INVESTIGATING THE RANGE OF SURGICAL EFFECTS ON SOFT TISSUE PRODUCED BY A CARBON DIOXIDE LASER

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ABSTRACT

The authors investigated the surgical and collateral effects on soft tissue of a carbon dioxide laser emitting at 9.3 micrometers. Specifically, incision widths and depths as well as effectiveness were studied. Three different laser modes were investigated: gated continuous wave, or Cw, Superpulse and OptiPulse (Medical Optics). Incision depths correlated positively with average power; higher powers produced deeper incisions. The gated Cw mode quickly produced wide, deep incisions; Superpulse achieved narrower, deep incisions; OptiPulse caused very narrow, shallow incisions. Collateral damage to adjacent tissues was reduced by a factor of about 2 using Superpulse, and by a factor of 10 using OptiPulse. A wide range of effects is achieved in soft tissue, depending on the laser parameter combination used.

Lasers have been advocated for a wide range of surgical applications. Many areas of routine CO_2 laser use for soft-tissue surgery have developed during the past 30 years, including orofacial surgery and periodontal applications. Advantages of this tool include precision, minimal intraoperative hemorrhage, sterilization of the surgical area and healing with minimal scarring, postoperative pain and swelling.[1-5] The clinician should be able to predict and achieve specific incisional or ablational effects. The required range of incisional effects in soft tissue is extensive. Wide or narrow, deep or shallow incisions may be indicated; alternately, fast large-surface ablation or microsurgical finesse may be desirable.

Laser effects on adjacent and underlying tissues such as bone or tooth must be considered, as there may be specific limits regarding collateral or thermal effects. Zach and Cohen,[6] for example, established stringent thermal tolerance thresholds for the dental pulp. Finally, there should be easy access with the laser device to any part of the mouth.

Laser effects on soft tissue are related to the absorption characteristics of light in the tissues, and on the laser parameters used. Light at 9.3 to 10.6 micrometers is absorbed strongly in water, and therefore in soft tissue. Excellent incisional and ablational effects can be achieved.[1] Previous studies have demonstrated that incisional and collateral effects on soft tissue are almost identical at 9.3 and 10.6 µm.[7] Conventional CO_2 lasers usually emit at a wavelength of 10.6 µm. But recently, CO_2 lasers that deliver light in the 9.3-µm region of the infrared spectrum through a coherent, flexible-beam delivery system have been developed.

These newer lasers facilitate easy access to all areas of the mouth. As they can emit at a wide range of parameters (peak and average powers, pulse durations, pulse intervals and pulse repetition rates), tailoring parameter combinations to individual clinical situations may become a reality. Moreover, the 9.3-µm wavelength matches the absorption characteristics of hydroxyapatite better than does the conventional 10.6-µm wavelength. It may be possible to modify[8] or ablate hard dental tissues with the same device used for soft tissues.

The objective of this investigation was to determine the range of clinical incision effects achieved in soft tissue using a wide range of

TABLE 1

LASER CONFIGURATIONS.

MODE	AVERAGE POWER (W)	APPROXIMATE PEAK POWER (W)	PULSE REPETITION RATE (Hz)	PULSE DURATION
Gated continuous wave	1-9	1-10	0.5-500	1, 20, 200 ms
Superpulse	1-7	20	170-1170	300 μs
OptiPulse	0.72-1.20	60-100	10-40	300 μs

laser modes and parameters at 9.3 μm. Laser effects on underlying and adjacent tissues at various soft-tissue thicknesses were also documented.

MATERIALS AND METHODS

Irradiation protocol. In 24 fresh pig mandibles, six standardized incisions 3 centimeters in length were made in the oral mucosa per laser parameter combination. A template was positioned 3 millimeters below the planned incision site as each incision was made. The laser handpiece was attached to a motorized slide to standardize the incision and to control movements; the pig jaws were immobilized on a veterinary mount. The setup was configured so that the waveguide was used in the straight configuration (not bent), as hollow waveguides can generate different spot shapes and sizes, depending on the extent of bending. Three incisions per parameter were positioned parallel to the border of the mandible, 5 mm below the gingival margin. The average thickness of these tissues measured 0.3 to 0.6 mm.

Three additional incisions per parameter were performed in the thicker soft tissues 5 mm from the lower border of the mandible. The average thickness of these tissues measured 0.7 to 2.7 mm. Duration of irradiation for each incision measured four seconds, and was timed with a stopwatch. A subjective evaluation of "ease of incision" and "incision cleanness" was made by one operator.

Laser device. The laser used (Duolase, Medical Optics Inc.) emitted at 9.3 μm; the light was delivered via a coherent hollow waveguide and a focusing handpiece. Spot size measured 250 μm. Beam characteristics were calibrated by a laser engineer directly before each irradiation episode, and photographic paper was used to measure and document spot sizes. Beam profiles were single-mode Gaussian. A PRJ-M powermeter (Gentec Inc.) was used to determine actual values directly before each laser incision.

Laser parameters. Three laser modes were used.

- The gated continuous wave, or Cw, consists of relatively long pulses (1 to 200 milliseconds, or ms). Peak powers (or maximum power reached during one pulse) were relatively low and approximated average powers.
- In the Superpulse mode, shorter pulses (300 microseconds, or μs) with a peak power of 20 watts during each pulse, irrespective of the total average power delivered, were used.
- In the OptiPulse mode, 300-μs pulses with very high peak powers (60 to 100 W during any one pulse), but very low average powers (0.72 to 1.2 W) were generated. Finally, the pulse repetition rate (the number of pulses emitted per second [expressed in hertz]) varied within each mode setting. The laser configurations are shown in Table 1.

Sample processing. Within three minutes of irradiation, incisions were dissected out, with a margin exceeding 5 mm, and divided into three sections with a scalpel. Bone underlying each incision was marked, labeled, photographed and frozen for future reference. The chief evaluation factor for bone was charring, which was selected as a gross indicator of significant laser-induced thermal damage.

The soft-tissue samples were fixed directly in 10 percent neutral buffered formalin and stored in buffered solution under refrigeration until embedded in paraffin wax. Wax blocks were prepared and 6-μm sections were cut routinely and stained with Serius Red. Measurements were made from either 15 or 30 slides per parameter and incision site. Incision depth and width, as well as depth and width of adjacent tissue damage, were determined. A typical slide with measurement locations is shown in the figure.

Collateral tissue effects were measured at the bottom of the crater to simplify interpretation of the damage zones: for beams with a Gaussian profile, subablation laser-tissue interactions complicate the histologic picture. In samples in which a line of dots resulted from irradiation, measurements were performed centrally within the dot. A photographic record was made of the results.

Statistics. General linear models procedures were performed.

RESULTS

Clinical impressions. In the gated Cw mode at all pulse durations, a pulse repetition rate of ≥ 2.5 Hz and powers of ≥ 3.5 W, a clean cut was rapidly produced. At lower pulse repetition rates, the incising process produced a "dragging" rather than a "clean cutting" sensation in the operator; at a power of 1 W and pulse repetition rate of 5 Hz, individual dots rather than a continuous line of incision resulted.

At the parameters tested, the Superpulse mode clinically provided a rapid, clean, effective incising effect. These incisions were similar in depth to those achieved in the gated Cw mode, but narrower and V-shaped. The OptiPulse mode produced clean, V-shaped incisions, but they were much shallower and narrower.

Incisional and collateral effects. Mean incision depth and width, as well as mean collateral vertical and horizontal damage measurements and standard deviations, are presented in Table 2. Mean incision depths and widths spanned a wide range: mean incision depths using gated Cw measured from 327.10 to 1,490.00 µm, mean incision widths from 65.10 to 696.00 µm. Using Superpulse, mean incision depths of 496.00 to 1,116.47 µm and mean widths of 39.22 to 413.85 µm were measured. In the OptiPulse mode, mean depths ranged from 168.49 to 338.99 µm, and mean widths of 76.42 to 273.89 µm were measured. Mean vertical damage measured from 34.10 to 107.00 µm for gated Cw, 22.17 to 53.79 µm for Superpulse and 15.50 to 16.59 µm for the OptiPulse mode. Mean horizontal damage measured from 32.60 to 153.50 µm for gated Cw, 99.20 to 167.40 µm for Superpulse and 15.50 to 31.00 µm for the OptiPulse mode.

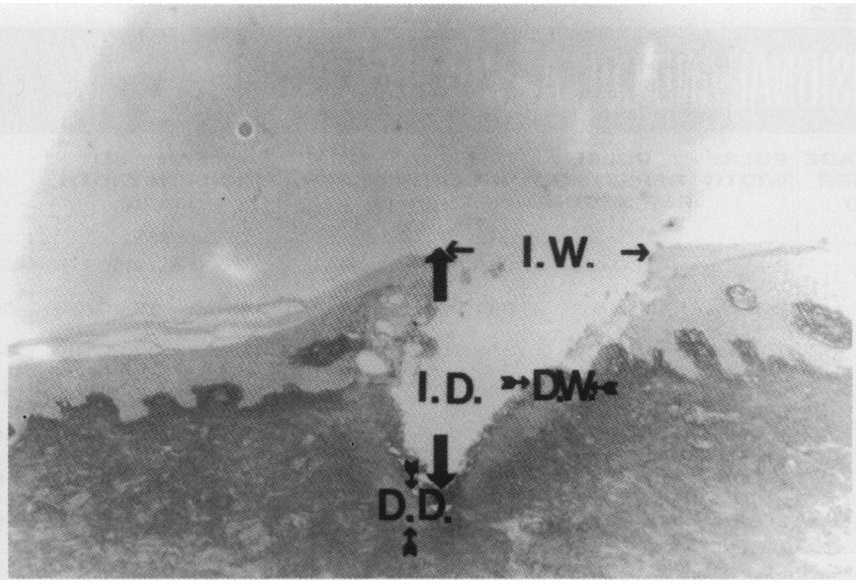


Figure. Measurement sites for histologic evaluation. I.D.: incision depth; I.W.: incision width; D.D.: tissue damage depth (horizontal damage); D.W.: tissue damage width (vertical damage).

Laser effects on underlying bone. To the naked eye, no laser damage was visible in bone underlying the incisions made in the thicker soft tissues (0.7 to 2.7 mm) located 5 mm above the lower border of the mandible at any of the laser parameters used. However, on bone underlying incision sites in the thinner soft tissues (0.3 to 0.6 mm) located 5 mm below the gingival margin, light charring was apparent after irradiation in the gated Cw mode at a pulse duration of 200 or 20 ms and a power of 9 W. Incisions at pulse durations of 1 ms in the gated Cw mode, or in the Superpulse or OptiPulse mode, produced no visible signs of thermal damage on the underlying bone.

Correlation analysis between laser parameters and histologic effects. Pearson correlation coefficients were used to establish the relationships shown in Table 3. The strongest single determinant factor for clinical outcome was average power used. The depth of incision correlated strongly and positively with average powers. The remaining interrelationships are fairly complex and are described in a separate publication; in this article, we discuss issues directly relevant to the clinician.

DISCUSSION

If dentists are to use lasers effectively and safely, they must be able to achieve a wide range of incisional and ablational effects predictably and consistently. In the mouth, for example, surgical needs in soft tissue in-

TABLE 2

INCISIONAL AND COLLATERAL EFFECTS.

AVERAGE POWER (W)	PULSE WIDTH	PULSE REPETITION PER SECOND (Hz)	MEAN ± SD* INCISION DEPTH, μm (n)	MEAN ± SD* INCISION WIDTH, μm (n)	MEAN ± SD* VERTICAL DAMAGE, μm (n)	MEAN ± SD* HORIZONTAL DAMAGE, μm (n)
1	200 ms	0.5	835.50 ± 21.70 (15)	355.00 ± 12.40 (15)	51.20 ± 7.75 (15)	62.00 ± 0.00 (15)
1	200 ms	1.5	681.90 ± 15.50 (30)	358.10 ± 26.40 (30)	66.70 ± 14.00 (30)	102.30 ± 12.40 (30)
1	200 ms	4	358.10 ± 57.40 (30)	348.80 ± 37.20 (30)	34.10 ± 21.70 (30)	60.50 ± 15.50 (30)
3.5	200 ms	1.5	1037.00 ± 108.50 (30)	446.40 ± 41.90 (30)	54.30 ± 14.00 (30)	77.50 ± 7.75 (30)
3.5	200 ms	2.5	457.30 ± 7.80 (30)	488.30 ± 23.30 (30)	45.00 ± 4.70 (30)	77.50 ± 0.00 (30)
3.5	200 ms	4	327.10 ± 15.50 (30)	372.00 ± 21.70 (30)	46.50 ± 6.20 (30)	72.90 ± 6.20 (30)
9	200 ms	4	1075.70 ± 20.20 (30)	313.10 ± 17.10 (30)	40.30 ± 9.30 (30)	46.50 ± 0.00 (30)
1	20 ms	5	717.70 ± 63.60 (30)	593.70 ± 35.70 (30)	100.80 ± 18.60 (30)	153.50 ± 6.20 (30)
1	20 ms	15	525.50 ± 72.90 (30)	395.30 ± 14.00 (30)	35.70 ± 7.75 (30)	62.00 ± 0.00 (30)
1	20 ms	25	437.10 ± 26.40 (30)	471.20 ± 23.30 (30)	49.60 ± 15.50 (30)	52.70 ± 9.30 (30)
1	20 ms	40	821.50 ± 37.20 (30)	516.20 ± 29.50 (30)	41.90 ± 12.40 (30)	125.60 ± 20.20 (30)
3.5	20 ms	15	1409.00 ± 76.00 (15)	696.00 ± 49.60 (15)	69.80 ± 12.40 (15)	100.80 ± 10.90 (15)
3.5	20 ms	40	953.30 ± 45.00 (30)	294.50 ± 41.90 (30)	107.00 ± 14.00 (30)	72.90 ± 12.40 (30)
9	20 ms	40	1061.80 ± 37.20 (15)	336.40 ± 18.60 (15)	46.50 ± 12.40 (15)	66.70 ± 12.40 (15)
1	1 ms	100	906.80 ± 65.10 (15)	666.50 ± 45.00 (15)	38.80 ± 7.80 (15)	86.80 ± 18.60 (15)
1	1 ms	333	375.10 ± 14.00 (15)	65.10 ± 15.50 (15)	83.70 ± 23.30 (15)	52.70 ± 9.30 (15)
1	1 ms	500	429.40 ± 37.20 (30)	407.70 ± 23.30 (30)	86.80 ± 9.30 (30)	82.20 ± 6.20 (30)
3.5	1 ms	333	1490.00 ± 48.10 (15)	134.90 ± 23.30 (15)	48.10 ± 12.40 (15)	113.20 ± 24.80 (15)
3.5	1 ms	500	348.80 ± 23.30 (15)	162.80 ± 12.40 (15)	46.50 ± 6.20 (15)	32.60 ± 4.70 (15)
0.7	300 μs (OP)†	40	168.49 ± 16.80 (15)	76.42 ± 9.30 (15)	16.59 ± 1.10 (15)	31.00 ± 2.70 (15)
1.0	300 μs (SP)§	143	496.00 ± 27.90 (30)	39.22 ± 5.30 (30)	53.79 ± 4.30 (30)	99.20 ± 10.0 (30)
1.2	300 μs (OP)	40	338.99 ± 21.00 (15)	273.89 ± 37.20 (15)	15.50 ± 1.70 (15)	15.50 ± 1.00 (15)
3.5	300 μs (SP)	583	1116.47 ± 67.00 (30)	413.85 ± 37.20 (30)	42.94 ± 3.70 (30)	128.19 ± 21.6 (30)
7.0	300 μs (SP)	1020	647.90 ± 36.70 (30)	105.40 ± 11.70 (30)	22.17 ± 1.90 (30)	167.40 ± 13.80 (30)

* SD: Standard deviation. † OP: OptiPulse. § SP: Superpulse.

clude large-area ablation of superficial structures such as benign, malignant or vascular lesions without adverse effects underlying bone. Alternately, narrow, deep incisions with minimal lateral effects may be required, perhaps for periodontal surgery in close proximity to teeth. A microsurgical capability to achieve finely controlled microincisions with minimal collateral thermal effects might be appropriate, perhaps, for intrapulpal applications.

Incision depth correlated strongly and positively with average power. This result is logical and is confirmed by the results reported from other investigations.[9-11] Incision shape and width were also strongly mode-dependent. The gated Cw mode produced relatively wide, straight-sided incisions. Thus, this mode can cut or ablate large amounts of tissue quickly and effectively in a controlled fashion. However, the proximity of underlying or adjacent bone or other heat-sensitive structures must be considered. In this investigation, laser powers exceeding 9 W at a pulse duration of 200 or 20 ms produced light charring on bone underlying soft tissues 0.3 to 0.6 mm in thickness.

The lack of charring and its sequelae observed in our samples at a pulse duration of 1 ms is confirmed by Walsh and colleagues,[12] who reported no charring after soft-tissue incision at pulse durations less than 2 ms. Lateral effects of irradiation extended from 32 to 338 μm into adjacent tissues. These figures agree with those determined by other authors[13-17] for this type of laser configuration. They confirm the need for caution where heat sensitivity is an issue, especially with relatively longer pulse durations and high average powers.

Laser incisions directly over or adjacent to heat-sensitive tissues are better performed with the Superpulse or OptiPulse modes. Incisions comparable in depth to those achieved using the gated Cw mode were completed equally quickly and efficiently at lower average powers with the Superpulse mode. No charring was observed on underlying bone, even at soft-tissue thicknesses of only 0.3 mm. These incisions were narrower

TABLE 3

CORRELATION ANALYSIS BETWEEN LASER PARAMETERS AND HISTOLOGIC EFFECTS.

PARAMETER	INCISION WIDTH	INCISION DEPTH	HORIZONTAL DAMAGE	VERTICAL DAMAGE
Pulse duration	-0.06531 $P = .1597$	-0.10480 $P = .0238$	-0.20456 $P = .0001$	-0.32514 $P = .0001$
Pulse repetition rate	-0.34841 $P = .0001$	0.04666 $P = .2724$	0.35174 $P = .0001$	-0.04168 $P = .3271$
Actual average power	-0.16152 $P = .0001$	0.46848 $P = .0001$	-0.03806 $P = .3709$	-0.14206 $P = .0008$

than those achieved using gated Cw mode, and V-shaped. The extent of collateral thermal effects was smaller by a factor of about 2 to 3 than that generated using gated Cw mode. Similar results have been reported by other authors,[17-19] and are attributed to the much shorter pulses (300 μs vs. 1 to 200 ms in this study) and higher peak powers (10 W vs. 1 to 20 W in this study) used in the Superpulse setting.

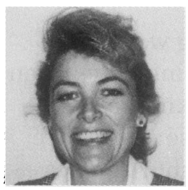
If dentists are to use lasers effectively and safely, they must be able to achieve a wide range of incisional and ablational effects predictably and consistently.

In the OptiPulse mode, very narrow, shallow incisions were achieved. Collateral effects were smaller by a factor of about 10 than those generated using gated Cw mode, and smaller by a factor of about 5 than those generated using Superpulse mode. No charring was observed on underlying bone, even at soft-tissue thicknesses of only 0.3 mm. These effects are attributed to the short pulses (300 μs) and low average powers (0.7 to 1.2 W), but high peak powers (60 to 100 W) were also used at this configuration, which permitted good incisional effects while minimizing heat movement into adjacent structures.

Thus, this laser configuration is well-suited to applications requiring skilled surgical finesse, or where the properties of adjacent and underlying tissues stipulate minimal thermal disturbance. Applications might include surgery within confined environments such as the periodontal structures or the dental pulp. The minimal extent of collateral effects induced by this laser configuration lies far below that determined for conventional Cw, gated Cw or Superpulsed configurations,[13-19] and greatly expands the scope of safe and appropriate laser applications in soft-tissue surgery.

CONCLUSION

This study determined that incisional and collateral effects in soft tissue of CO_2 laser irradiation at 9.3 μm can vary extensively. The use of higher average powers correlates with increasing depths of incision. Incision width and collateral damage are the results of complex interactions between the different laser parameter variables (to be discussed in another study). The results of this investigation demonstrate that a wide range of clinical effects can be achieved consistently and predictably in soft tissue, depending on the parameter configuration selected. ■



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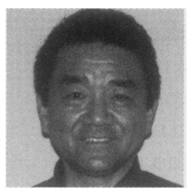

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