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ISBN
9780819420466

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Publication Date
1996-04-23

DOI
10.1117/12.238775

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Effects of diverse laser parameters at 9.3μm on soft tissue and bone

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1. ABSTRACT

These investigations were performed to determine thermal, histological and incisional effects in soft tissue of laser irradiation at 9.3um. Specifically, the consequences of varying pulse duration, interval and frequency, peak and average powers and energy densities were studied.

In fresh pig's jaws, 6 standardised incisions, 3cm in length, were made per parameter using a template and motorised jig. Incisions were made at various standardised anatomical sites, and surface thermal events monitored using an IR camera. Laser parameters investigated: power: 1-11W, duty cycle: 10-90%, Pulse duration: 1-200ms, at gated continuous wave (Cw). Superpulse and OptiPulse™ modes with 300us pulses were also investigated. Incision width and depth as well as collateral tissue effects were assessed statistically. They were directly related to the parameters used. Ease of incision and effects on underlying bone were also parameter-related.

2. INTRODUCTION

Over the past 25 years, areas of routine CO_2 laser use in oro-facial surgery have progressed to include frenectomies, periodontal surgery, tumor resections and excision of lesions such as hyperplasias, papillomas, hemangiomas, lymphangiomas and mucoceles. Clinical and laboratory investigations have consistently confirmed the advantages of this tool: precision, minimal intraoperative hemorrhage, sterilization of the surgical area and healing with minimal scarring, postoperative pain and swelling (1-5).

The CO_2 laser emits light energy which 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 at the focal point (6,7), producing zones of incision or ablation. The energy applied to the target tissues will also affect, to a varying degree, adjacent or underlying tissue structures. The extent of collateral damage is related to the absorption characteristics of light in the tissues, and the laser parameters used. At a given wavelength, longer pulse durations will tend to result in higher levels of coagulation and necrosis in collateral structures, as they allow thermal energy to accumulate and penetrate to a greater extent than short, transient pulses. For clinical applications, the zone of thermal damage to adjacent structures should ideally be kept to a minimum, as it may impede wound healing, graft take, and reduce wound tensile strength, especially if it is extensive. Furthermore, laser-induced temperature increases can threaten the vitality of adjoining structures such as teeth, pulp or periodontium. Conversely, very short pulse durations may hinder haemostasis and reduce ease of incision or ablation; attempts at compensating for this phenomenon by increasing pulse frequency can result in an exacerbation of thermal effects.

In the CO_2 lasers traditionally available to clinical dentistry, light at 10.6u is delivered by means of an articulated arm or a hollow waveguide and a handpiece to the surgical site. Recently, CO_2 lasers that deliver light in the 9.3u region of the infrared spectrum through a coherent, flexible beam delivery system have been developed for clinical use. Previous studies have demonstrated very similar incision, thermal and histological effects in soft tissues of the two wavelengths in the continuous wave mode (8). 9.3um better matches the absorption characteristics of

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hydroxyapatite, providing an improved capability for modification (9) or ablation in hard dental tissues without thermal damage to pulpal structures.

The aim of these investigations was to determine thermal, histological and incisional effects in soft tissues at 2 intra-oral sites of laser irradiation at 9.3um. Specifically, the thermal and histological consequences of varying pulse duration, duty cycle/ frequency, and power were studied. Ease of incision and effects on underlying bone were also investigated.

3. MATERIALS AND METHODS

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

Using the laser, 6 standardised incisions 3cm in length were made in the oral mucosa per laser parameter. 3 incisions were positioned parallel to the border of the mandible, 5mm below the gingival margin. Tissue thickness in this location measured 0.3-0.6mm. 3 further incisions were performed in the thicker soft tissues 5mm from the lower border of the mandible. Tissue thickness in this location measured 0.7-2.7mm. To standardise the incision length, a template was positioned 3mm below the planned incision site during the performance of each incision. The laser handpiece was attached to a motorised slide to standardise the incision and eliminate variable movements; the pig's jaws were immobilised on a veterinary mount.

A subjective evaluation of "ease of incision" and "incision cleanness" was made by one operator.

Laser parameters

Three modes were investigated: gated Cw, superpulse, and OptiPulse™.

During and after laser irradiation, thermal events were monitored using an IR camera (Inframetrics 600) at a scan speed of 60 Hz.

Laser device

The laser used (Duolase 9.3™, Medical Optics Inc., Carlsbad,CA) emitted at 9.3u, the light being delivered via a coherent hollow wave-guide and a focusing handpiece. Spot size measured 250u. Beam characteristics were calibrated by a laser engineer directly before each irradiation episode and photographic paper was used to measure and document spot sizes. A PRJ-M power meter (Gentec) was used to determine actual values directly prior to each laser incision.

The following parameters were investigated:

In the gated Cw mode:
Power: 1-12W; Duty cycle: 10-100%; Pulse duration: 1,20,200 msec

In the superpulse mode:
Power: 1-7W; Frequency: 170-1170Hz; Pulse Duration: 300usec.

In the OptiPulse™ mode:
Energy: 18-30mJ/pulse; Frequency: 10-40Hz; Pulse Duration: 300usec.

Within 3 minutes of irradiation, incisions were dissected out with a margin exceeding 5mm and divided into 3 sections using 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. Wax blocks were prepared and 6u sections were cut routinely and stained with Serius Red. A minimum of 10 slides and 30 measurements were used per parameter

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and incision site. Incision depth and width as well as depth and width of adjacent tissue damage were determined. Collateral tissue effects were measured at the bottom of the crater to simplify interpretation of the damage zones: for beams with a Gaussian profile, sub-ablation laser-tissue interactions at the lateral incision margins complicate the histological picture.

In samples where a line of dots resulted from irradiation, measurements were performed centrally within the dot. A photographic record was made of the results.

Statistics

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

4. RESULTS

1. Ease of incision

1.1. In the gated Cw mode

At all pulse durations, a duty cycle of $\geq$ 50% and powers of $\geq$3.5W gave the impression of rapidly producing a clean cut. At average powers of 3-10W and duty cycles of 10% the incising process produced a "dragging" rather than a "clean cutting" sensation in the operator. At a power of 1W and duty cycles of 10%, the incision effectiveness was reduced to the extent that individual dots rather than a continuous line of incision resulted.

1.2. In the superpulse and OptiPulse™ mode

At the parameters tested, superpulse mode clinically provided an effective incising effect. The OptiPulse™ mode produced clean, but shallower, narrower cuts.

2. Thermal events

Mean maximum surface temperatures measured during irradiation ranged from 2-8^{o}C. Temperatures were highest at high powers and duty cycles and longer pulse durations. Moreover, "hot spot size" and duration varied. Interpretation of these extensive data lies outside the scope of this publication and will be published elsewhere.

3. Histological Data

Figs. 1-2 depict incision depth and width at the parameters investigated. Figs 3-4 represent the extent of vertical and horizontal tissue damage related to the incision site.

At most parameters, incision depth and width and collateral tissue damage were not significantly affected by duty cycle used (in gated Cw mode), except at 1ms pulse durations ($p<0.05$).

At most parameters, incision depth and width and collateral tissue damage were not significantly affected by the pulse durations used (in gated Cw mode) ($p<0.05$). An exception to this trend was seen at low powers and duty cycles in the 1msec pulse duration group, where incising effectiveness became significantly reduced, without much effect on the extent of collateral damage.

In nearly all groups, incision depth increased significantly ($p<0.05$) with greater power outputs. For incision widths

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and collateral damage measurements, this observation did not apply consistently. The superpulse mode provided far greater incision depths ($p<0.01$), but narrower incision widths ($p<0.05$) than gated Cw parameters at comparable power levels. The OptiPulse™ mode produced significantly finer, narrower ($p<0.05$), but shallower ($p<0.01$) incisions. with significantly less collateral damage ($p<0.01$) than all other parameters.

4. Laser Effects in Underlying Bone

To the naked eye, no laser damage was visible in bone underlying the incisions made in the thicker soft tissues (0.7-2.7mm) located 5mm above the lower border of the mandible. However, in bone underlying incision sites in the thinner soft tissues (0.3-0.6mm) located 5mm below the gingival margin, charring was apparent after irradiation at the following parameters:

A pulse duration of 200msec, power >3.5W and duty cycle of 80 - 100%
A pulse duration of 200msec, power of 12W and duty cycle of 30 - 100%
A pulse duration of 20msec, power >3.5W and duty cycle of 80 - 100%
A pulse duration of 20msec, power of 7W and duty cycle of 50 - 100%
A pulse duration of 20msec, power of 12W and duty cycle of 30 - 100%

Incisions at pulse durations of 1msec or in the superpulse or OptiPulse™ mode produced no visible signs of thermal damage in the underlying bone.

5. DISCUSSION

Of the clinically common dental lasers, the CO_2 laser usually produces narrower zones of necrosis in soft tissues than the Nd:YAG, due to the greater absorption of CO_2 light by soft tissues (11-13). Recent studies have reported very similar effects in soft tissue for the CO_2 laser at 10.6 and at 9.3um (8).

An optimal incising effect in soft tissues was determined in the gated Cw mode, at duty cycles of $\geq$50% and powers of $\geq$3.5W. Maximum depth of incision was achieved at 10-12W at any of the pulse durations used (1-200msec.). The incising effect resembled that achieved using the Cw mode at these powers. At decreasing power levels, incision depths decreased more dramatically at 1ms pulse durations than at 20 or 200msec. As soft tissue ablation at these parameters is mainly achieved by thermal mechanisms, and the above-cited parameters induce the greatest thermal effects due to high pulse frequency and power, these results are not surprising.

Using the superpulse mode, good incising effects were achieved at far lower average powers: at 3.5W and approximately 580Hz, a similar depth of incision was achieved as at the gated Cw powers of 10-12W. These results can be attributed to the shorter pulse durations (300usec) but far higher peak powers and frequencies used in this mode. This mode rapidly and effectively produces clean surgical incisions. In the OptiPulse™ mode, at pulse energies of 18-30mJ, incision depth and width were much reduced compared to the other modes used. This mode also delivers 300usec pulses, but the frequency at 10-50Hz is far lower than in the superpulse mode, producing greatly reduced thermal effects and thermally-mediated ablation. In the OptiPulse™ mode, collateral damage was minimal. Clinical implications of these observations would include enhanced safety when working in proximity to delicate tissues, and microsurgical precision and control.

Surface temperatures measured during laser irradiation are in agreement with the results of previous investigations (8): the radius and duration of the "hot" spot varied with the parameters to a greater extent than the maximum temperature measured.

Many studies undertaken at 10.6u report an average zone of damage after laser incision in soft tissues of <0.3mm (12-16). Thus our results at 9.3u fall well within the range of these reported histological effects. The zones of vaporization and damage from heat conduction will depend directly on the laser parameters used. In this study we

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demonstrated that use of an OptiPulse™ mode, based on the principles of high irradiance with short duration pulses and adequate pulse intervals reduced thermal necrosis by a factor of 2-7. Similar, although somewhat less marked effects have been described in the literature using the superpulse mode at a wavelength of 10.6um (13,18). 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.

To the naked eye, no laser damage was visible in bone underlying the incisions made in the soft tissues approx. 0.7-2.7mm thick located 5mm above the lower border of the mandible. However, in bone underlying incision sites in the thinner soft tissues measuring approx. 0.3-0.6mm in thickness, charring was apparent after irradiation with 200msec and 20msec pulses. This effect was related to the powers and duty cycles used, with either higher powers or increased duty cycles serving to raise the thermal loading of the tissues and produce this effect. Incisions at pulse durations of 1msec or in the superpulse/OptiPulse™ mode produced no visible signs of thermal damage in the underlying bone. These results are also related to the thermal mechanisms described above, with shorter laser pulses producing less heat concentration and dissipation to adjacent tissues.

In summary, this study investigated events resulting from soft tissue incision using a CO_2 laser at 9.3u. Incisional, thermal and histological effects were related to parameters used. Detailed statistical assessment of the interactions between the different variables investigated in this study will be published in a forthcoming paper. 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 using lasers as surgical tools, to ensure predictability, parity and consistency of results.

6. ACKNOWLEDGMENTS

This study was supported by DOE grant DE 903-91ER 61227, ONR grant N00014-90-0-0029 and NIH grant RRO1192.

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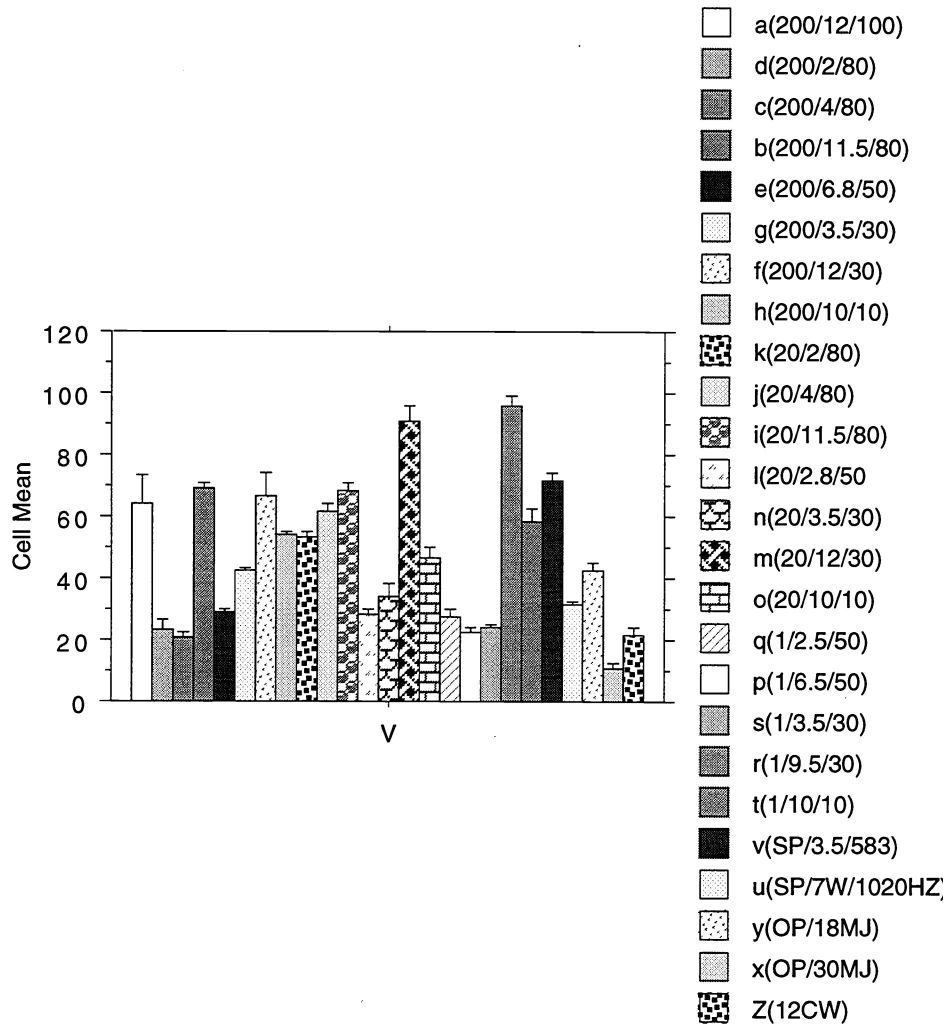

Fig. 1: Incision depths in units (1unit = 15.5μm). S.D. is depicted when greater than zero.

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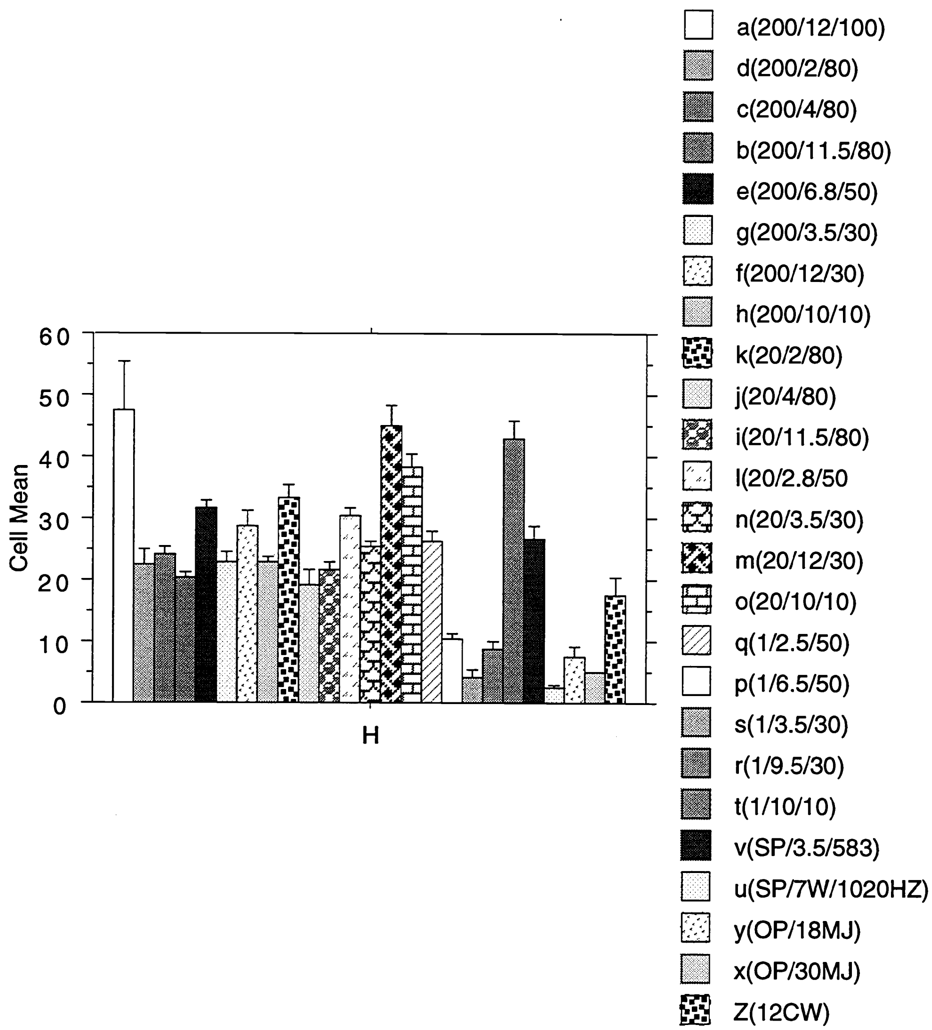

Fig. 2: Incision widths in units (1unit = 15.5μm). S.D. is depicted when greater than zero.

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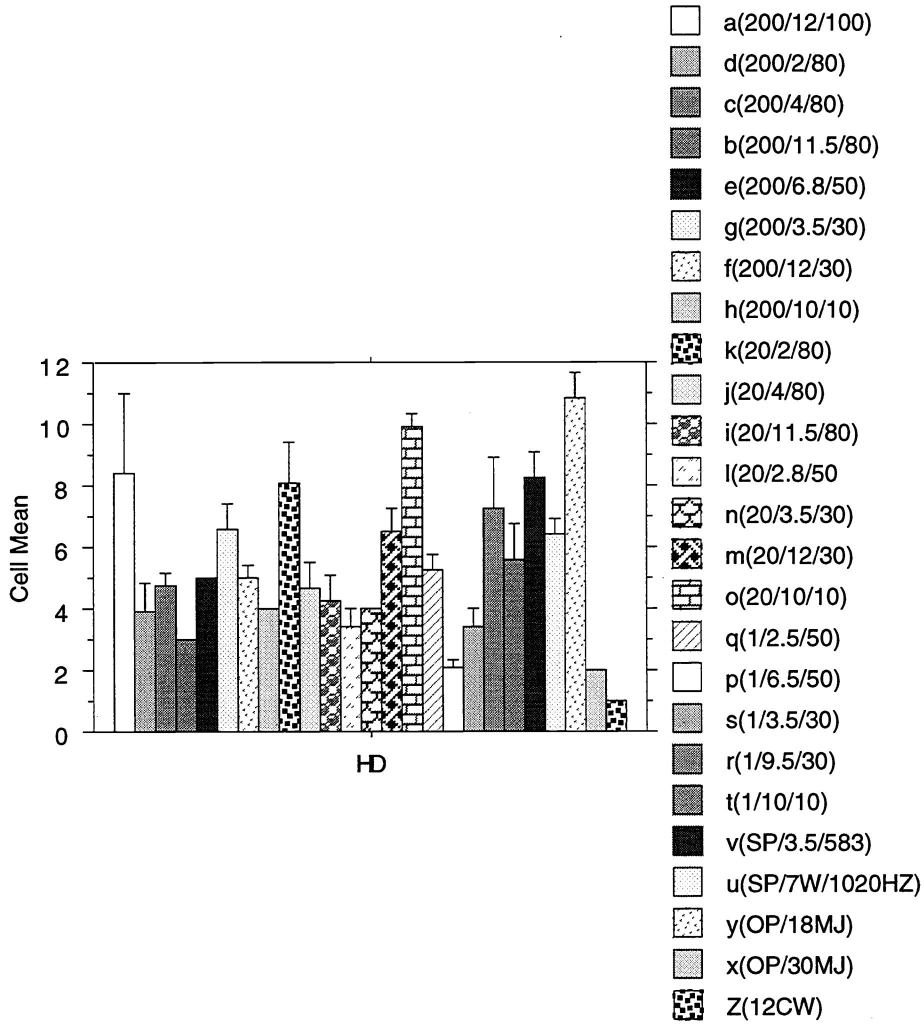

Fig. 3: Collateral damage widths in units (1unit = 15.5μm). S.D. is depicted when greater than zero.

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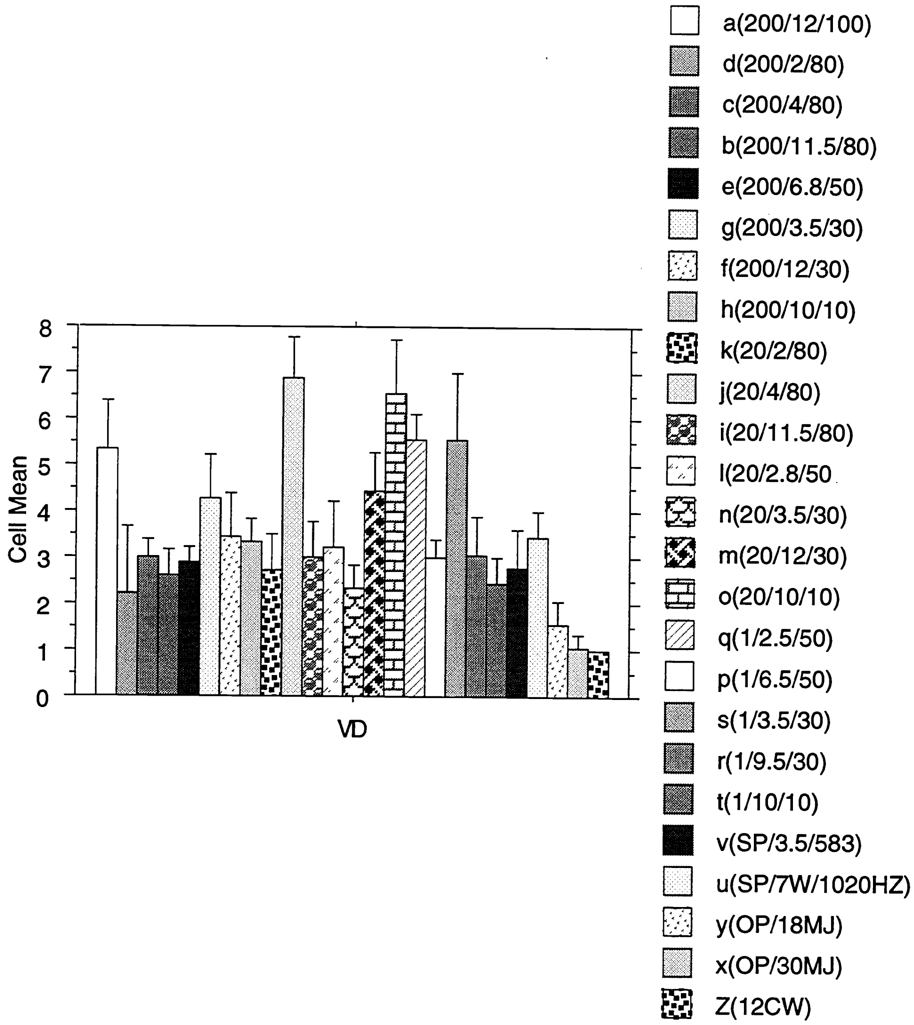

Fig. 4: Collateral damage depths in units (1unit = 15.5μm). S.D. is depicted when greater than zero.

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