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EVALUATION OF ERBIUM:YAG LASER RADIATION OF HARD DENTAL TISSUES: ANALYSIS OF TEMPERATURE CHANGES, DEPTH OF CUTS AND STRUCTURAL EFFECTS

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Abstract

Temperature elevations, depths of cuts and structural changes produced by 2.94 micron pulsed Erbium:YAG laser radiation of hard dental tissues, at different power levels and exposure times of the laser, were studied. The depth of cut produced was found to vary significantly as a function of power level and exposure time on dry teeth. The mean temperature rise with laser radiation was also influenced both by power level and time of exposure. The effect of water flow on the teeth during laser exposure was evaluated; the results indicate that the ablation efficiency was better, temperature elevations lower and structural changes minimal to absent in the presence of water as compared to teeth that were dry during laser radiation.

Key Words: Erbium:YAG, laser, ablation, dental hard tissues, water spray.

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Introduction

The dental profession is acutely aware of the dislike that the patient population has toward the dental drill, a mechanical, contacting drill with the grinding and whirring noise, and which usually causes a lot of pain if used without adequate anesthesia. In view of this, research has continually been directed towards a "kinder" drill. Researchers have developed and marketed a method that can minimize drilling by removing minimal amounts of carious tooth tissue by chemical means rather than mechanical. Other research is directed to develop a "silent" drill.

When lasers were first considered for dental use in 1964 [26], it was thought they would replace the dental drill. But the high-energy densities needed with the ruby and the CO_2 lasers evaluated led to cracking of the surface enamel[4, 5, 25] and the high temperatures could cause irreversible pulp damage. As a result, interest in laser drilling of teeth declined. Some studies were done on the ultrastructural changes in enamel and dentin following laser irradiation[27], but most dealt with laser-induced reduction in subsurface demineralization[2], reduction in enamel solubility[16] and fusing of pit and fissure sealants[28]. Melting of the enamel surface to seal defects and cracks was also attempted [17]. Other researchers worked on caries removal with the CO_2[14] and Nd:YAG lasers[15]. Curing of composites has been an important application of the argon laser[23]. Endodontic applications investigated include biomechanical preparation of the canal[22] and sterilization of endodontic instruments[10]. In addition, the laser has been used for procedures not feasible by conventional materials, such as fusing dentin plugs in the canals[32] and sealing off the root apex by the laser[33]. Clinical applications have been limited to soft tissue procedures, such as excision of lesions[3] and gingivectomies[21]. However, neither the Nd:YAG, the CO_2, nor the Argon laser have been shown to be effective for drilling intact hard dental tissues.

However, better results have been presented upon applying the 308 nm XeCl excimer laser[6] and the 2.94 micron pulsed Erbium:YAG laser on hard dental tissues. Keller and Hibst reported the first descriptions of Erbium:YAG laser effects on hard dental tissues[11].

Paghdiwala reported results of the effects of Er:YAG laser application on extracted human teeth[18, 19]: clinically significant holes were drilled in enamel and dentin, 1.0 - 2.5 mm deep. No cracking or chalkiness and slight to no charring was produced at the target spots. Temperature rise as measured by thermocouple placed at the pulpal wall averaged 4.3°C. It has been shown that temperature elevations below 5°C are within physiologically tolerable thermal limits of dental pulp[1].

In 1989, Hibst and Keller[7] showed that the diameters of the craters formed by Er:YAG laser exposure on teeth became larger as the energy increased, but were unaffected by the number of pulses delivered. With a fixed radiant exposure of 30J/sq.cm., the depth of the cut in dentin was proportional to the number of pulses whereas marked deviations were obtained for enamel as the number of pulses increased. The depth in enamel could be linearly related to radiant exposure per pulse. However, their study did not measure the resultant temperature elevation at the pulpal wall. One of the prime concerns with laser application on vital teeth is to ensure that there is no thermal damage to the pulp from thermal diffusion from the target spot. Keller and Hibst[12] also presented light and scanning electron microscopy findings comparing effects of CO_2 and Er:YAG laser radiation of enamel and dentin. Whilst the CO_2 laser produced charring, cracking and fissuring in the tissue around the lased area, the Er:YAG produced round craters with well defined margins, and the surrounding tissues had no cracks and no charring.

While Paghdiwala[18] and Hibst[7] quantified the changes produced by fixed exposure times, Hoke et al[9] measured the pulpal temperature changes resulting from typical cavity preparation on extracted human teeth. They also used a water mist on the teeth during laser exposure. Using thermal probes embedded in the pulp, they reported an average temperature rise of 2.2°C with exposure times varying from 5 to 17 minutes in the presence of the water mist. In contrast, the dry control teeth showed considerably higher temperature elevations from laser exposure.

One disadvantage of embedding thermal probes in the pulp chamber and measuring the temperature elevations resulting from laser irradiation on the labial enamel surfaces of teeth, as done by Paghdiwala[18] and Hoke et al[9] is that the thickness of the tooth tissue conducting the temperature changes is not the same in all the teeth in the study. In addition, since the thickness of enamel decreases from incisal to cervical margins, even in teeth having identical thicknesses from labial surface to pulpal wall, the relative thicknesses of enamel and dentin may not be the same if the laser impact is more incisal in one tooth compared to the other. This means that a comparison of the resultant temperature elevations and depths of cuts from laser impact should take into consideration the differences in the thickness of the labial walls irradiated. If the enamel and dentin are ground into separate slices of predetermined thicknesses and then irradiated individually, as done by Hibst and Keller[7], the resulting temperature changes and depths of cuts in different samples could be more readily compared. However, since a primary concern in laser application on teeth is the potential of thermal damage to the pulp, it is useful to measure temperature changes at the pulpal wall resulting from laser exposure of the labial surfaces, just as would be done in an in vivo procedure. Also, since potential thermal damage is of prime importance in laser applications for cutting intact hard dental tissues, the effects of methods that may diminish the temperature elevations also need to be evaluated. Hoke et al[9] have published the only report utilizing a water spray during laser exposure and more investigation would be useful.

The aim of this study was to evaluate the temperature and structural changes caused by Er:YAG laser on teeth, with and without a water flow during the laser exposure.

Materials and Methods

This three-part study was performed on freshly extracted human teeth which had been stored in normal saline to prevent desiccation. Using a high speed drill with air-water spray, the lingual surface of each tooth was ground off such that the labial wall of the pulp chamber was clearly visible and accessible. Each tooth was examined under a light microscope under reflected and transmitted light to examine for the presence of cracks. The thickness of the tooth tissue between the labial enamel wall and the pulpal wall was measured with a micrometer. Each tooth was radiographed and then mounted in a holder capable of movement in the x-y-z axis.

A J-type thermocouple (Omega Engineering, Stamford, Conn.), diameter 0.127 mm. and response time 40 millisec. was placed against the dentin on the labial wall of the pulp cavity. A small amount of thermally conductive joint compound (Omega) was placed between the thermocouple and the dentin surface to ensure heat conductance to the thermocouple. The thermocouple was connected to a Metra Byte Data Acquisition Unit Model DAS-8 (Metra Byte Corp., Taunton, MA) board mounted in an IBM compatible 386 computer via a MetraByte J37 Thermocouple module. The data acquisition unit was capable of attaining 4000 data samples per second or 25μ sec./ sample; we chose to record 12 samples/sec. The thermocouple module had an accuracy of 0.05%.

The labial surfaces of the teeth were exposed to pulsed Erbium:YAG laser light. The laser used was a flashlamp-pumped, pulsed solid-state erbium:YAG laser system, LASER 1-2-3 (Schwartz Electro-Optics), emitting at 2.94 microns. Each laser pulse consisted of a large number of energy spikes, each about 1 micro-second in duration, which overlapped in time to create a pulse width of about 250 μs at high flashlamp energies. The laser light was focused by means of a quartz biconvex lens (f = 25mm).

The Laser 1-2-3 can be operated at a repetition rate of 1 -10 Hertz with a maximum output power of 10 Watts. In a preliminary study, we had obtained promising results when 4 second exposures had been made on all the teeth, power output 2.2W and pulse repetition rate 6 Hz. In this study, too, the repetition rate was kept constant at 6 Hz. Another study with different repetition rates is also in progress, since Hibst and Keller have shown that the repetition rate has a very important influence on the temperature [27]. In the first part of the study, the teeth were air-dried prior to laser exposure. The spot diameter was 0.3mm. Power levels of laser irradiation were set at 1.1 W., 2.2 W. and 3.3 W (Scientec), at fluences of 260 to 780 J per sq. cm. To quantify the temperature changes and cutting effects, exposure times of 1 sec., 2 sec. and 3 sec. were chosen. For each power level, 3 teeth were irradiated by the laser for each exposure time. 27 teeth were thus exposed and 27 sets of temperature readings were recorded from the start of laser irradiation to the return of the tooth to the baseline temperature. In the second part of the study, 12 other teeth were exposed to the laser at 1.1 W power and exposure times of 1, 2 and 3 seconds, the difference being that a water stream was maintained on the teeth during the laser irradiation. The purpose was to evaluate the effect of water flow on the cutting process. Finally, in part three, another set of teeth was exposed to the laser, with the water flow on, this time decreasing the power of the laser to 0.3 W, 0.45 W and 0.6 W, (at fluences of 159 J/sq. cm., 238 J/sq. cm. and 318 J/sq. cm.) for 1 and 2 second exposures; the spot diameter was 0.2 mm.

Immediately after laser exposure each tooth was replaced in its vial of normal saline to prevent dehydration. The diameters of the lased holes were measured in an x-y axis using a Nikon Measurescope (Nippon Kogaku, Japan). The teeth were sliced (with a high-speed handpiece with an air-water spray) along the transverse axis of the drilled holes and the depths of the drilled holes determined by measuring the distance from the labial surface to the bottom of the hole, using the Nikon Measurescope.

Considerable importance was given towards evaluating the lased teeth for structural damage, particularly with regards to cracking and fissuring. The light of a dental composite curing unit was conveyed to within a few millimeters of the teeth by the fiber optic bundle and the teeth were then examined in intense transmitted and reflected light at 40X and 100X by the light microscope for the presence of cracks. An SEM analysis of representative samples in each category was done (Hitachi-S2500).

Results

Temperature changes:

The temperature elevations produced as a result of 1, 2 and 3 second exposures of the erbium:YAG laser on dry teeth at power levels of 1.1W, 2.2W and 3.3W are shown in Fig. 1.

Although the thermocouple had a response time of 40 millisec., a minimum interval of 2.7 sec. elapsed from the start of laser exposure before any temperature rise was recorded. Analysis of variance (ANOVA) showed that the average temperature elevations were significantly different for power levels as well as exposure times at p = 0.05 level of significance.

The different levels of power and exposure were tested using least significant difference (LSD) test and it was observed that the mean temperature changes were significantly different between 1.1W and 3.3W, whereas the differences were not significant between 1.1 and 2.2W and between 2.2 and 3.3W. Further, the temperature changes were significantly different between each exposure level.

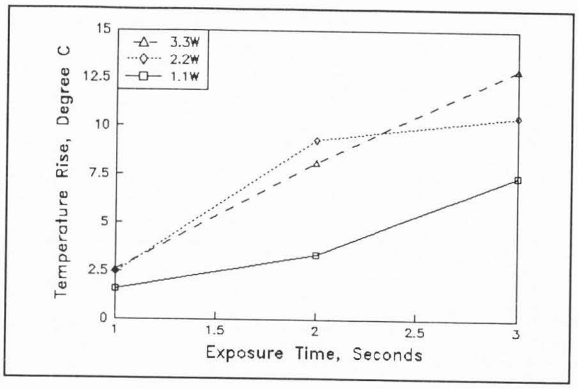

Figure 1: Mean temperature rise as a function of exposure time at different power levels (dry teeth).

As all the teeth in the study were not of equal thickness, (Table 1), an analysis of covariance (ANCOVA) was carried out (using thickness as auxiliary information) to evaluate the effect of thickness of tooth tissue on the temperature. ANCOVA showed that tooth thickness affected the change of temperature at p = 0.01 level of significance: greater the tooth thickness, lower is the temperature rise. This information explains why the rise of temperature at 2.2W and 2 sec. is higher than the rise at 3.3W and 2 sec., as seen in Fig. 1; the mean thickness of teeth exposed to 2.2W for 2 sec. was 2.40 mm. while that at 3.3W for 2 sec. was 2.91 mm. A review of the temperature changes in all the samples confirmed that for identical power levels and exposure times, thicker teeth showed lower temperature elevations. Transverse sections showed that thicker teeth had a correspondingly greater enamel thickness than thinner teeth. Also, evaluation of the depths of cuts, presented below, showed that thicker teeth (with greater enamel thickness) generally have shallower cuts than thinner teeth. As enamel has higher calcium content than dentin, enamel ablation by Er:YAG laser radiation is clearly less than dentin ablation[7]. Thus, it can be expected that at any given energy level, for a given exposure time, more energy would be expended on cutting through the thicker enamel layer of thick teeth, resulting in a shallower dentin cut. In thinner teeth, with thinner enamel layers, after cutting through the enamel there would still be relatively more energy left over to cut through the less densely calcified dentin, resulting in a deeper cut. As a result, for the same energy level, in thinner teeth, the remaining dentin thickness after laser exposure would be less, proximity to the pulp would be greater, and tempera-

Table 1. Mean temperature rise and (SD) as a function of power level, exposure time and tooth thickness (T).

Exposure (Sec.)	1.1W	2.2W	3.3W
1	1.55 (0.64) T=2.31	2.44 (0.50) T=2.87	2.61 (2.33) T=3.18
2	3.34 (0.87) T=2.77	9.28 (3.13) T=2.40	8.12 (2.25) T=2.91
3	7.40 (0.30) T=2.70	10.49 (3.32) T=2.08	12.94 (0.69) T=3.03

ture rise would be greater. It is felt that knowing the thickness of tooth tissue between labial wall and pulpal wall prior to laser exposure permits a comparison of the temperature changes after laser exposure without actually measuring the thickness of remaining dentin after laser exposure. It should be mentioned that in a study measuring intra-pulpal thermal changes caused by rotary cutting instruments, Zach and Cohen[31] did not correlate their temperature findings with the thickness of dentin remaining after drilling the teeth for selected lengths of time; they stated, just as we have, that smaller teeth, such as incisors, showed greater temperature rise than larger teeth such as molars. The question then arises that when differences in temperature elevations are noticed, how can we determine whether they are due to different laser exposure factors or due to differences in tooth thickness? The answer is statistical analysis, using tooth thickness as a co-variant, as mentioned above.

Several researchers have performed studies evaluating heat tolerance limits of dental pulp, and have reported that a temperature rise of 5°C due to externally applied heat does not cause irreversible pulpal damage[1]. In our study we evaluated the rise of temperature due to laser radiation from this important aspect, and only power levels and exposure times in which temperature elevations were statistically significantly less than 5°C were considered acceptable. With laser exposure in the presence of a water flow on the teeth, and at lower power levels, the temperature rise was lower (Tables 2, 3).

Table 2 shows that after taking into account the differences in tooth thickness, the temperature rise was lower with water flow on the teeth during laser exposure. At 0.3 W, (Table 3), for a 2 second exposure, a maximum temperature rise of only 0.49°C was observed; the thickness of tooth tissue was 2.77 mm.

Cutting effects

The Er:YAG laser irradiation of teeth produced fine holes. The diameters of the holes made on dry teeth (Table 4) were found to increase with power levels but not with exposure times. Also, the diameters at 1.1 W were identical on dry and wet teeth.

Table 2. Comparison of tooth thickness (T) and temperature rise (t) at 1.1W power level with and without water flow.

Exposure (Sec.)	Dry Teeth		Wet Teeth	
	T (mm)	t (°C)	T (mm)	t (°C)
1	2.33	1.55	2.05	1.47
2	2.77	3.34	1.64	4.39
3	2.70	7.40	3.18	4.52

Table 3. Temperature Rise (°C) in the presence of water flow.

Exposure (Sec.)	POWER		
	0.3W	0.45W	0.6W
1	0.24	0.49	1.20
2	0.49	0.49	0.73

Table 4. Mean hole diameters (mm.) of dry teeth.

Power Level	Diameter
1.1W	0.31
2.2W	0.41
3.3W	0.47

Depth of cuts: The depths of the cuts produced by the laser exposure on the dry teeth at the experimental levels are shown in figure 2.

ANOVA showed significant interaction between exposure times and power levels. The 2-way table for power levels and exposure times showed that at an exposure level of 1 sec. there were no significant differences in the depths of cuts for different power levels. At exposure levels of 2 sec. or 3 sec. the depths of cuts were significantly different between power levels. At each power level, there were significant differences in depths of cuts for different exposure times. The significance of all results was judged at $p = 0.05$ level of significance. It was noted that, in general, thicker teeth showed shallower cuts than thinner teeth.

When a water flow was applied on the teeth during the lasing process, at 1.1W the depths of cuts were greater than those on the dry teeth (Fig. 3). At 0.3W, with a water flow, the hole depth was 0.46mm. after a 1 sec. exposure.

Structural Analysis

When the laser drilled areas on the dry teeth were examined under a light microscope, they were found to be round holes with well-defined margins. In some teeth these margins were bevelled, either partially or totally around the

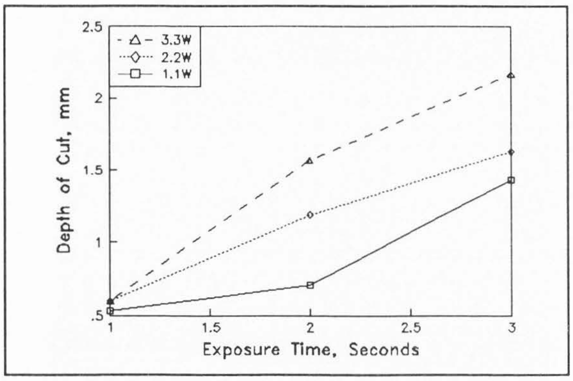

Figure 2: Mean depth of cut as a function of exposure time at different power levels (dry teeth).

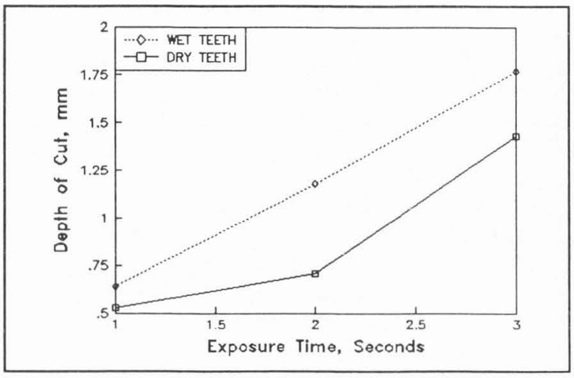

Figure 3: Depth of cut(mm) at 1.1W as a function of exposure time on dry and wet teeth.

periphery, while in some these margins were rolled and raised. The enamel at the periphery was usually dull, white, flaky, with shelf-like striations. No charring or carbonization was present. However, the rolled, raised portions, where present, were glistening, glassy, amorphous. Looking down into the holes and focusing on the floors of the holes, the dentin did not appear charred.

Through the microscope, fine cracks were noticed on 33% of the dry teeth exposed for 1 sec. and on 100% of the dry teeth exposed for 3 sec. at all power levels. Cracks that could be attributed to the laser impact were arranged radially around the periphery of the laser drilled holes, and spread out like sun-rays. This characteristic was used to differentiate them from pre-existing cracks, which often traversed the laser drilled holes in various directions and which could usually be found to be originating on unexposed areas of the tooth surface.

Almost all the teeth which were dry during the lasing were found to have developed very fine crazing or microfissuring of the enamel immediately surrounding the holes.

Table 5. Structural Changes at lower power levels with water flow on teeth.

Nature of change	0.6W	0.45W	0.3W
Cracking	Absent	Absent	Absent
Micro-fissures	Present	Present	Absent
Enamel at margins	Dull, white, flaky	Normal to flaky	No change, well demarcated, bevelled

These micro-fissures were usually arranged in an irregular, cob-web pattern. An important finding was that teeth exhibiting cracking around the periphery usually had very scanty micro-fissures. In sharp contrast, in presence of a water flow during the lasing process, 1 sec. and 2 sec. exposures at 1.1W showed no cracking, and even 3 sec. exposures caused sparse cracking over very small portions of the periphery. Adverse structural changes diminished as the power decreased (Table 5). The shade of the enamel did not appear to have any influence on the occurrence of structural changes.

Scanning electron microscopic examination

Margins of the laser drilled holes: All the holes exhibited margins that were either:

i) Unaltered structurally, sharp, distinct, well defined

ii) Bevelled all around. These bevels were roughly 20 - 100 microns wide. Their deepest point, at their junction with the hole walls, was 15 - 20 microns deep. In the bevelled zone the enamel was devoid of any typical configuration but otherwise appeared unaltered.

iii) Rolled and raised. In a very few teeth, and usually along small portions of the margin, the enamel appeared to have a smooth, amorphous appearance, was raised and rolled over onto the tooth surface. The normal crystalline configuration of enamel was totally lost. It appeared that as the enamel was melting as a result of the laser energy, it did not vaporize completely and as it was being extruded out of the cavity, this molten enamel recondensed around the margins of the hole.

Walls of the holes: The most striking feature noticed upon looking down into the laser drilled holes was that the enamel was arranged in concentric striations along walls that were sloping towards the bottom of the hole. A 1 sec. exposure of a 1.1 W laser beam on a dry tooth resulted in loss of parallel orientation of the enamel rods along the wall (Figure 4).

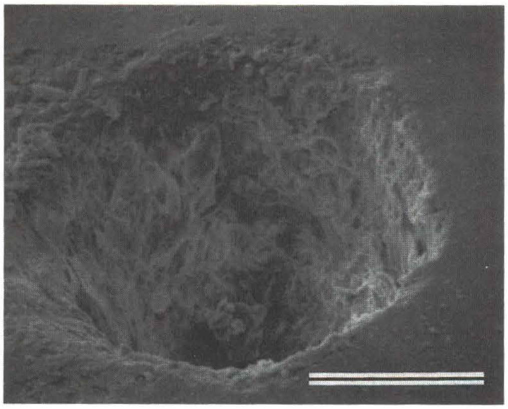

Figure 4: SEM view showing margins and walls of laser drilled hole on enamel surface. 1 sec. exposure at 1.1W., 0.3 mm spot diameter, tooth dry during exposure. Bar = 200 μm.

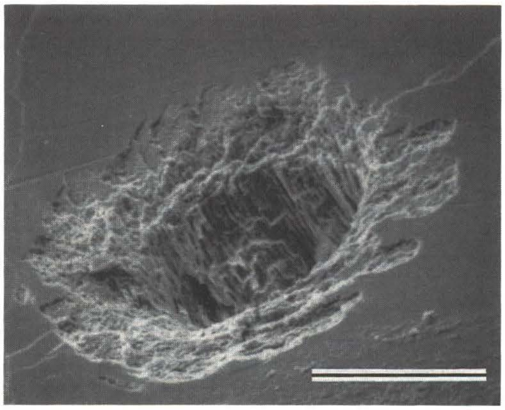

Figure 5: SEM view of laser drilled hole on enamel surface. 1 sec. exposure at 0.3W., 0.2mm spot diameter, water flow present during exposure. Bar = 150 μm.

In some spots the enamel that had been cut was clumped together in little clusters along the walls of the holes. The irregularity of enamel rod arrangement was more pronounced at higher power levels and longer exposure times, and microporosities and even a few cracks were noted.

The water flow on the tooth during the lasing process resulted in a marked decrease in structural alterations. Even a 2 sec. exposure at 1.1W in the presence of the water flow exhibited a distinct parallel orientation of the enamel rods along the walls. As the power was reduced to 0.6W, 0.45W and 0.3W with the water flow, the resultant holes showed relatively smoother walls with little flakiness or fragmentation of the enamel (Fig. 5).

Longitudinal sections made along the hole diameters revealed that the hole configuration duplicated the beam profile as it penetrated the tooth. An extremely significant finding was that even at the maximum levels investigated, 3.3W power for a 3 sec. exposure, the holes did not penetrate the pulp chamber.

Floors of the holes: The hole walls gently sloped into rounded floors. If the floors were located within enamel, the underlying enamel did not reveal any cracks, there was no disorientation in the direction of the enamel rods and dentino-enamel junction appeared intact. In those teeth where the hole extended into the dentin, the dentin appeared structurally unaltered and dentinal tubules were clearly visible.

Discussion

When hard dental tissues are exposed to pulsed Erbium:YAG laser radiation, fine holes are drilled at the exposure site, accompanied by a rise in the temperature at the pulpal wall and some structural alterations in the calcified tissues immediately surrounding the exposed area. The temperature elevations are proportional to the power and exposure time, and are inversely proportional to the thickness of tooth tissue. Since the thickness of tooth tissue varies from sample to sample, when the pulpal wall temperature is measured following laser exposure on the labial enamel wall of teeth, it is difficult to compare temperature elevations between samples. To further complicate the issue, even in two samples of equal thickness, the relative thicknesses of enamel and dentin may not be the same. However, even with these limitations, the results serve as a guideline for the temperature changes that can be expected to occur following the application of the Er:YAG laser on teeth at the exposure levels studied. Teeth included in this study ranged from thin mandibular central incisors to thick maxillary molars, and the temperature rise was 0.29° C. following a 1 sec. exposure and 0.49° C. after a 2 sec. exposure at 0.3W (50 mJ/pulse) in the presence of a water flow on the tooth; the tooth thickness in this case was 2.77 mm. These temperature elevations are well within the 5°C. limit beyond which irreversible pulpal changes have been found by researchers following externally applied heat on teeth[1].

In this study, both the laser and the teeth were stationary, and all the pulses were fired at the same spot. In a clinical situation, the laser beam would be moved over the tooth surface instead of being focused on one spot, thereby diminishing the heat buildup at that one spot. Thus, though most restorative procedures involving drilling of intact enamel and dentin with the laser, for example, for cavity preparation, would entail laser exposures for longer exposure times than those tested in this study, continuous movement of the laser beam over the tooth would minimize thermal buildup. Hoke et al[9] measured a temperature rise of 1°C. when pulsed Er:YAG laser energy of 56 mJ/pulse was delivered at 10 Hz. for 2440 pulses to produce a cavity preparation in sound enamel and dentin. They applied a water mist simultaneously with the laser radiation.

Teeth exposed in absence of a water flow showed temperature elevations that exceeded the 5°C. threshold for pulpal damage after a 3 sec. exposure at 1.1W and only 2 sec. at 2.2W and 3.3W. Hoke et al [9] also found that dry teeth showed considerably higher temperature rise compared to teeth exposed in presence of air-water spray. Therefore, incorporation of a water spray should be included in the design of a delivery system for applying the erbium:YAG laser on hard dental tissues.

Thermal rise can be minimized by lowering the repetition rate of the laser pulses, while keeping the energy/pulse constant[8]. This would slow down the cutting process, but allow less thermal buildup. This would be very helpful during cavity preparation: as the remaining dentin thickness decreases and proximity to the pulp increases, lowering the pulse repetition rate, along with copious water flow can avoid thermal injury to the pulp. The beneficial effects of pre-cooling the tooth with a few seconds of air-water spray prior to actual drilling with rotary cutting instruments has been demonstrated, as far as preventing intra-pulpal temperature increases is concerned: after a 10 second use of the spray, the pulpal temperature reached equilibrium 7.8°C. below the starting temperature before the spray[31]. A similar pre-cooling needs to be evaluated prior to laser exposure on the tooth.

While evaluating lasers for drilling intact enamel and dentin, it is essential to note that the mechanical drills used currently have been shown to produce severe inflammatory results if misused. The high-speed air-turbine handpiece with air-water spray has not been shown to cause irreversible inflammatory reactions[24], but slow speed handpieces, without a coolant, cause a linear, progressive, intrapulpal temperature increase which becomes critical after 20 seconds. The amount of heat generated also increases with increasing pressure and time of cutting and when burs and diamond points dull or when the coolant is not precisely directed at the contact point of bur with tooth. In addition, prolonged drilling procedures and fiberoptic handpieces can cause the water temperature to rise so as to allow intrapulpal temperatures increases to critical levels [13]. A degenerative response of odontoblasts on opposing pulpal walls (opposite to the area of drilling) has also been noted, probably due to harmonic vibrations induced by the high-speed drills[30]. Robinson et al[24] stated that the risk of pulp injury is no greater with one method of cavity preparation or another if precautions, such as avoidance of excessive heat by use of adequate coolants and avoidance of undue pressure are observed. Laser drilling of dental hard tissues is non-contact, non-pressure type, and if heat buildup is minimized by careful selection of exposure parameters and by use of a water spray, then pulp damage should not occur.

On teeth that were dry during laser exposure, after 1 sec. exposures at 1.1W, 2.2W and 3.3W the mean depths of cuts were almost identical, from 0.53 - 0.60 mm., whereas for longer exposures the depth was proportional to the power. In the presence of water, even at 0.3W the depth approached that at 1.1W dry; at 1.1W wet, the depth exceeded that at 3.3W dry. Thus the ablation efficiency is also better with water flow on the teeth during laser exposure. Hoke et al[9] feel that, when desiccation of enamel occurs, the efficiency of ablation decreases (similar to the desiccation effect reported by Walsh[29]) for bone; a constant water supply on the enamel and dentin surface promotes efficient ablation. We feel that on dry teeth, ablation efficiency decreases due to plasma formation, as evidenced by a bright flash of light extending from the target spot following each laser pulse. The plasma absorbs some of the laser radiation, thereby decreasing the energy available for ablation.

Structural analysis of the dry teeth revealed fine cracks, extending for very short distances around the laser drilled holes; the incidence of the cracks increased with time of exposure. In contrast, at comparable energy levels, Keller and Hibst[12] found no cracking even after 20 sec. This can probably be due to the fact that our study was at 6 pulses per sec. and theirs at 1 pulse per sec.: the lower pulse rate probably diminished the thermal and structural changes.

It should be mentioned that in transverse sections cut through the laser drilled holes, the cracks were not found to extend more than approximately 50 microns below the surface. Dye penetration studies should be performed to determine if these cracks are of an extent that adversely affects the tooth. Moreover, even extracted teeth, with surfaces that appear intact on visual examination, and which probably served as vital, functional teeth in a patient's mouth prior to extraction, show innumerable cracks and surface defects when examined microscopically. Therefore, fine, microscopic cracks resulting from laser exposure should be evaluated further and may not necessarily be a critical factor in the prognosis of the tooth.

The structural alterations were greatly diminished in the presence of a water flow on the teeth during the laser exposure, and at 50 mJ/pulse, there was no charring, cracking or fissuring of the surface, the margin was beveled without any raised or rolled areas. These bevelled margins may be beneficial for the placement of light-cured composite filling materials. This is in conformity with the findings of Hoke et al [9] and compare very favorably with the results obtained with CO_2 lasers, which produce charring, cracking and fissuring of hard dental tissues at energy levels necessary to produce cuts that can have clinical applications for drilling purposes[12]. Dental enamel has absorption peaks for radiation of 2.94 microns, which is the wavelength of the erbium laser, and also for 9.6 microns, which is close to the wavelength of the CO_2 laser (10.6 microns). If absorption of a laser into the mineralized component of dental enamel was the only factor governing efficiency of cutting, then both the erbium:YAG and the CO_2 lasers should cut enamel equally effectively. However, it has been shown that cutting enamel with the erbium laser is considerably more acceptable than with the CO_2 laser[12], in that charring and cracking are markedly absent.

This difference in cutting efficiency may be attributed to the difference in the absorption of the laser in the organic component of the enamel. Water has its strongest absorption peak at 2.94 microns, which corresponds to the wavelength of the erbium:YAG laser. In fact, the water absorption of infra-red energy at 2.9 microns is almost ten times that at 10.6 microns, the wavelength of the CO_2 laser.

On account of this high absorption of erbium laser energy in the hydrous content of enamel, it may be hypothesised that the initial effect of an erbium laser exposure on enamel is to vaporize the hydrous interprismatic matrix, leading to a loosening and disruption of the enamel rods. As the laser exposure continues and more energy is deposited at the target site, a portion of the laser energy brings about melting and vaporization of the inorganic component of enamel, resulting in cavitation. As the high-pressure vapor tries to escape out of the cavity, it ejects some of the loosened, disrupted enamel rods even before they reach their melting temperature. This forceful expelling of the dislodged, unmolten rods, referred to as micro-explosions[12, 9], may be a very important factor accounting for the more favorable behavior of the erbium laser on dental enamel. A rapid repetition of the concurrent processes of vaporization of the organic matrix, melting and vaporization of some rods and ejection of other rods results in deeper penetration of the drilling process at lower laser energy levels, which in turn diminish temperature elevations, charring and cracking. Keller and Hibst[12] and Hoke et al[9] have proposed that enamel and dentin are removed by the erbium:YAG laser by water vaporization and micro-explosions, without any melting of inorganic tissues. However, microscopically, we have detected areas of smooth, glistening inorganic material around the periphery of some of the holes and feel that these areas represented molten enamel and dentin that recondensed around the hole margins while being expelled from the cavity. The water content of enamel (2.5%) may not be sufficient to create vapor pressure high enough to cause microexplosions without some melting and vaporization of the inorganic component. In dentin, the water content (13.5%) may produce vapor pressure strong enough to cause micro-explosions even at low energy levels that are not capable of melting and vaporizing the inorganic elements.

Since the 2.94 micron erbium laser energy is very strongly absorbed in water, when a constant water flow is maintained on the tooth during laser exposure, it is possible that a portion of the erbium energy is absorbed by the water, thereby attenuating the energy reaching the tooth. At the same time, vaporization of the water at the target site can result in heat loss, accounting for the lower temperature rise noticed. Also, as the water vapor tries to escape out of the lased area, it can facilitate the expelling of the ablated inorganic tissue particles, increasing the efficiency of cutting.

Further investigations are needed of the rate and temperature of the water flow, the effect of longer exposure periods and of varying the pulse repetition rates, and of the effect of Er:YAG laser on carious enamel and dentin. An adequate delivery system also has to be developed. While the Nd:YAG and Argon laser energies can be easily transmitted through silica fibers and the CO_2 through a hollow wave-guide, lack of a practical delivery system for the Er:YAG energy is a major drawback to clinical application. Zirconium fluoride fibers have been shown to be capable of transmitting erbium laser energy at levels found in this study to be adequate for hard tissue use; however, they are very brittle and deteriorate rapidly. Unless they are improved, an articulated arm, with mirrors and a focusing handpiece, may be the best approach to deliver the laser intra-orally. One of the main applications clinically would be in operative dentistry, for cavity preparations. The Nd:YAG laser has been shown to selectively evaporate carious tooth tissue, but it has not been shown to be effective on sound, non-carious tissue and so the dentist would still have to utilize the conventional drills for the cavity margins that will be placed in sound enamel and dentin. The erbium laser could prepare cavity margins, it could be used to cut tooth tissue to obtain access to the pulp chamber to initiate endodontic therapy and also to excise the roots of endodontically treated teeth in root resection procedures[20].

When sound hard dental tissues are exposed to pulsed Erbium:YAG laser radiation, there is a significant difference in the resulting changes when a water flow is maintained on the teeth during the laser exposure. On dry teeth, temperature elevations exceeded the 5°C threshold for pulp injury after only 3 sec. at 1.1W. Since most operative procedures involving drilling of intact enamel in vital teeth would be for longer exposure times than those studied, power levels above 1W should never be employed, especially on dry teeth, without a water flow.

In sharp contrast, the presence of water diminished the temperature elevations and improved the ablation efficiency, and fine, clean holes, free of charring and cracking could be produced using 50 mJ/pulse. The depths of such holes after 1 sec. were 0.46 mm., and if the laser beam would be moved over the tooth surface, a succession of such precise holes drilled could allow adequate cavity preparations. More studies, with longer exposure times, are needed, but the incorporation of a water flow on the teeth is strongly emphasised.

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Editor's Note: All of the reviewer's concerns were appropriately addressed by text changes, hence there is no **Discussion with Reviewers**.