Wet versus dry enamel ablation by Er:YAG laser

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The purpose of this study was to observe tooth structure and pulpal temperature changes in extracted human teeth subjected to a pulsed Er:YAG (2.94 μm) laser. Two teeth were irradiated while dry and three teeth while moistened by a fine water mist. When the dry teeth were irradiated, there was minimal enamel ablation. SEM of the resulting surface showed rounded fragments of enamel rods, enamel melting, cracks, and smooth-edged voids. Intrapulpal temperature measured by thermal sensor rose more than 27°C. When the laser application on the teeth was pulsed with a constant fine water mist, enamel and dentin were efficiently ablated. SEM of the resulting surfaces showed fissures and conical craters with sharp enamel projections remaining. Intrapulpal temperatures rose an average of 4°C. These results indicate that pulsed Er:YAG (2.94 μm) used with a water mist removes enamel and dentin without producing significant pulpal temperature changes. (J PROSTHET DENT 1992;67:847-51.)

The widespread use of laser technology in dentistry has been restricted1 in part because of the inability of currently available lasers to remove particles of enamel effectively and because of the thermal changes produced in the dental pulp. The surface changes produced by ruby,2 carbon dioxide (CO2),2,3 neodymium:yttrium aluminum garnet (Nd:YAG),4 argon,5 and erbium:YAG (Er:Yag) lasers6,7 have been described with terms such as crazing, cratering and glazing. No effective cavity preparations in vital teeth with sound enamel have been reported.

Ferreira et al.3 recently determined that the enamel changes made by laser energy were dependent on the energy density used and on enamel prism orientation. The melt-sealing that occurs with CO2 laser irradiation appears to increase resistance to dental caries5,9 and to increase the microhardness of enamel by changing the organic matter. Boggren et al.10 however, noted increased permeability. Wolbarsht11 reasoned that because bone and calcified structures contain small amounts of water, removal of those tissues could be produced if the tissues were subjected to laser energy the water would absorb.

Erbium is a metallic element of the rare-earth group that occurs with yttrium and is also used as a source of laser irradiation. An Er:YAG laser is a solid state, pulsed laser that has a maximum emission in the midinfrared region at 2.94 μm. Water absorbs strongly in this region; the water absorption coefficient for radiation produced by an Er:YAG laser is 10 times that of radiation produced by a CO2 laser. Laser surgery performed with an Er:YAG laser apparently results in water in the target tissue absorbing radiant energy and heating to boiling to produce water vapor. The water vapor builds up in pressure at the surgical site until a microexplosion occurs and a small portion of tissue is ablated. Keller and Hibst6 compared CO2 and Er:YAG laser effects on enamel and dentin. They found that, even though the absorption spectrum of CO2 and Er:YAG should be suitable for destruction of dental hard substances, the Er:YAG laser gave more encouraging results. They found that the CO2 laser caused charring, fusing, and fissuring not seen with the Er:YAG laser. The Er:YAG laser had the ability to remove particles in microexplosions and vaporize them, a process called ablation. The ablation of enamel by 10 pulses of the Er:YAG laser created a crater with flakes and scales along the wall.

Hoke et al.12 recently described the effects of Er:YAG laser on enamel and dentin when combined with a fine water mist. They were able to produce controlled enamel and dentin ablation in extracted teeth by keeping the tooth moist with a fine water spray. This method produced little heat rise in the pulp. They concluded that long-pulse Er:YAG laser may be an effective new method for tooth reduction applications when used with a water mist.

An Er:YAG laser is a solid state laser system that emits laser radiation at a wavelength of 2.94 μm, or 2940 nm, in the midinfrared spectrum. The system consists of a laser head, water cooler, and power supply.

The power supply consists of a controller and a high-voltage charging unit. The controller allows the operator to

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control the generation of the laser energy and the high voltage charging unit supplies voltage to the laser head, where the laser radiation is generated.

The laser head consists of an optical resonator and optical rail. The resonator itself consists of the mirror assemblies and pumping module, which are mounted on the 1-meter optical rail for proper alignment. In the pumping module are the electrical and optical components that use the high voltage to generate the laser radiation.

The water cooler is a self-contained system that provides water to the pumping module to keep the pump activity within the pumping module cool and allow efficient generation of the laser radiation.

Because heat is generated by absorption of the laser beam by the enamel and dentin, Hoke et al., performed a series of experiments to determine an optimum energy for ablation. In their study, laser energy of 95 millijoules (mJ) delivered at 6 pulses per second caused a 6.6°C rise in pulpal temperature whereas laser energy of 56 mJ delivered at 10 pulses per second caused a rise of only 1°C. The rate of ablation was not significantly affected by reducing the energy level from 95 mJ to 56 mJ if the pulses per second were increased. Heat rise of 5°C in the pulp may be safe for survival of the pulp. Greater than 21°C is not recommended for pulpal temperature.

MATERIAL AND METHODS

Extracted, noncarious human premolar and molar teeth that had been stored in saline solution were used. They were removed from the storage solution and clamped securely to a graduated stage calibrated for precise movement in the X-Y-Z planes. The laser used was an Er:YAG laser (ER 3000, Schwartz Electro-Optics, Inc., Orlando, Fla.) at 2.94 μm wavelength in the free-running long pulse mode, 2.5 μs individual pulses, 14 μs cycle time, 250 micro-

second train length. The laser beam was focused by means of a biconvex lens (FL 150 mm) and a mirror to a point determined by observation through a binocular microscope. Thermocouples (NCC Hi-Lo Temp, Type T, Mallinckrodt, Inc., Argyle, N.Y.) had previously been embedded in the pulp chambers of the teeth with composite filling material and attached to a digital temperature monitor (NCC Hi-Lo Temp, Model 8200, Mallinckrodt, Inc.) with a resolution of 0.1°C at three samples per second. Temperature was monitored and recorded during pulsed radiation. Two teeth were subjected to laser ablation at 58 mJ of energy while kept dry. Three teeth were subjected to laser ablation at 56 mJ, 60 mJ, and 95 mJ each while the teeth were kept moist by a fine water mist sprayed on the laser-irradiated surface. The water mist was provided by a spray from a hand-pumped plastic container similar to pumps used to dispense household cleaners or disinfectants. The volume of water was regulated to keep the tooth moistened. If the volume was too high, vaporization of water occurred without enamel ablation. If the volume was too low, enamel ablation was inefficient and heating of the tooth became significant. Thus the amount of moisture was regulated according to the ablation rate. As tooth structure ablation occurred, the teeth were moved slowly in each plane in an attempt to produce a typical cavity preparation on the occlusal tooth surfaces. The starting temperature and the temperature at ablation intervals were recorded at each energy level. The teeth were then sectioned, dehydrated, and sputter-coated with gold and palladium. A Cambridge S-200 scanning electron microscope (Leitz Co., Deerfield, Ill.) was employed to observe the surfaces produced by using the laser without and with the water mist.

RESULTS

When the air-dried teeth were subjected to Er:YAG laser energy of 58 mJ at 10 pulses per second, enamel ablation was inefficient. Even after more than 4000 pulses, approximately 6.6 minutes, the surface produced was irregular in configuration and unpredictable in depth of effect. No cavity preparation-shaped ablation occurred because no tooth structure was removed after the first few laser pulses in one place on the tooth. SEM studies showed extensive flecks of ash and no uniform pattern of ablation (Fig. 1). In areas where ablation occurred, there was extensive melting and flowing of enamel with bubble-like voids, large cracks, and irregular fissures (Fig. 2).

When Er:YAG laser energy of 56 mJ at 10 pulses per second was used with a constant fine water mist spray, enamel ablation was efficient. Laser energy of 8397 pulses in approximately 12 minutes produced cavity preparations that were comparable in size and shape to conventional preparations produced by rotary instruments (Fig. 3). Movement of the calibrated stage allowed predictable control of size and depth of the cavity preparation. The enamel surface produced at the margin of the ablation showed fractured enamel with sharp edges and ridges. At numer-
ous points in the enamel, crater formation occurred when multiple pulses were directed at the same location (Fig. 4). No melting or rounding of remaining enamel edges was observed in the enamel of any of the teeth subjected to Er:YAG (2.94 µm) with a fine water mist.

Because the ablation of enamel was not effective on the dry teeth, no dentin portions of the teeth were subjected to SEM. When the fine water mist was added and the enamel penetrated, the dentin was ablated more rapidly than the enamel. SEM study of resulting surfaces showed more smoothly fractured projections and depressions corresponding to the dentin tubules. The edges of the tubules were rounded, without ash or crack formation (Fig. 5).

The differences in temperature changes when the Er:YAG was used dry and with the water mist were significant. When the dry premolar and molar teeth were subjected to laser irradiation of 58 mJ energy at 10 pulses per second, heat was rapidly produced. The intrapulpal temperature in the first premolar rose from 20.6°C in 1000 pulses while the tooth was moved in the X-Y planes. No movement occurred in the Z plane because enamel ablation was not produced deep enough to escape the focus of the laser energy and no dentin was uncovered. Further pulses up to approximately 5000 resulted in an intrapulpal temperature rise to a maximum of 51.6°C (Table I). Cooling was allowed to occur for approximately 30 seconds between the pulse trains noted in Tables I and II.

In the second dry tooth, a molar, thermal changes were slightly less than in the first dry tooth. A rise from room temperature at 23.1°C to 36.7°C at 1200 pulses and 46.3°C after 4373 pulses was produced (Table II). The rise in temperature of 51°C in the first tooth and of 31°C and of 22.5°C in the second tooth indicates significant heating of the tooth and pulp.

The temperature rises in the premolar teeth subjected to Er:YAG plus water mist were minimal. In the test of 95 mJ at 6 pulses per second, a rise from 22.4°C starting temperature to 29.1°C maximum temperature occurred with ablation of enamel and dentin in approximately 10 minutes (Table III). Reduction of energy to 60 mJ (Table IV) and then to 56 mJ at 10 pulses per second (Table V) showed progressive improvement in thermal changes without significantly affecting ablation efficiency. At 56 mJ energy delivered at 10 pulses per second the temperature rose from 20.3°C to 21.3°C in 2440 pulses and from 19.7°C to 20.7°C at 2990 pulses.
Fig. 5. Dentin surface produced by Er:YAG irradiation plus water mist. (Original magnification x184.)

Table I. Temperature change produced by 58 mJ at 10 pulses per second with Er:YAG on dry premolar

<table>
<thead>
<tr>
<th>Pulse No.</th>
<th>Start temp (°C)</th>
<th>End temp (°C)</th>
<th>Max temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1023</td>
<td>30.6</td>
<td>38.1</td>
<td>36.6</td>
</tr>
<tr>
<td>1023-2916</td>
<td>28.6</td>
<td>46.5</td>
<td>46.8</td>
</tr>
<tr>
<td>2916-4882</td>
<td>30.3</td>
<td>50.2</td>
<td>51.6</td>
</tr>
</tbody>
</table>

DISCUSSION

The difference in ablation efficiency of the dry tooth versus the moist tooth was remarkable. When the dry tooth was irradiated, no surface changes could be seen through the observation microscope after the first few pulses and the sound produced during the pulsed energy changed from a sharp pop to a dull hiss. This observation supports the feeling of Wolbarsht that enamel and dentin are removed by water vapor expansion as the water absorbs the wavelength of the energy used. Once the available water in the enamel had been vaporized and a small amount of enamel ablation had occurred, no additional water was available for absorbing the energy and no further removal of enamel was produced. Instead, the enamel irradiated was heated by the laser energy and showed heat-related changes of enamel melting and bubblelike voids and cracks. As continued pulses were directed at the tooth, the heat rose in the pulp chamber and the tooth structure did not have sufficient time between pulses to dissipate the heat. The heat produced in only 600 pulses caused a temperature rise of 5.6° C, which is greater than that considered safe for pulp survival. After 2000 pulses, the temperature rise was as much as 21.6° C, which was more than the temperature determined by Laurichesse and Santoro to cause irreversible pulpal changes. The lack of ablation and the increases in pulpal temperature combine to restrict the usefulness of Er:YAG irradiation of dry teeth. Combining the pulsed Er:YAG with a fine water mist produced encouraging results. Enamel ablation occurred with little difficulty, exposing dentin that was ablated even more rapidly. After approximately 500 pulses of laser energy there was progress of ablation trough enamel. In 2000 to 8000 pulses, outline forms of standard occlusal cavity preparations had been made in enamel and dentin. During application of this energy, the pulpal temperature rise of less than 5° C was safe for the pulp. The margins of the ablated enamel showed sharp edges and projections. This effect would be created by explosive forces fracturing enamel instead of generating the heat required to melt the enamel. Because the water content of dentin is greater than that of enamel, as expected, dentin was more easily ablated.

These results strongly suggest that an Er:YAG laser should be used with a water mist if vital teeth are subjected to testing. This suggestion corresponds with the speculations of Keller and Hibst that the Er:YAG would produce little thermal damage to the dental pulp. Because the absorption of 2.94μm by water causes vaporization and microexplosions, they thought that enamel and dentin could be ablated releasing the heat instead of storing heat in the tissues. Severe pulpal changes have been produced by ruby, CO₂, and Nd:YAG by thermal injury. Eliminating significant thermal changes as illustrated in the water mist technique used in this experiment appears to circumvent the problems encountered with other laser sources.

The comparisons of heat generated become more signif-

Table II. Temperature change produced by 58 mJ at 10 pulses per second with Er:YAG on dry molar

<table>
<thead>
<tr>
<th>Pulse No.</th>
<th>Start temp (°C)</th>
<th>End temp (°C)</th>
<th>Max temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1200</td>
<td>23.1</td>
<td>36.7</td>
<td>36.7</td>
</tr>
<tr>
<td>1200-1808</td>
<td>31.7</td>
<td>35.2</td>
<td>36.6</td>
</tr>
<tr>
<td>1808-4837</td>
<td>33.5</td>
<td>46.3</td>
<td>46.5</td>
</tr>
</tbody>
</table>

Table III. Temperature change produced in premolar by 95 mJ at 6 pulses per second with Er:YAG plus water mist on premolar

<table>
<thead>
<tr>
<th>Pulse No.</th>
<th>Start temp (°C)</th>
<th>End temp (°C)</th>
<th>Max temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6569</td>
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<tr>
<td>569-1650</td>
<td>24.3</td>
<td>25.4</td>
<td>25.5</td>
</tr>
<tr>
<td>(Reset counter)</td>
<td>0-1566</td>
<td>20.6</td>
<td>25.7</td>
</tr>
<tr>
<td>1566-2079</td>
<td>25.7</td>
<td>29.1</td>
<td>29.1</td>
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</table>
Table IV. Temperature change produced in premolar by 60 mJ at 8 pulses per second with Er:YAG plus water mist on premolar

<table>
<thead>
<tr>
<th>Pulse No.</th>
<th>Start temp (°C)</th>
<th>End temp (°C)</th>
<th>Max temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2964</td>
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<td>24.4</td>
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<td>2964-4645</td>
<td>19.8</td>
<td>22.7</td>
<td>22.7</td>
</tr>
<tr>
<td>4645-5397</td>
<td>22.7</td>
<td>24.3</td>
<td>24.3</td>
</tr>
</tbody>
</table>

Table V. Temperature change produced in premolar by 56 mJ at 10 pulses per second with Er:YAG plus water mist on premolar

<table>
<thead>
<tr>
<th>Pulse No.</th>
<th>Start temp (°C)</th>
<th>End temp (°C)</th>
<th>Max temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2440</td>
<td>20.6</td>
<td>21.3</td>
<td>21.3</td>
</tr>
<tr>
<td>2440-2990</td>
<td>19.7</td>
<td>20.7</td>
<td>20.7</td>
</tr>
</tbody>
</table>

significant if the distance from the point of laser contact to the thermal sensor is measured. Because the enamel was not penetrated by the Er:YAG used dry, the remaining thickness of the enamel and the unaffected dentin could have been a factor in temperature changes. The possibility that the nonirradiated enamel and dentin served as a heat sink dispersing a portion of the heat away from the sensor is more likely than that the enamel and dentin were directly conducting the heat only to the temperature sensor. If distance from the point of ablation to the sensor tip is considered, the results would have been a more significant temperature rise in the moist Er:YAG irradiated teeth because of extensive enamel and dentin ablation creating proximity of the laser energy to the sensor.

This experiment also demonstrated that 56 mJ energy delivered at 10 pulses per second caused the smallest degree of temperature change recorded. The 56 mJ energy level was as efficient for enamel ablation as the 95 mJ energy level. Testing in this manner allowed further refinements of techniques that are likely to be useful with vital teeth in a clinical setting.

CLINICAL IMPLICATIONS

This experiment has shown that pulpal damage is likely to occur because of the heat generated if a dry vital tooth is subjected to Er:YAG laser radiation. The addition of a water mist during irradiation not only enables rapid ablation of enamel and dentin, but offers thermal protection to the pulp. This research suggests that energy levels of a laser system that cause pulpal heat changes may be modified by adding a water spray. Future laser use should incorporate these modifications. Clinicians currently using CO₂ or Nd:YAG lasers in the oral cavity should be mindful of thermal changes and potential methods of improving pulpal health.

Progress on laser systems that ablate enamel and dentin is being made. The wide acceptability of laser technology in medicine makes utilization of lasers in dentistry attractive, especially if a laser can be developed that is safe for tooth preparation. This research describes a step toward realization that cavity preparations may be accomplished by the Er:YAG without significant heat change in the pulp. Further study of this system for vital teeth is suggested.

CONCLUSIONS

1. Tooth structure ablation is produced by a long pulse train (2.5 µs) Er:YAG (2.94 µm) laser.

2. The application of a fine water mist to the irradiated tooth surface increases ablation efficiency.

3. The application of a fine water mist during tooth structure ablation by Er:YAG laser application results in lower temperature rise than if the laser energy is used on dry teeth.

REFERENCES


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