Laser is now established as a suitable tool for the selective and precise removal of carious dental tissue, as well as for many other applications.1-8 If correctly used, laser ablation minimizes healthy tissue removal and increases patient comfort. The reduced noise and mechanical vibration result in less pain, making the procedure tolerable for the majority of patients.9,10 Aside from removal of carious dental tissue, the removal or modification of composite resin restorations is also quite a common procedure. The conventional tools employed in these cases are the low- and high-speed rotating instruments, and in some cases, an aluminum oxide micro-etcher jet. As described previously,11-12 advantages such as the possibility of selective resin removal and preserving healthy tissue are important issues to be considered. The use of laser for this purpose requires knowledge of the basic features of composite resin laser ablation. Such information is basically absent from the literature, making clinical application progress difficult in this area. The knowledge of the basic aspects of resin laser ablation can lead to the development of procedures that allow the selective removal of composite resin, preserving the dental tissue.12 Basically, all high-intensity laser systems available

Ablation Rate and Morphological Aspects of Composite Resins Exposed to Er:YAG Laser

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\textbf{Purpose:} The aim of this work was to investigate the ablation rate and the morphological aspects of three composite resins using Er:YAG laser irradiation.

\textbf{Materials and Methods:} Three different types of composite resins were chosen (microfilled, hybrid, condensable) regarding their chemical and structural composition. Composite tablets were irradiated with an Er:YAG laser at different energy levels per pulse (100, 200, 300, and 400 mJ). The diameter and depth of each composite resin tablet were measured, as was the microcavity produced by laser ablation, and from this the overall volume removed was calculated. Observations of morphological aspects were performed using electron microscopy. The ANOVA and Tukey tests were used to statistically analyze the volume results.

\textbf{Results:} The only variable that influenced the ablation rate of the composite resins tested was the energy level per pulse.

\textbf{Conclusion:} Examining the basic features of laser ablation of composite resin represents the first step to understanding the mechanism of composite resin ablation by Er:YAG laser and the numerous differences due to resin composition and structure.

\textbf{Keywords:} ablation rate, morphological aspects, Er:YAG laser, composite resin.

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for dental clinical application can remove restorative materials. Nevertheless, since Er:YAG laser is the system mainly used for dentistry, we have chosen it as the starting point for a series of studies. We are planning to achieve a full understanding of laser ablation of composite resin, involving different types of laser radiation.

The purpose of this study was to investigate ablation rate and morphological effects of Er:YAG laser on three types of composite resin: microfilled, hybrid, and condensable.

Because Er:YAG laser interacts with tissues through an explosive thermomechanical mechanism resulting from the interaction of laser with water droplets present in the ablation region, interaction with different resin types may result in different morphological aspects as well as different rates of material removal.

**MATERIALS AND METHODS**

**Experiment I – Thermal Mapping**

Thermal mapping during laser ablation was performed to confirm that this laser is a safe tool for the proposed use.

Using a metallic mold, we made six 4-mm-thick cylindrical tablets with a diameter of 4 mm. An A2 hybrid composite resin (batch OWN 2003-05, Z100, 3M, St Paul, MN, USA) was used as a restorative material. The resin tablets were compressed and then cured under a halogen lamp (KM200R, K&M, São Carlos, Brazil) for 80 s.

After this step, a cylindrical cavity of 2 mm depth and 1.5 mm diameter was prepared in the base of each tablet using a #1091 diamond bur (SSWhite, Brazil). This cavity was filled with a thermal conducting paste (Implastec, Votorantim, São Paulo, Brazil) and a thermocouple (Model 120-202 EAJ, Fenwal Electronic, Milford, MA, USA) was introduced as shown in Fig 1.

The experimental setup is depicted in Fig 2. The laser system used was the Twin Light Er:YAG laser (Fotona Medical Lasers, Ljubljana, Slovenia), operating at 2940 nm, peak energy up to 500 mJ, frequency up to 15 Hz, and pulse duration of 200 to 450 ms. For this experiment, a 12.0-mm focal distance (focused laser beam), frequency 10 Hz, exposition time of 10 s, and energy levels of 80, 400 and 500 mJ per pulse were set. Each parameter was repeated three times and an average value to plot a curve was calculated for them.

**Experiment II – Ablation Rate and Morphological Evaluation**

Using the same methodology, we made sixty 2-mm-thick cylindrical tablets with a diameter of 8 mm. Three different materials were chosen: a microfilled resin A2 (batch A30122, Durafil VS, Heraeus Kulzer, Hanau, Germany), an A2 hybrid composite resin (batch OWN 2003-05, Z100, 3M), and an A2 condensable composite resin (batch 39722 2002-12, Alert, Jeneric Pentron, Wallingford, CT, USA).

The composite resin tablets were compressed and then cured under conventional light (halogen lamp, KM200R, K&M) for 40 s for the hybrid composite resin and 20 s for the others, following the manufacturer’s recommendations.

The laser system used was the same as above. The smallest possible diameter of the laser beam is around...
700 µm. For the present experiment, we set a distance of 12.0 mm, fixed the frequency at 10 Hz, an exposure time of 10 s, and energy levels at 100, 200, 300 and 400 mJ per pulse. Each sample was ablated at 12 spots with three repetitions for each energy level.

The samples were immersed in epoxy resin for further processing and the micromorphological aspects of the ablated volume were evaluated under a scanning electron microscope (SEM; DSM 960, Zeiss, Oberkochen, Germany). The diameter and the depth of the ablated regions were optically measured, which allowed the determination of the ablated material volume. We first focused on the top surface of the microcavity and then on the deepest part of the ablated cavity. A calibrated micrometer allowed the depth to be measured. The diameter was measured using a calibrated micrometer slide coupled with the microscopy images.

RESULTS

Experiment I – Thermal Mapping

Temperature values were stored and plotted in a computer. As a result, plots show the temperature profiles as a function of time for each parameter used.

Figure 3 shows the obtained data. All curves demonstrate the same performance: laser radiation starts to ablate the target at the 3rd second, visible on the curves as a decrease in temperature. After that, temperature increases up to the 13th second, when the laser irradiation ceases. Then, the curves drop, representing the thermal relaxation of the composite resin.

The graphs allow the calculation of temperature variation during laser ablation for each energy per pulse.

Experiment II – Ablation Rate and Morphological Evaluation

Figure 4 shows the macroscopic morphology of the ablated region for all composite resins at 300 mJ. Characteristics such as ablation regularity and shape can be obtained from these observations.

At higher magnification, the microstructure of the ablated region can be observed. Figure 5 shows the microstructure at 1000X magnification of a microfilled composite resin ablated at four different energy levels. Equivalent results are presented in Figs 6 and 7 for hybrid and condensable composite resins, respectively.

The observed ablation effect for different laser energy levels is clearly peculiar to each composite type and very dependent on the energy delivered per pulse.

In all samples, the microcavities obtained using laser irradiation show shapes that resemble a conical cavity. The diameters and the depths of the ablated regions were measured for each irradiated sample. In order to simplify the comparison, Figs 8 and 9 present the measured diameter and depth, respectively, for the ablated surfaces for the three composite resin types.

The removed volume was calculated for each prepared cavity based on the conical shape and the diameter and depth values (Fig 10). The results of the removed volume were submitted to ANOVA and Tukey’s test. Comparing all variance factors, a statistically significant difference \((p < 0.01)\) was observed (Table 1) when different types of composite resins and energy per pulse were considered. It means that all these factors may be statistically significant concerning the influence on the volume removed. However, the Tukey test \((p < 0.05)\) showed that 300 mJ was able to ablate the highest material volume.

Figures 5 to 7 show important aspects of laser-material interactions.

DISCUSSION

Thermal mapping during composite resin ablation with Er:YAG laser showed an average temperature variation from ca 0.7°C (80 mJ per pulse) to 0.9°C (400 and 500 mJ per pulse) (Fig 3). These temperature variations are not damaging to the pulp\(^{14}\) or the periodontal tissue.\(^{15}\)
Although our experimental setup did not include any additional cooling source, it is mandatory to consider that dental organs (teeth and supporting structures) possess complex physiological cooling systems. Thus, it is probable that composite resin ablation with the Er:YAG laser under clinically acceptable parameters does not result in damage to the pulp or periodontal tissues.

In contrast to natural dental tissue, observations of the ablated regions of the composite resins show a very regular ablation pattern. The edges visible in the micrographs of Fig 4 are well defined in all three composite resin types. This uniformity is probably a consequence of the homogeneity of the material itself. There are, however, small variations from one resin type to the next, due to the differences in filler-polymer matrix bond energy in each composite type, resulting in differences in the ablation resistance. Greater cohesion in the material will result in greater resistance to laser ablation.

The overall aspect of the ablated area reveals resin behavior itself as a soft material under laser irradiation. It seems that the hybrid composite resin can be more easily and efficiently removed by the Er:YAG laser than the microfilled and condensable ones. That may be due to the microfiller microstructure, the resistance of which relies entirely on the polymeric matrix, which, once ablated, releases the filler particles. The two composite resin types with cores consisting of polymer with dispersed fillers (microfiller and hybrid) show equivalent aspects. The condensable composite resin seems, at least macroscopically, to be more resistant to laser ablation.

SEM analysis shows a different microstructure in the ablated region for each composite resin. The surface features presented in Fig 5 show that for the microfilled composite resin, laser ablation occurs mainly through the polymer matrix. The spaces previously occupied by microparticles are left behind. An increase of energy in the laser pulse does not seem to change the
overall aspects, but clearly produces greater modification of the polymer matrix.

For the hybrid composite (Fig 6), the microstructure of the irradiated surface does not show severe modification even when laser pulse energy varies. Nevertheless, larger energies seem to produce an ablated surface with a more regular aspect.

In both the microfilled and hybrid composite resins discussed above, the low cohesion energy manifests as an apparent regularity in the ablated area. There seems
to be no evidence of resistance offered by the material during ablation.

On the other hand, the condensable composite resin (Fig 7) behaves differently from the two previously discussed cases. Here, the low energy per pulse parameter seems to produce little effect on the material. At this level, the energy of the laser is insufficient to overcome the cohesion of the material and promote the ablation. Increase of energy seems to overcome this apparent barrier exposing the heterogeneity of the
structure. The presence of fiberglass became evident, and the general shape of the fibers seems preserved. Increasing the energy clearly causes a breakdown, easily removing the inter-fiber polymeric matrix. At the highest energy level per pulse, the micrographs clearly show that the fiberglass arrangement is being disassembled.

Concerning the diameter of the ablated area, Fig 8 shows that the behavior of all composite resins is similar. Extrapolation of E (mJ) = 0 per pulse provides an
irradiated diameter on the order of 0.75 to 0.80 mm, which is consistent with the nominal beam diameter of about 0.7 mm. Clearly, the ablated diameter increases as the laser energy increases and tends to saturate at values of ca 1.2 mm. The increase of diameter with the pulse energy is a consequence of better use of the energy tail present on the beam spot. Higher energy in the tail makes it more similar to the hot part of the beam, therefore causing ablation in a wider area. The curve showing progressive decrease in the rate of diameter increase with energy is probably a consequence of the limited amount of water in the irradiated region, which is intrinsically related to the ablation mechanism for the Er:YAG laser. Water is essential for ablation.

Figure 8 shows that in almost all situations, the ablated diameter is the smallest in the condensable composite resin when compared to the others. The condensable composite resin, having the fiberglass component, presents better resistance to material removal. On the other hand, the hybrid composite resin shows, for all conditions, the highest ablation rate concerning the diameter, which is also related to the structure. The variety of particle sizes makes the material easier to be disassembled.

Concerning the depth of penetration (Fig 9), the results show the existence of a threshold energy per pulse before its penetration into the target tissue. This is more evident in the condensable composite resin, but it is present to some extent in microfilled and hybrid ones as well. The overall observed behavior for penetration is the following: from zero energy up, the speed of penetration seems to be quite low until the threshold value ($E_{th}$) is reached, whereupon the penetration rate rapidly increases. After this fast increase, the penetration depth seems to keep increasing at a rate that decreases with increase of energy, again (similarly to the diameter phenomenon) with a possible sat-
uration effect, even though less evident than in the di-
ameter case. The leveling out effect in penetration may
be based on several factors. First, the amount of water
interacting with the laser in the ablation mechanism can
determine the maximum potential ablation. Second,
the increase of energy per pulse increases the ablation
ability, but the system’s ability to eject the ablated ma-
terial is also limited, causing a saturation effect. The
threshold value (Eth) can be estimated from Fig 9. This
can be done through the prolongation of the steepest
part of the curves. As indicated in Fig 9, Eth values for
hybrid, microfilled and condensable composite resins
are approximately 55 mJ, 80 mJ, and 110 mJ, respec-
tively. These threshold values indicate the conditions of
cohesion for the resin. In this study, the hybrid com-
posite resin showed the lowest cohesion level com-
pared to the others, while the condensable composite
resin presents the highest. This is in agreement with
Luo et al.,16 who evaluated the effect of filler porosity
on abrasion resistance, and concluded that porous par-
ticles prepared via sol-gel show some promise in terms
of improving the wear resistance of photopolymerized
composite resins. The Z100 fillers are produced as a
result of sol-gel chemical reaction.

In this study, the condensable composite resin show-
ed the highest resistance to ablation, followed by the
microfilled and finally the hybrid composite resins. This
is in fact in agreement with the observed microstruc-
tural morphology after laser irradiation under several
conditions, and is also supported by Berlin et al.,17 who
state that regarding polymer composites with reinforc-
ing fibers, the mechanism of stress transmission from
the matrix to the filler depends on the filler particle
configuration.

Finally, Fig 10 shows the results concerning removed
material volume as a function of energy per pulse. The
graph shows similar depth penetration curves. For the
ablated volume, there is Eth per pulse to start material
removal. From zero energy up, the removed volume
seems to be quite low until the threshold energy value
is reached, after which the volume removed rapidly in-
creases. Just after this fast increase, the volume in-
creases at a rate that decreases with increase of
energy. A possible saturation, similar to the penetra-
tion depth is observed. The existence of Eth shows that
there is a minimum energy able to overcome the en-
ergy that holds the resin together.

This study presents a new finding: when Er:YAG
laser removes cured composite resin, the ablation
mechanisms involved are explosive vaporization fol-
lowed by a hydrodynamic ejection. Rapid melting cre-
ates large expansion forces due to the volume change
of the material upon melting. Liquid expansion is op-
posed by the liquid surface energy or surface tension.
These counteracting forces combined with the composites
ite resin structure result in the formation of surface
protrusions which are accelerated away from the sur-
face as droplets.

CONCLUSION

Our findings allow us to conclude that energy level per
pulse is the only factor that influenced the ablation rate

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<th>Table 1  ANOVA test results</th>
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<td>Between composite resins (R)</td>
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<td>Residue II</td>
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Calculated critical Tukey value: 0.18115
of the composite resins studied here. Micromorphological aspects resulting from Er:YAG laser irradiation depend on the chemical composition and structure of all types of composite resin. The existence of a threshold energy of ablation is consistent with the cohesion of the material. A different mechanism of composite resin ablation was observed: the explosive vaporization followed by a hydrodynamic ejection. This is an interesting discovery in the search for a more convenient laser system to ablate composite resin using the real ablation mechanisms involved in that operation. The next step will be a comparative study of laser ablation of resin and natural material.

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