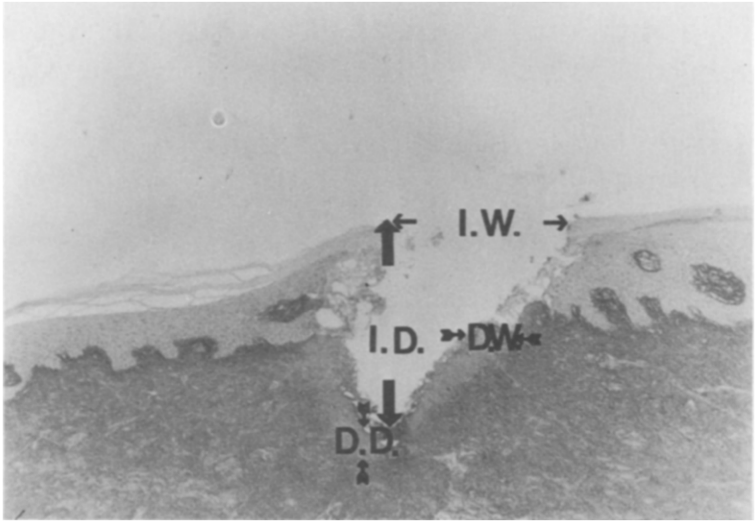

Fig. 1. Measurement sites for histologic evaluation: ID = Incision depth; IW = incision width; DD=tissue damage depth; DW = tissue damage width.

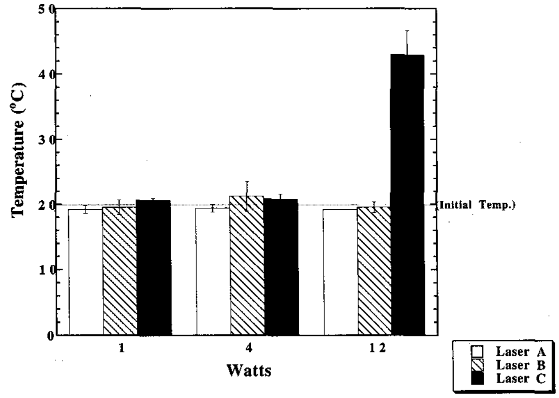

Fig. 2. Temperature after 3 second laser irradiation. SD is depicted when greater than zero.

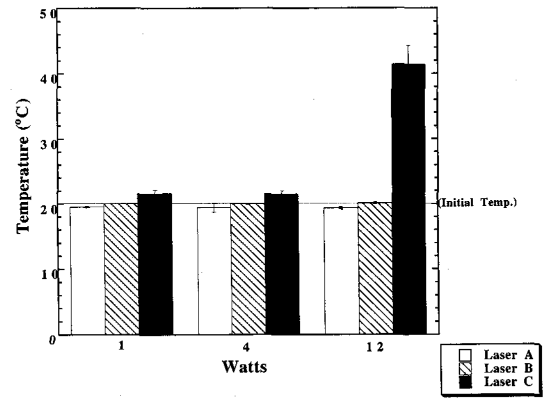

Fig. 3. Temperature after 6 second laser irradiation. SD is depicted when greater than zero.

system. Recently, CO_2 lasers that deliver light in the 9.3 μm region of the infrared spectrum have also been developed for clinical use; 9.3 μm better matches the absorption characteristics of hydroxyapatite, providing improved ablation characteristics in hard tissues and consequently greater protection for pulpal tissues. Technologic advances have now allowed manufacture of a coherent beam delivery system for this wavelength.

It was the aim of this investigation to determine thermal events, incision characteristics, and soft tissue damage resulting from standardized laser incision using three different CO_2 lasers: one emitting light at 9.3 μm via a hollow waveguide delivery system, the second emitting light at 10.6 μm with an articulated arm delivery system, the third also emitting light at 10.6 μm and fitted with a hollow waveguide delivery system.

MATERIAL AND METHODS

In this investigation, nine fresh pig's mandibles were used not more than 6 hours after the animal's death. The mandibles were cooled until 1 hour before use, then returned to room temperature.

Standardized incisions 3 cm in length were made with a laser in the oral mucosa parallel to the border of the mandible and 5 mm below the gingival margin. To standardize the incision length, a template was positioned 3 mm below the planned incision site during the performance of each incision. A total of 30 incisions were made. A minimum of three per parameter were made with each laser type; one of these in-

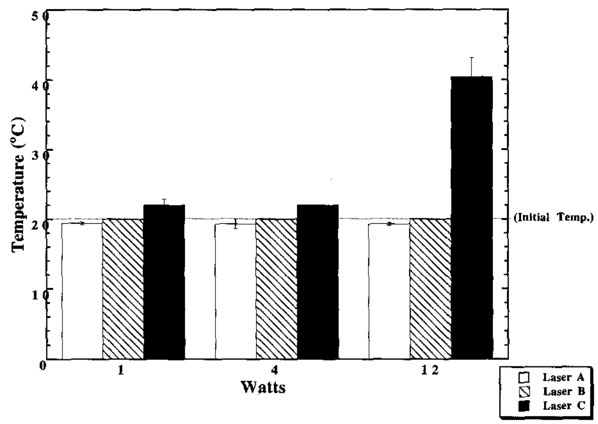

Fig. 4. Temperature after 10 second laser irradiation. SD is depicted when greater than zero.

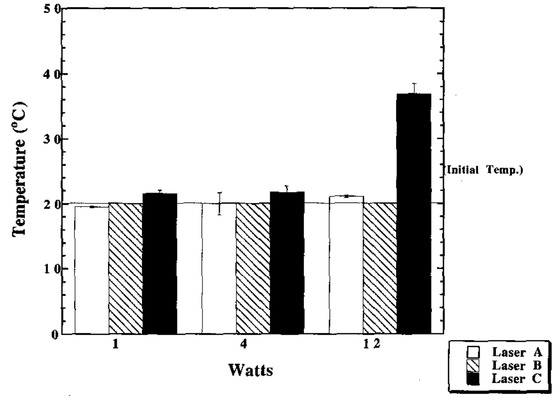

Fig. 5. Temperature after 30 second laser irradiation. SD is depicted when greater than zero.

cisions was performed in the anterior third of the mandible, the second in the middle third, and the final incision in the posterior third. Three different CO_2 lasers were used; one emitted at 9.3 μm, the other two emitted at 10.6 μm.

Before laser irradiation, a copper-constant thermocouple Philips Type K (Omega Engineering, Inc., Stamford, Conn.) with 0.25 mm diameter and a 63% response time of 7 ms was inserted into the soft tissue, directly below its surface and halfway (1.5 cm) along the length of the incision. Laterally, the thermocouple was positioned at a distance of 1 mm plus one half of the spot size from the incision line. Thus, for laser A, the thermocouple was located 1.12 mm lateral to the line of incision; for laser B it was positioned 1.11 mm laterally and for laser C 1.15 mm laterally.

Laser parameters

Laser A (Medical Optics Inc., Carlsbad, Calif.) emitted light at 9.3 μm; the light was delivered via a coherent hollow wave-guide and a focusing handpiece. Spot size measured 250 μm. Laser B (Sharplan Lasers, Inc., Allendale, N.J.) emitted light at 10.6 μm via an articulated arm beam delivery system and a focusing handpiece. Spot size measured 220 μm. Laser C (Luxar Corp., Bothell, Wash.) also emitted light at 10.6 μm; the light was delivered through an incoherent hollow fiber waveguide to produce a spot size of 300 μm. All lasers were set to the continuous wave mode. Beam characteristics for each laser were calibrated by one laser engineer to conform to manufacturer's specifications directly before this investigation. Photographic paper was used to measure and document spot sizes before each irradiation. Distance from the point of emission of laser light to the tissues was standardized by using a jig. Duration of irradiation for each incision measured 4 seconds and was timed with a stop watch.

Actual power levels emitted were 1, 4, and 12 W. A PRJ-M power meter (Gentec) was used to determine actual values directly before each laser incision. These specific power levels were selected as they represent the range of minimum to maximum available in many clinical devices.

Within 3 minutes of irradiation, incisions were dissected out with a margin exceeding 5 mm and divided into three sections with the use of a scalpel. These tissue samples were fixed directly in 10% neutral buffered formalin and stored in buffered solution under refrigeration until embedded in paraffin wax. A total of 81 wax blocks were prepared; 6 micron wax sections were cut routinely and stained with serius red. A minimum of three slices from each block were used to obtain 10 slides per incision site, that is, 30 slides per laser parameter. From each slide a measurement of incision depth and width as well as depth and width of adjacent tissue damage was made by the same investigator who was not told of the groupings. Fig. 1 depicts the locations of each measurement site. A photographic record was made of the results.

The student's t test for paired data was used to compare zones of vaporization, zones of tissue damage, and thermal events.

RESULTS

Thermal events

Figs. 2 through 5 depict thermal events and standard deviations during laser irradiation at 1, 4, and 12 W.

Thermal events during laser irradiation. During irradiation with lasers A and B, no significant temperature rise was measured during irradiation at any time points or power settings ($p < 0.05$). Significant ($p < 0.05$) temperature increases did occur during ir-

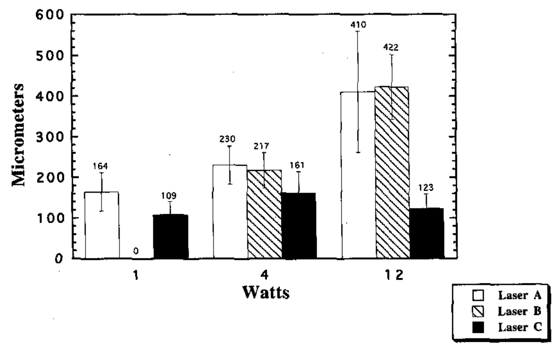

Fig. 6. Incision depth at 1, 4, and 12 W. No values are plotted for the Sharplan laser at 1 W because no incision resulted from irradiation at this parameter. SD is depicted when greater than zero.

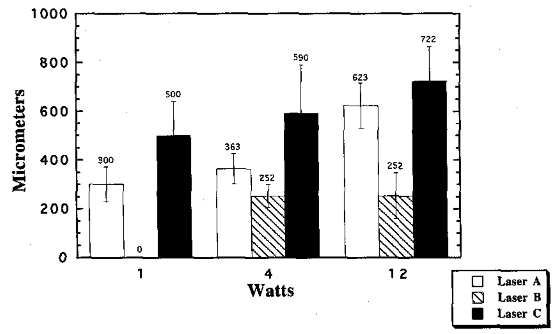

Fig. 7. Incision width at 1, 4, and 12 W. No values are plotted for the Sharplan laser at 1 W because no incision resulted from irradiation at this parameter. SD is depicted when greater than zero.

radiation with laser C at 1 W after 6, 10, and 30 seconds; at 4 W after 6, 10, and 30 seconds; and at 12 W after 3, 6, 10, and 30 seconds.

Comparison between laser types. Results were very similar for lasers A and B, with significantly different results ($p < 0.05$) obtained only at the 12 W setting. Temperatures were consistently and significantly higher with laser C as compared with laser A at all time points at 1 W and at 12 W and at all time points except 3 seconds at 4 W ($p < 0.05$). Statistical comparison of thermal results from laser C and laser B also revealed significantly higher temperatures using laser C ($p < 0.05$) at all time points and parameters except 3 seconds at 1 and 4 W.

Histologic data

Figs. 6 and 7 depict incision depth and width at 1, 4, and 12 W. For lasers A and B, vertical incision depths and horizontal incision widths did not differ significantly ($p < 0.0001$) at 12 and 4 W. At 1 W no clear incising effect was obtained with laser B. Incision depths were significantly greater for lasers A and B at all power settings than for laser C, and incision widths were significantly smaller ($p < 0.0001$) with the exception of laser B at 1 W when a clear incision was not obtained.

Figs. 8 and 9 represent the extent of vertical and horizontal tissue damage adjacent to the laser incision. These measurements did not differ significantly ($p < 0.0001$) between lasers A and B at 12 and 4 W. As no clear incising effect was obtained with laser B at 1 W, no useful comparison was possible at this power setting. These two lasers consistently produced significantly greater horizontal and vertical zones of tissue damage ($p < 0.0001$) than laser C.

DISCUSSION

Several authors have conducted investigations comparing the histologic and thermal effects of lasers versus scalpels or of lasers versus electrosurgery. Obviously, scalpels do not cause thermal necrosis, but they also fail to provide hemostasis, bacterial elimination, and contact-free incision. Several authors report zones of thermal damage 3 to 5 times wider after electrocautery use than after CO_2 laser use.[8-12]

Studies have also been published regarding laser effects on soft tissues at various wavelengths and parameters. Of the clinically common dental lasers, the CO_2 laser (at 10.6 μm) usually produces narrower zones of tissue damage in soft tissues than the Nd:YAG laser because of the greater absorption of CO_2 light by soft tissues.[13-15] However, little information is available comparing the soft tissue effects of continuous-wave CO_2 lasers at 9.3 μm and at 10.6 μm.

During irradiation with lasers A and B, no significant temperature rises were measured in the soft tissues directly adjacent to the incision site at a distance of approximately 1 mm from the margin of the actual incision. This result is in agreement with many studies undertaken at 10.6 μm that report an average zone of damage after laser incision in soft tissues of <0.6 mm.[15-19] The results from this study indicate that the danger of thermal damage to adjacent structures during laser incision of soft tissues at 9.3 or 10.6 μm at the parameters investigated is minimal unless the adjacent structures are directly impacted by the laser beam. This finding is directly relevant to clinical dentistry, because of concerns regarding possible damage to neighboring structures such as teeth or bone during soft tissue laser surgery. In this situation the use of the 9.3 μm wavelength may be particularly favorable because of its greater absorption by hydroxyap-

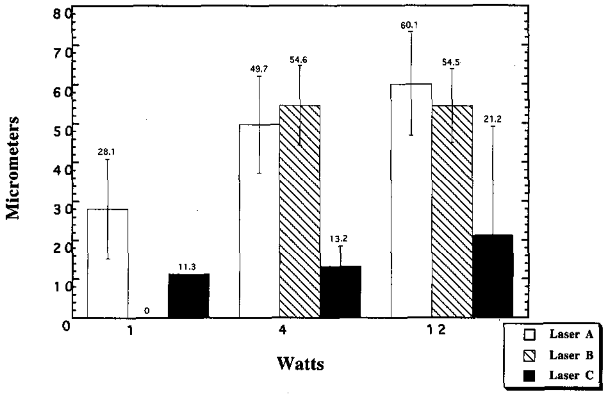

Fig. 8. Vertical damage at 1, 4, and 12 W. No values are plotted for the Sharplan laser at 1 W because no incision resulted from irradiation at this parameter. SD is depicted when greater than zero.

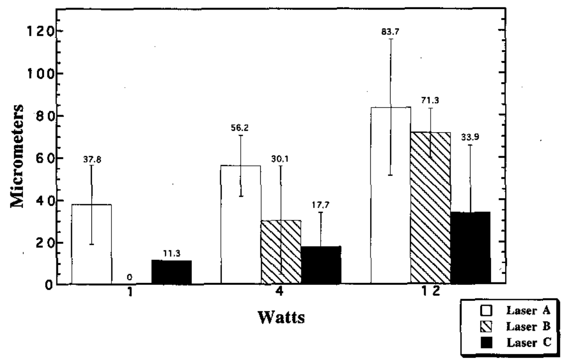

Fig. 9. Horizontal damage at 1, 4, and 12 W. No values are plotted for the Sharplan laser at 1 W because no incision resulted from irradiation at this parameter. SD is depicted when greater than zero.

atite, which should serve to reduce the possibility of pulpal damage by inadvertent laser irradiation.

Temperature increases recorded during laser irradiation with laser C were significant after 6 seconds or more of irradiation at 1 and 4 W but remained small (<3° C). An almost immediate temperature rise of up to 20° C was determined directly adjacent to the incision site at 12 W. The difference between results at 12 W compared with 1 or 4 W can be explained as follows: laser energy absorbed by tissues can be released in the form of heat. If sufficient energy is delivered to a spot on the surface of the tissue so quickly that the volume of that tissue is heated to its vaporization temperature, the tissue can be ablated before any significant amount of heat flows to the surrounding tissue. Succeeding energy arriving at the same spot after residual heat has dissipated by heat flow into surrounding tissues will progressively ablate similar volumes. However, in this investigation, continuous-wave, that is nonpulsed settings only were used. Thus no pulse intervals were available to allow for thermal relaxation or cooling of the irradiated, unvaporized tissues. At higher power levels, more heat was generated locally in the tissues than could adequately dissipate into surrounding tissues and structures, resulting in a build-up of heat and temperature increases.

Thermal results from lasers A and B did not differ significantly at comparable parameters except at all time points with 12 W. As the absorption of light in water at these two wavelengths is almost identical and absorption characteristics in soft tissues resemble to a great extent those in water because of high soft tissue water content, these results should be similar. Furthermore, both lasers A and B beam profiles are monotonic decreasing, gaussian, or gaussian-like. Both lasers have coherent delivery systems and focusing handpieces. The differences at 12 W were barely significant and can probably be attributed to variations associated with the different beam delivery systems, which become increasingly significant at higher power levels.

Temperatures measured during irradiation were generally higher with laser C. In contrast to lasers A and B, this laser's beam profile demonstrates spatially rapid excursions from the median, with the median approximating a "top hat." Furthermore, in laser C, the light passes through an incoherent waveguide and a handpiece with accessory tips.

Although the temperature increases measured in the course of this study were generally small, several additional factors should be taken into account when transposing our data to the clinical situation. Temperature measurement was performed with thermocouples that were placed approximately 1 mm from the lateral margin of the incision site. Absolutely reproducible and precise location of the thermocouples with respect to the incision site and beam delivery was difficult, and yet it is directly relevant to the results obtained. More extensive investigations need to be performed with the use of noninvasive devices located outside of the tissues under investigation such as thermal cameras detecting within the infrared range. Such studies are currently being undertaken by our group. Furthermore, maximum duration of irradiation in this study measured 30 seconds. In the clinical situation, irradiation times may well be significantly longer, which can give rise to greater temperature increases than those measured in this study. To avoid this complication, use of short-duration, high-power pulses with adequate pulse intervals is often preferable, providing good incision characteristics with greatly diminished heat accumulation and thermal effects as required in the clinical setting. It is for this reason that most lasers (including those investigated in this study) offer a range of pulse choices.

In this study we chose to use simple, nonpulsed parameters over a relatively short period of time to provide basic widely applicable information on the characteristics of the lasers under investigation. The data will be used as a basis for further studies more directly related to the clinical situation.

Examination of histologic data revealed little difference between lasers A and B. Lateral and vertical damage adjacent to the laser incisions was consistently smaller from laser C. These discrepancies between lasers at comparable settings are again linked to differing optics/beam characteristics incorporated into the laser devices as described earlier in this discussion. Incision width was greater with laser C, and incision depth was generally smaller, no doubt directly related to the larger spot size and incoherent beam of this laser.

It is often stated that histologically evident effects of the CO_2 laser extend approximately 60 μm into soft tissues.[19] Thus our results at 10.6 and 9.3 μm fall well within the range of previously reported histologic effects. Although it is true that 99% of the laser light is absorbed within 60 μm, the zones of vaporization and damage from heat conduction will depend directly on the laser parameters used. Factors include energy density, constant/pulsed mode, pulse durations/intervals, and exposure times. When we refer to the physics of vaporization applications of the CO_2 laser we see that to vaporize a given volume of tissue, the energy necessary is a product of power multiplied by time. Thus the use of high powers by the surgeon results in rapid and effective vaporization along the incision line. However, use of high power densities in a continuous wave mode can lead to accumulation of heat and thermal damage to adjacent structures.[20] Indeed, in our investigation we did observe a trend of greater damage to lateral tissues at higher power levels with the use of the constant wave mode. This effect may be put to good use, for example, to enhance thermocoagulation to achieve hemostasis and provide a bloodless surgical field. However, in general, for cutting without coagulation, very short pulses at the highest power density that can be controlled should be applied for the shortest time possible during incision of soft tissues to achieve the desired result with the least risk of unwanted thermal damage. Other authors have demonstrated that use of a superpulsed mode based on the principles of high irradiance with short duration pulses and adequate pulse intervals will reduce thermal necrosis by a factor of 2 or more.[16, 21]

In summary, this study determined thermal and histologic events resulting from soft tissue incision using CO_2 lasers at 9.3 or 10.6 μm fitted with a hollow waveguide or an articulated arm beam delivery system. Thermal and histologic effects were related to the parameters used and beam characteristics rather than wavelength. Clinically, these results are significant in demonstrating that many variables are involved in determining the surgical characteristics of any laser. Thus it is important that all parameters be taken into consideration when lasers are used as surgical tools, to ensure predictability, parity, and consistency of results.

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