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Assessment of the Ability of Er:YAG Laser to Remove Composite Resin Restorations

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Purpose: The purpose of this study was to assess in vitro Er:YAG laser efficacy for composite resin removal, as well as the thermal alterations occurring during laser irradiation.

Materials and Methods: Cavity preparations (1.0 mm deep) in bovine teeth were restored with resin and divided into 2 groups: the control group, in which restorations were removed with a high-speed bur, and the experimental group, in which restorations were removed with Er:YAG laser at 250 mJ output energy, 80 J/cm^2 energy density, and 6 Hz pulse repetition rate. The removal time was measured and the temperature alteration was checked. After the removal, the specimens were split in the middle, and the surrounding and deep walls were analyzed to check for the presence of restorative material.

Results: The results revealed that the temperature rise during composite resin removal in both groups occurred on the substrate underneath the restoration. Although the temperature rose during composite filling removal, none of the groups presented a temperature increase higher than 5.6°C, which is considered the critical temperature increase above which there may be irreversible thermal damage to the pulp. Regarding the time for composite filling removal, it was observed that the laser group required more time than the control group for complete elimination of the material from the cavity walls.

Conclusion: Although there was a greater temperature increase during composite resin removal with Er:YAG, it did not reach the critical temperature value above which there may be irreversible thermal damage to the pulp.

Keywords: ablation, Er:YAG laser, composite resins, temperature, time, efficacy.

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Alternative methods such as air abrasion, ultrasound and laser irradiation have been proposed for adhesion, cavity preparation[1] and superficial treatment of the substrates.[2] Some positive aspects of laser use are treatment without anesthesia on children and adults,[3,4] and less discomfort during cavity preparation[5,6] due to the elimination of such factors as vibration, pressure, noise, and the patient's stress during conventional procedures with rotating instruments.

Different kinds of lasers have been employed in dentistry. Currently, the Er:YAG laser shows superior performance as regards cavity preparation in dental hard tissues,[7] showing its ability to remove enamel, dentin, and caries, with less thermal damage to the tooth, which is one of the greatest problems associated with other lasers, such as Nd:YAG and CO_2.[8,9] The Er:YAG laser causes vaporization of water and hydrated organic components of the tissues. The energy striking the dental structure during irradiation is just sufficient to vaporize water. The greatest part of this energy is spent in the ablation process and only a small fraction of it results in heating of the remaining dental structure.[10] The studies that evaluated temperature increases with the use of Er:YAG laser present great differences with respect to power settings, frequency, size, and depth of the preparations.[6,11,12] However, there is consensus on the importance of using water cooling for laser cavity preparations.[13,14]

Another use of laser is the effective removal of cements and composite resin restorations, comparable to the way enamel and sound dentin are removed.[14-16] A selective differential ablation of composite resin can be made in the case of old and unsatisfactory restorations in enamel, remains of resinous material from the flat surfaces of enamel, and after removal of orthodontic brackets or periodontic splints.[15]

The Er:YAG laser irradiation produces a photomechanical interaction mediated by water during the process of ablation of dental hard tissues. In spite of this, the removal of composite resins seems to occur with very little water-mediated mechanical action. Actually, there is direct absorption of laser energy by the resinous material, generating heat that will result in an explosive vaporization, followed by hydrodynamic ejection.[14,15]

Some studies[17,18] assessed the uses of laser for the removal of dental hard tissues, focusing mainly on the ablation efficiency and the thermal effects caused by the heat transfer through enamel and dentin to the pulp during cavity preparations. Hibst and Keller[19] tested the ablation of some restorative filling materials, including composite resin, and a greater thermal side-effect on adjacent substances was suggested compared to enamel and dentin. However, the literature contains little on real effects of laser on the pulp when used for the removal of composite resin restorations.

Considering the increasing use of esthetic restorative materials and the improvement of the techniques for their removal, the aim of this study was to evaluate the ability of the Er:YAG laser to remove composite resin restorations, assessing the time required for this removal and analyzing the temperature alteration caused by the laser.

MATERIALS AND METHODS

Twenty freshly extracted bovine incisors were selected for this study. The teeth were thoroughly cleaned with a hand scaler and rubber cup/pumice paste, and were stored in distilled water at 4°C until use.

The teeth were decoronated at the cementoenamel junction. The crowns were bisected longitudinally with a water-cooled diamond saw in a sectioning machine (Minitom, Struers A/S; Copenhagen, Denmark), dividing the tooth into a labial and a lingual fragment. The lingual fragment was discarded, providing a total of 20 labial specimens (4 x 4 x 2.5 mm). Each labial fragment was fixed in a polytetrafluoroethylene cylinder with its surface parallel to the device and ground wet with #400-grit silicon carbide paper in a polishing machine (Politriz, Struers A/S) until obtaining 0.5-mm-thick enamel on the labial side and 1.5-mm-thick dentin on the inner side.

Class I cavities (2 x 2 x 1 mm) were prepared with a #245 high-speed carbide bur and etched with 35% phosphoric acid gel (3M ESPE; St. Paul, MN, USA) for 15 s, thoroughly rinsed, and excess water was blotted with absorbent paper. Two consecutive layers of a single-bottle adhesive system (Single Bond, 3M ESPE) were applied, gently air thinned for 5 s, and light cured for 20 s using a visible light-curing unit with 480 mW/cm^2 output (XL 3000; 3M ESPE), as measured with a curing radiometer. The cavities were restored with a hybrid light-cured composite resin (Z250; 3M ESPE, shade A4), inserted in two increments, and each polymerized for 20 s (Fig 1). The restored specimens were stored in distilled water at 37°C for 24 h and thereafter the restorations were polished with aluminum oxide-impregnated disks (Super-Snap, Shofu; Tokyo Japan) in a decreasing order of abrasiveness.

The specimens were randomly assigned to 2 groups (n = 10), according to the technique used for composite filling removal. In group I (control), the restorations were removed using a water-cooled #1092 cylindrical diamond bur (KG Sorensen, São Paulo, SP, Brazil) in a high-speed handpiece (Dabi-Atlante S.A., Ribeirão Preto, SP, Brazil). Each bur was discarded after five preparations. In group II, the composite restorations were removed using a Kavo Key II Er:YAG laser device emitting at 2.94 mm wavelength (Kavo Dental; Biberach, Germany), 250 mJ, energy density (fluence) 80 J/cm^2, 6 Hz pulse repetition rate. The laser beam was delivered in noncontact, focused mode, with a fine water mist at 5 ml/min. Laser beam spot size (0.63 mm) was verified through SEM measurement at a 12-mm distance of irradiation, pulse duration was 250 to

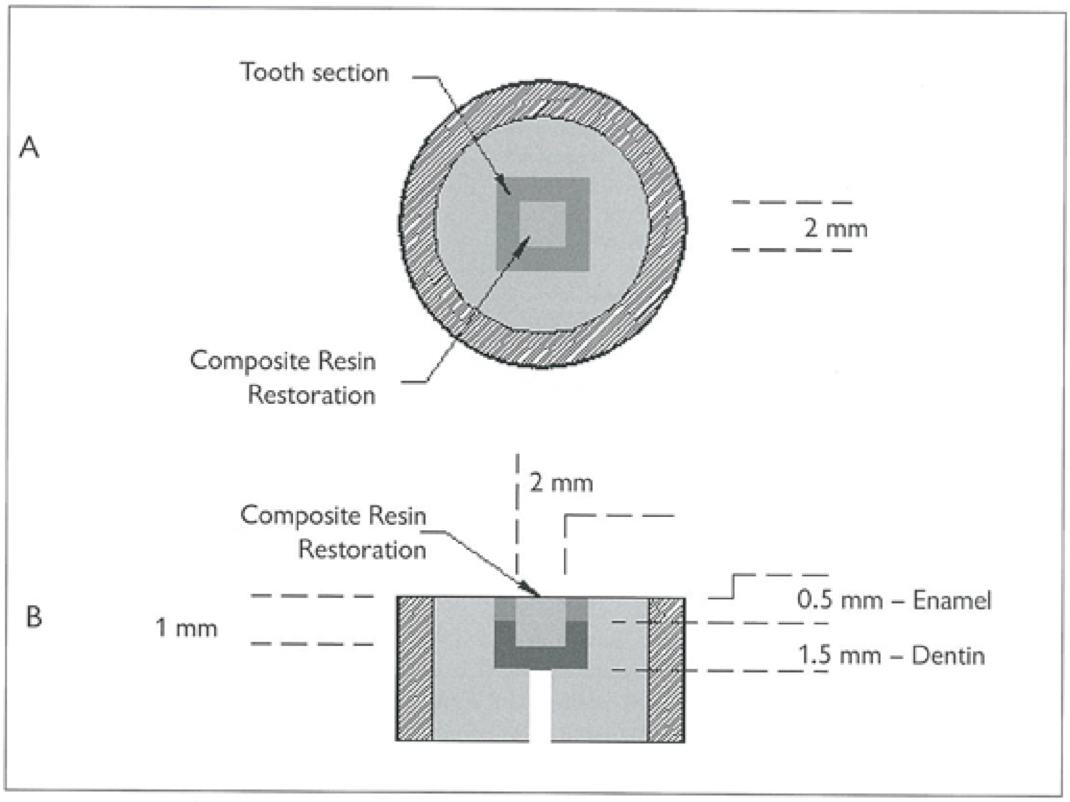

Fig 1 Schematic illustration of specimen
A: top view; B: transverse cut.

500 ms, and the 2051 handpiece was used with a removable tip attached to a flexible fiber delivery system. The irradiation distance was standardized by using a custom-made apparatus consisting of two parts: a holder to fix the laser handpiece in such a way that the laser beam was delivered perpendicular to the specimen surface at a constant working distance from the target site, and a semi-adjustable base, on which a plexglass plate with the fragment attached to it was firmly fixed with wax. Two operators operated the apparatus' micrometer screws so that the semi-adjustable base was alternately moved in both right-to-left and forward-to-back directions, thus allowing the laser beam to act on the entire composite restoration. For every specimen, the irradiation distance was checked with a ruler.

The thermocouple was put in contact with the specimen at the dentin wall. The temperature was recorded immediately before and after the removal of the composite restorations (Fig 2). The time (in seconds) required for removing the restorative material in each group was measured with a chronometer.

In both groups, completion of restoration removal was established by visual inspection. The composite resin shade used in the experiment was easily distinguishable from the dental structure. Next, the specimens were cleaved longitudinally in the middle, and the surrounding and deep walls were analyzed with a stereomicroscope under 40X magnification in order to check for the presence of restorative material.

Means of working time and temperature change were calculated for each group and data were analyzed statistically by the non-parametric Mann-Whitney test.

RESULTS

Group I (control), in which restorations were removed with a rotating instrument, showed an average temperature increase of 1.2°C, and group II, in which restorations were removed with laser, the average temperature increase was 4.0°C, statistically significantly different from the control group. The data are summarized in Table 1.

The time spent for the removal of restorations was 25.6 s for those performed with a rotating handpiece, as opposed to 49 s for the removal with laser, which is a statistically significant difference. The time required for restoration removal is summarized in Table 1.

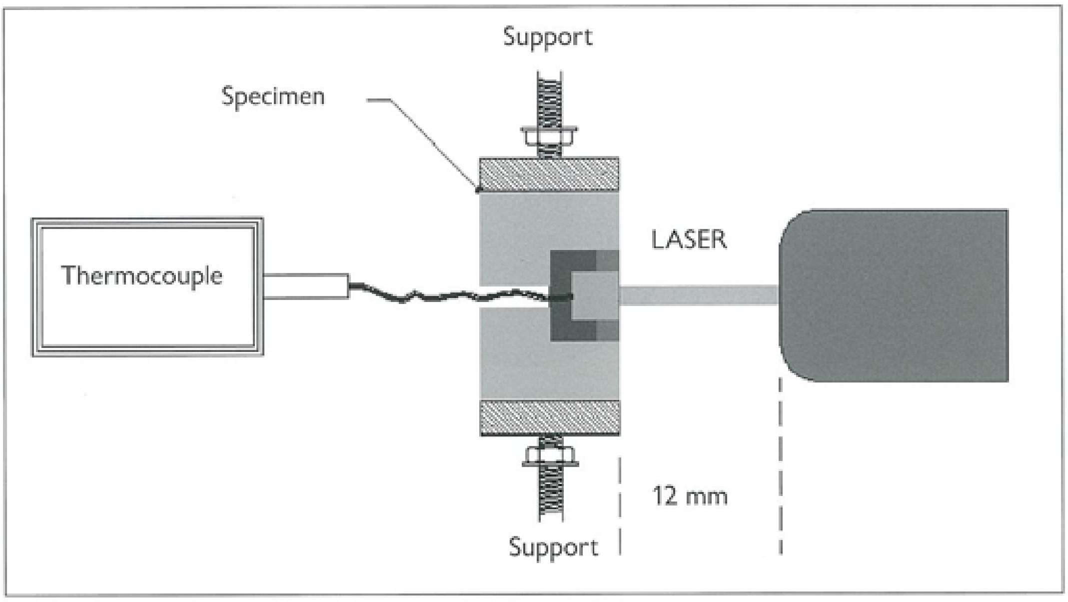

Fig 2 Specimen, support, thermocouple! Schematic illustration of removal of the restoration with laser and temperature measurement.

Table 1 Medians, means, and standard deviations of temperature rise and time required for composite resin removal

	High-speed handpiece		Laser Er:YAG	
	Median	Mean (SD)	Median	Mean (SD)
Temperature (°C)	1.0	1.2 (±1.1)	3.7	4.0 (±1.8)
Time (s)	20.0	25.6 (±10.3)	47.0	49.0 (±4.5)

It was also observed that more specimens in the laser group than in the rotating instrument group presented an incomplete removal of the restoration; in this case, it was noticed that the remainder of the restoration was restricted to a tenuous resin layer in the cavity.

DISCUSSION

Analyzing the time spent for restoration removal, it can be observed that the laser took twice the time of the rotating instrument. It was also observed that the cavities produced by the laser exhibited irregular walls and incomplete removal of restorations. This irregularity also was observed in a study by Dostalová et al,[17] in which the laser ablation presented greater surface irregularity upon caries removal.

The laser promotes a fusion of the composite resin, and during removal, it was observed that the thinner the remainder of restoration, the more difficult it was to visualize the difference between the restorative material and the dentin of the cavity. These factors made it difficult for the operator to assess the result, leading to incomplete removal of the composite resin.

The longer time spent for restoration removal by laser may be caused by the parameters employed, which were chosen to minimize increases of temperature, since there are no established parameters from previous studies for the removal of filling material.

The temperature increase of 4.0°C observed with the laser is consistent with that observed for cavity preparation in enamel and dentin.[10,18] However, some authors reported smaller temperature increases in dental hard tissues when compared with composite ablation.[20] In spite of the greater temperature increase than that found for the removal with the rotating instrument (1.2°C), the temperature increase caused by laser probably did not cause any damage to the pulp, according to a study[21] which demonstrated that pulp damage could be caused by temperature increases higher than 5.6°C and total pulp necrosis with a 16°C increase. Other research[20] has shown that temperature increase is also related to the employed energy as well as to the required ablation rate. Thus, other parameters should be tested.

Although it has been demonstrated that the laser presented results lower than the rotating handpiece, clinical studies show that approximately 70% of the patients do not feel any vibration during the laser microexplosions and 100% of the patients feel no pain or discomfort, thus indicating that this is a safe method for the pulp.[17] Besides, due to its ability to ablate dental tissues, the Er:YAG laser has been pointed out as an excellent technology for operative dentistry, being the most promising alternative to rotating instruments. Nevertheless, further studies are still required before it becomes a routine method in the dental practice.

CONCLUSION

With advances in dentistry and dental care, a decrease in the incidence of primary carious lesions has been observed. However, many existing restorations are clinically unsatisfactory. Therefore, many clinicians lose a great part of their time and get a substantial part of their incomes replacing restorations. Thus, this study is relevant for dental research due to the great demand for the substitution of restorations and the good cost:benefit ratio of laser equipment.

Based on the above results, it may be concluded that with the parameters used, the Er:YAG laser is safe for the removal of composite resin restorations, despite the fact that it required a longer time for the procedure and presented some difficulty for the total removal of restorative material.

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Er:YAG Laser and Desensitizing Effects on Dentin and Dental Cervices

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Purpose: The aim of this clinical study is to compare the desensitizing effects on dentin and dental cervices of different desensitizing gels or liquids with the use of Er:YAG laser.

Materials and Methods: In this split-mouth-design study, 25 patients suffering from hypersensitive dental cervices or dentin were treated with DentinProtector (Vivadent, Liechtenstein) in the first quadrant, in the second quadrant with Er:YAG laser [(KEY III, KaVo, Biberach) at 80 mJ and 3 Hz, Handpiece 2060 with water irrigation, defocused, 2 min per tooth)], in the third quadrant with Duraphat, and the fourth quadrant served as an untreated control group.

Results: Compared to the control group, all three treatment methods showed reduction of discomfort after 6 months.

Conclusion: Desensitizing with Er:YAG laser was effective. In comparison to the use of Duraphat and DentinProtector, the good results persisted longer. It seems that the Er:YAG laser is a suitable tool for treatment of dentin hypersensitivity.

Keywords: Er:YAG laser, hypersensitivity, DentinProtector, Duraphat, desentizising effects, maintenance.

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The aim of this clinical study was to compare the desensitizing effects on dentin and dental cervices of DentinProtector, Duraphat, and Er:YAG laser.

Dentin hypersensitivity presents as an emergency condition requiring that the clinician have an effective means of providing immediate relief at his or her disposal.[1]

In private dental offices, dentin hypersensitivity has for years been a common cause of discomfort in patients. In an average of 10% of patients, dentin hypersensitivity is a severe problem, and also involves moderate cervical pain.[2,3] The reasons for dentin exposure are gingival recession following periodontal disease or periodontal therapy, trauma from tooth brushing,[4] and dietary acids.[5]

Dentine hypersensitivity is a common, painful condition about which relatively little is known. A review of the literature reveals that most research has been concerned with the clinical assessment of therapeutic agents,[6] but a successful reduction of hypersensitivity over long periods has not been reported at all. Furthermore, little is know about the etiology of dentin hypersensitivity.[7]

The most common therapy of hypersensitive dentin is the use of fluoride solutions,[8] and iontophoresis with fluorid paste.[9,10] Of the various in-office treatments,

Table 1 Pain Scale

Degree	Description
1	No discomfort during application of the stimulus
2	Slight discomfort during application of the stimulus
3	Mild discomfort or pain during application of the stimulus
4	Severe discomfort or pain during and continuing for longer than 5 s after application of the stimulus

Duraphat was the most cited choice of varnish/primer options.[11]

Since beginning of the 90s, the use of laser systems has shown good results. In the literature, two different laser methods for treating hypersensitivity are desribed: one, the indirect method is laser combined with stannous fluoride application, and two, the direct application of laser irradiation.[12,13]

There are a number of studies using Nd:YAG laser,[14,15] CO_2 laser,[16] GaAlAs laser,[17-19] and Er:YAG laser[20] to treat hypersensitivity. Few of them were able to show positive long-term results.

MATERIALS AND METHODS

Twenty-five patients (11 females and 14 males, aged between 18 and 46 years, mean age 32 years) participated, bearing a total of 172 contralateral pairs of hypersensitive and caries-free teeth. There were no carious lesions on neighboring or selected teeth, no desentizising therapy during the last 9 months, and no cervical fillings.

Study design

According to the split-mouth design, teeth in the first quadrant were treated with DentinProtector (DP) (Ivoclar-Vivadent; Schaan, Liechtenstein), in the second quadrant with Er:YAG laser (KEY III, KaVo; Biberach, Germany; 80 mJ, 3 Hz, handpiece 2060 with water irrigation, defocused mode, 2 min per tooth), in the third quadrant with Duraphat 5% sodium fluoride varnish (Colgate-Palmolive; Hamburg, Germany), and the fourth quadrant served as an untreated control group.

All patients were members of the oral hygiene program and received the last professional tooth cleaning 4 weeks before treatment. Immediately prior to treatment, the teeth were cleaned by dental floss and polishing.

A 3-s cool air blast (18-20°C) from a distance of 2 mm was the qualitative stimulation on the site to be tested. The other test sites received an application of DentinProtector or Duraphat according to the respective manufacturer's instructions.

The neighboring teeth were shielded by casting material (Panasil, Kettenbach; Eschenburg, Germany.).

The assessment of hypersensitivity was done according to a pain scale of four degrees (Table 1).

Hypersensitivity was recorded before treatment (baseline; Table 2) , immediately after treatment (Table 3), 1 week (Table 4), 1 month (Table 5), 2 months (Table 6) and 6 months (Table 7) after treatment by a blinded examiner.

Differences in the mean pain scores between the baseline and the 6-month recording were used to determine the reduction in dentin hypersensitivity.

RESULTS

No complications were observed. All treatment forms resulted in reduced discomfort immediately and after one week.

After one month, hypersensitivity examinations showed that the DP group increased up to 56%, the Duraphat group increased up to 57%, and the laser group increased up to 42% of the baseline score (Table 5).

After two months, the hypersensitivity examination showed the DP group had increased up to 64%, the

Table 2 Pretreatment values

Patient	Er:YAG 1st quadrant	Dentin-protector 2nd quadrant	Duraphat 3rd quadrant	Control 4th quadrant
1	4	4	3	4
2	4	4	3	4
3	4	4	4	4
4	4	4	4	4
5	3	4	4	4
6	3	4	4	4
7	3	3	4	3
8	4	3	3	4
9	3	3	4	3
10	4	4	3	4
11	3	4	4	3
12	3	4	3	3
13	3	3	3	3
14	3	3	3	3
15	3	4	4	3
16	3	3	4	4
17	3	4	4	4
18	4	3	4	4
19	4	4	3	3
20	4	3	4	4
21	4	4	4	3
22	4	3	4	4
23	4	4	3	3
24	3	4	4	4
25	4	3	3	4
Results	3.52	3.6	3.6	3.6

Table 3 Results directly after treatment

Patient	Er:YAG 1st quadrant	Dentin-protector 2nd quadrant	Duraphat 3rd quadrant	Control 4th quadrant
1	1	1	1	4
2	1	1	1	4
3	1	1	1	4
4	1	1	1	4
5	2	1	1	4
6	2	2	1	4
7	2	2	1	4
8	1	2	1	4
9	1	1	2	4
10	1	1	2	4
11	2	1	2	3
12	1	2	2	3
13	2	2	2	3
14	1	2	1	3
15	2	2	2	3
16	2	2	2	3
17	1	3	2	3
18	1	2	1	4
19	1	2	2	3
20	1	2	3	4
21	2	2	2	3
22	1	1	2	4
23	1	1	2	3
24	2	1	2	4
25	1	2	2	3
Results	1.36	1.6	1.64	3.56

Duraphat group up to 68%, and the laser group stayed nearly unchanged at 42% of the baseline score (Table 6).

After six months, the hypersensitivity in the DP group increased up to 102%, the Duraphat group increased up to 103%, and the laser group slightly increased up to 55% of the baseline score (Table 7).

The control group showed no decrease in hypersensitivity at any examination over the 6-month observation period.

Compared to the control group, all three treatment methods reduced discomfort at each examination interval over the 6-month observation period (Table 8).

The decrease of the positive effect with Er:YAG laser was observed after 6 months, whereas the decrease of the positive effect of DentinProtector and Duraphat occurred after 2 months.

CONCLUSION

Desensitizing with Er:YAG laser was effective. In comparison to the use of Duraphat and DentinProtector, the reduced hypersensitivity persisted longer.

After 6 months, there was a slight increase in discomfort in the Er:YAG laser group as well. It seems that the Er:YAG laser is a suitable tool for treatment of dentin hypersensitivity.

SCIENCE

Table 4 Results 1 week after therapy

Patient	Er:YAG 1st quadrant	Dentin-protector 2nd quadrant	Duraphat 3rd quadrant	control 4th quadrant
1	1	2	2	4
2	1	2	2	4
3	1	2	2	4
4	1	2	2	4
5	1	2	2	4
6	1	2	2	4
7	1	1	2	3
8	2	1	2	3
9	2	1	3	3
10	2	3	3	4
11	2	2	2	3
12	2	2	2	4
13	2	2	2	3
14	2	2	2	4
15	1	3	2	4
16	1	3	2	4
17	1	3	2	3
18	2	3	3	3
19	2	2	2	3
20	2	2	2	3
21	2	2	2	3
22	1	2	3	4
23	1	1	2	3
24	1	1	3	4
25	2	1	1	3
Result	1.48	1.96	2.16	3.52

Table 5 Results 1 month after therapy

Patient	Er:YAG 1st quadrant	Dentin-protector 2nd quadrant	Duraphat 3rd quadrant	Control 4th quadrant
1	1	2	2	3
2	2	2	3	4
3	2	1	3	4
4	1	1	2	4
5	2	1	2	4
6	1	1	2	3
7	2	2	2	3
8	2	3	2	3
9	1	2	2	3
10	1	3	2	4
11	1	2	3	3
12	1	2	3	4
13	1	2	3	3
14	1	3	2	3
15	1	3	2	4
16	2	3	2	4
17	2	1	1	4
18	2	2	1	3
19	2	2	1	3
20	1	1	1	3
21	2	2	3	3
22	2	3	3	3
23	2	2	1	3
24	2	3	2	3
25	1	2	2	3
Result	1.52	2.04	2.08	3.36

Further studies are needed over a longer time period to evaluate the long-term stability of the positive results.

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Table 6 Results 2 months after therapy

Patient	Er:YAG 1st quadrant	Dentin-protector 2nd quadrant	Duraphat 3rd quadrant	Control 4th quadrant
1	1	2	2	3
2	1	2	1	3
3	1	2	2	3
4	1	2	2	3
5	2	2	3	3
6	2	3	2	3
7	2	2	3	3
8	3	3	2	4
9	2	2	3	4
10	3	3	2	4
11	2	2	3	3
12	2	3	2	4
13	1	2	3	3
14	1	3	2	4
15	1	2	3	3
16	2	3	3	4
17	1	2	3	4
18	1	2	3	3
19	1	3	3	4
20	2	3	3	3
21	1	2	2	4
22	1	2	2	4
23	2	2	3	4
24	1	2	3	4
25	1	2	2	4
Result	1.52	2.32	2.48	3.52

Table 7 Results 6 months after therapy

Patient	Er:YAG 1st quadrant quadrant	Dentin-protector 2nd quadrant	Duraphat 3rd quadrant	Control 4th quadrant
1	3	2	4	4
2	3	4	4	3
3	2	4	4	3
4	2	3	4	3
5	2	4	3	4
6	2	3	4	3
7	2	4	4	4
8	2	4	3	3
9	2	4	4	3
10	2	4	3	3
11	2	4		4
12	3	3	3	4
13	3	3	4	4
14	3	4	4	4
15	1	4	4	4
16	1	4	4	4
17	1	3	4	4
18	1	3	4	4
19	1	4	4	4
20	1	4	4	4
21	2	4	3	4
22	2	4	4	4
23	2	4	3	4
24	2	4	3	4
25	2	4	4	3
Result	1.96	3.68	3.70833333	3.68

Table 8 Summary of results

	before	immediately after	1 week	1 month	2 months	6 months	differences
Er:YAG Laser	3.52	1.36	1.48	1.52	1.52	1.96	1.56
Dentin Protector	3.6	1.6	1.96	2.04	2.32	3.68	-0.08
Duraphat	3.6	1.64	2.16	2.08	2.48	3.71	-0.11
Control	3.6	3.56	3.52	3.36	3.52	3.68	-0.08

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ORIGINAL ARTICLE

Shear bond strength of composite bonded to erbium:yttrium-aluminum-garnet laser-prepared dentin

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Abstract The purpose of this study was to evaluate the dentin bond strength to resin composite following erbium: yttrium-aluminum-garnet (Er:YAG) laser preparation using different adhesive systems. Seventy dentin specimens prepared from human molar teeth were randomly assigned to seven groups of ten. The first five groups were prepared with an Er:YAG laser 2940 nm at the manufacturer's recommended settings and (1) acid etched, and etch-and-rinse adhesive Excite was applied; (2) Excite was applied; (3) two-step self-etching adhesive AdheSE was applied; (4) laser etched (120 mJ/10 Hz), and Excite was applied; (5) laser etched, and AdheSE was applied. The last two groups were added as controls (prepared with a diamond bur): (6) acid etched, and Excite was applied; (7) AdheSE was applied. Nanohybrid composite cylinders 4 mm×2 mm were bonded to the dentin surfaces. After the specimens had been stored in distilled water and had undergone thermocycling, the shear bond strength was tested and the data were analyzed statistically. The Duncan multiple comparison test showed that specimens prepared with a diamond bur and with acid and Excite applied showed the highest mean bond strength (13.01±2.09 MPa), followed by those prepared with Er:YAG and with AdheSE applied (11.5±3.59 MPa) and those prepared with a diamond bur and with AdheSE applied (10.75±1.95 MPa), but there were no significant differences among them ($P>0.05$). Er:YAG-prepared specimens, with acid, Excite (3.28±0.95 MPa) and specimens that were laser etched and with AdheSE applied (3.37± 0.63 MPa) showed the lowest mean values for bond strength ($P<0.05$). The results suggested that dentin surfaces prepared with Er:YAG laser may provide comparable composite resin bond strengths depending on the adhesives used.

Keywords Shear bond strength · Er:YAG laser · Dentin · Adhesive · Nanohybrid composite

Introduction

The treatment of dental tissues prior to adhesive restorative procedures is an extremely important step in the bonding protocol and accounts for the clinical success of restorations [1, 2]. Although all adhesive materials and procedures were originally developed to act on tooth substrate prepared by conventional techniques, new investigations search for alternative techniques that could produce better effects than acids produce. Among the innovations for substrate treatment, the role of the erbium:yttrium-aluminum-garnet (Er:YAG) laser has been highlighted [3].

The Er:YAG laser is one of the most recommended types of lasers to be used on dental hard tissues, because its wavelength (2.94 μm) coincides with the main absorption band of water (3.0 μm), and it is also well absorbed in hydroxyapatite [4]. The Er:YAG laser acts on dental substrate by thermo-mechanical ablation, vaporizing its water content, which causes expansion, followed by micro-explosions that produce the ejection of both organic and inorganic tissue particles, providing a surface with open dentinal tubules and no smear layer. The Er:YAG laser can

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effectively remove dental hard tissue, due to its high absorbability in both water and hydroxyapatite [4–6]. Upon laser irradiation, water within the mineral substrate is vaporized, giving volume expansion and disruption. Owing to this thermo-mechanical process, dental hard tissue is ablated, with minimal thermal damage to the surrounding tissues. Therefore, the Er:YAG laser is considered to be the device of choice for the preparation of dental hard tissue and alteration of the tooth surface [4, 6, 7].

The strength of the bond to Er:YAG-lased tooth substrate reported in the literature is often confusing and even contradictory [8–12]. Some studies report higher strengths of bonds to laser-conditioned dentin than to acid-etched dentin [13]. Others report significantly lower bond strengths, whereas, also, no significant differences were found [10, 14]. Nevertheless, the literature available on the Er:YAG laser presents varying parameters and results. Our study aimed to determine dentin shear bond strength to a nanohybrid resin composite following Er:YAG laser preparation with an etch-and-rinse and two-step self-etch adhesive system.

Materials and methods

Table 1 shows the materials used in this study. Seventy extracted, caries-free, unrestored, human molars were used. Any remaining soft tissues were thoroughly hand-scaled and cleaned from the tooth surfaces and disinfected in 0.5% chloramine solution and placed in distilled water for up to 1 month at −20°C. The teeth were rinsed in running distilled water for 30 min and then embedded in auto-polymerizing acrylic resin (Simplex Rapid, Kemdent, Associated Dental Products Ltd, Wiltshire, UK), with the buccal surfaces positioned for surface treatment and composite bonding. After polymerization of the embedding resin, the buccal surfaces were abraded and then sequentially polished in a polishing machine (Mecapol P230, Presi Tavernoles 38, Brieet Angonnes, France) using 400 grit and 600 grit silicon carbide paper until a uniform layer of peripheral dentin was observed. After the dentin surfaces had been controlled for the absence of enamel and/or pulp tissue with a stereo-microscope (Nikon SE, Tokyo, Japan), they were randomly divided into seven groups. The first five groups were prepared with an Er:YAG laser (Fidelis, Fotona Medical Lasers, Ljubljana, Slovenia), and last two groups were prepared with a high-speed diamond bur and served as control groups:

Group 1 The dentin surfaces were irradiated with an Er:YAG laser with 2.94 μm wavelength and a contact tip with a repetition rate of 20 Hz/200 mJ and pulse duration of 100 μs, under water spray. The laser beam spot size was 0.6 mm and was moved in a sweeping fashion by hand over an area 4 mm in diameter. The specimens were then chemically etched with 37% phosphoric acid (Vivadent, Ivoclar, Schaan, Liechtenstein) for 15 s and rinsed with distilled water for 15 s. To prevent desiccation of the treated surfaces, the excess water was carefully removed with a damp cotton pellet instead of being dried with com-

Table 1 Materials used in the study

Brand name	Manufacturer	Material type	Composition	Application procedures	Batch number
Excite	Ivoclar, Vivadent, Schaan, Liechtenstein	Etch-and-rinse adhesive system	HEMA (hydroxymethyl methacrylate), dimethacrylates, phosphonic acid, acrylate, silicon dioxide, ethanol photo-initiators	Apply 1 coat, gently agitate for 10 s, thoroughly air dry, light cure for 20 s.	J01968
AdheSE	Ivoclar, Vivadent Schaan, Liechtenstein	Self-etching adhesive system	Primer: phosphonic acid, acrylate, bis-acrylamide, water, initiators, stabilizers	Apply primer and when thoroughly coated, brush for 15 s. Disperse excess amounts with a strong stream of air	H36141
			Adhesive: dimethacrylate, hydroxyethyl methacrylate, highly dispersed silicon dioxide, initiators, stabilizers	Apply bond, disperse with a very weak stream of air, light cure for 10 s	H34680
TetricEvo Ceram	Ivoclar, Vivadent Schaan, Liechtenstein	Nanohybrid composite resin	Dimethacrylates, barium glass filler, ytterbium tri-fluoride, mixed oxides, prepolymers, additives, stabilizers, catalysts, pigments	Light cure for 40 s	H24275

pressed air. Excite, an etch-and-rinse dentin bonding agent, was used as adhesive, according to the manufacturer's instructions.

Group 2 Dentin specimens were treated with Er:YAG laser as in group 1, and Excite was applied in the same manner but without acid etching

Group 3 Dentin specimens were irradiated with Er:YAG laser, and AdheSE, a two-step self-etching adhesive, was used as bonding agent, according to the manufacturer's instructions.

Group 4 Dentin specimens were irradiated with Er:YAG laser and conditioned by Er:YAG laser with a contact tip, a repetition rate of 10 Hz/120 mJ and pulse duration 100 μs. Excite was applied as above.

Group 5 Dentin specimens were irradiated with Er:YAG laser, laser etched as in group 4, and AdheSE was applied as before.

Group 6 Dentin specimens in this group were prepared with high-speed diamond bur (Standard 837 R, Diatech, Switzerland) at approximately 200,000 r.p.m. with air/water coolant. The specimens were acid etched, and Excite was applied as in group 1.

Group 7 Dentin specimens were prepared with high-speed diamond bur as in group 6, and AdheSE was applied as mentioned above.

Following the respective pretreatment sequences, a Teflon tube with an inner diameter of 4 mm and a height of 2 mm was attached to the prepared dentin surfaces. A nanohybrid composite resin (TetricEvo Ceram, Vivadent) was applied and polymerized for 40 s (Elipar Free Light, 3M Espe, St Paul, MN ,USA). After curing had been completed, the Teflon tube surrounding the composite was carefully removed. The specimens were stored in distilled water at 37°C for 24 h and thermocycled for 500 cycles between 5°C and 55°C, with a dwell time of 30 s each. The specimens were then tested in shear mode with a knife-edge testing apparatus in a universal testing machine (LR50K, Lloyd Instruments Ltd., Fareham, Hants, UK) at a crosshead speed of 1 mm/min. Shear bond strength was calculated as the ratio of fracture load and bonding area expressed in megapascals (MPa). Data were subjected to analysis of variance (ANOVA) and Duncan multiple comparison tests.

Results

Table 2 and Fig. 1 show the means and standard deviations of shear bond strength for the tested treatment groups. Averages and standard deviations were calculated, and the data were submitted to ANOVA. As the results showed differences among the measurements, they were subjected to the Duncan multiple comparison test. Dentin specimens that had been prepared with a diamond bur, were acid etched and had had Excite applied, showed the highest mean bond strength (13.01±2.09 MPa), followed by Er:YAG-prepared specimens (using the power setting of 20 Hz/200 mJ) and with AdheSE applied (11.5±3.59 MPa), and diamond bur-prepared specimens with AdheSE applied (10.75±1.95 MPa), but there were no differences among them ($P>0.05$). The specimens prepared with Er:YAG (20 Hz/200 mJ), acid etched and with Excite applied (3.28±0.95 MPa), and the specimens prepared with Er:YAG (20 Hz/200 mJ), laser etched (10 Hz/120 mJ) and with AdheSE applied (3.37±0.63 MPa), showed the lowest mean bond strengths ($P<0.05$).

Table 2 Shear bond strengths (in megapascals) of resin composite bonded to dentin. There are no significant differences in groups with the *same superscript letter*

Groups	Number	Mean	Standard deviation	Minimum	Maximum
1^a	10	3.28	0.95	2.10	5.30
2^b	10	7.31	2.13	4.30	10.10
3^c	10	11.5	3.59	7.40	18.30
4^b	10	5.75	0.95	4.60	7.40
5^a	10	3.37	0.63	2.50	4.30
6^c	10	13.01	2.09	10.35	17.43
7^c	10	10.75	1.95	7.64	13.93

Discussion

Our study compared the in vitro shear bond strength of a nanohybrid composite resin to human dentin that was prepared with an Er:YAG laser and treated with two different adhesive systems (a conventional etch-and-rinse method that required prior conditioning with phosphoric acid, and self-etching). For comparison with the laser system, dentin surfaces prepared with a regular grid diamond bur commonly used clinically to prepare cavities for adhesives were also added to the study. The extracted teeth were stored in distilled water at −20°C, the preferred method for testing the bond strength of resin composites to dentin, as suggested by Titley and others [15]. Dentin adhesives tend to function well in bond strength tests when tested shortly after application [16, 17]. Clinically, the oral environment represents a challenge to durability of bond strength because of temperature changes, masticatory load cycling, water sorption and pH fluctuations. Although thermal cycling represents only one of these challenges, the specimens were subjected to thermal cycling and shear bond strength tests within 2 days.

It is known that the hydrophobic nature of restorative composite renders bonding to hard dental tissues difficult.

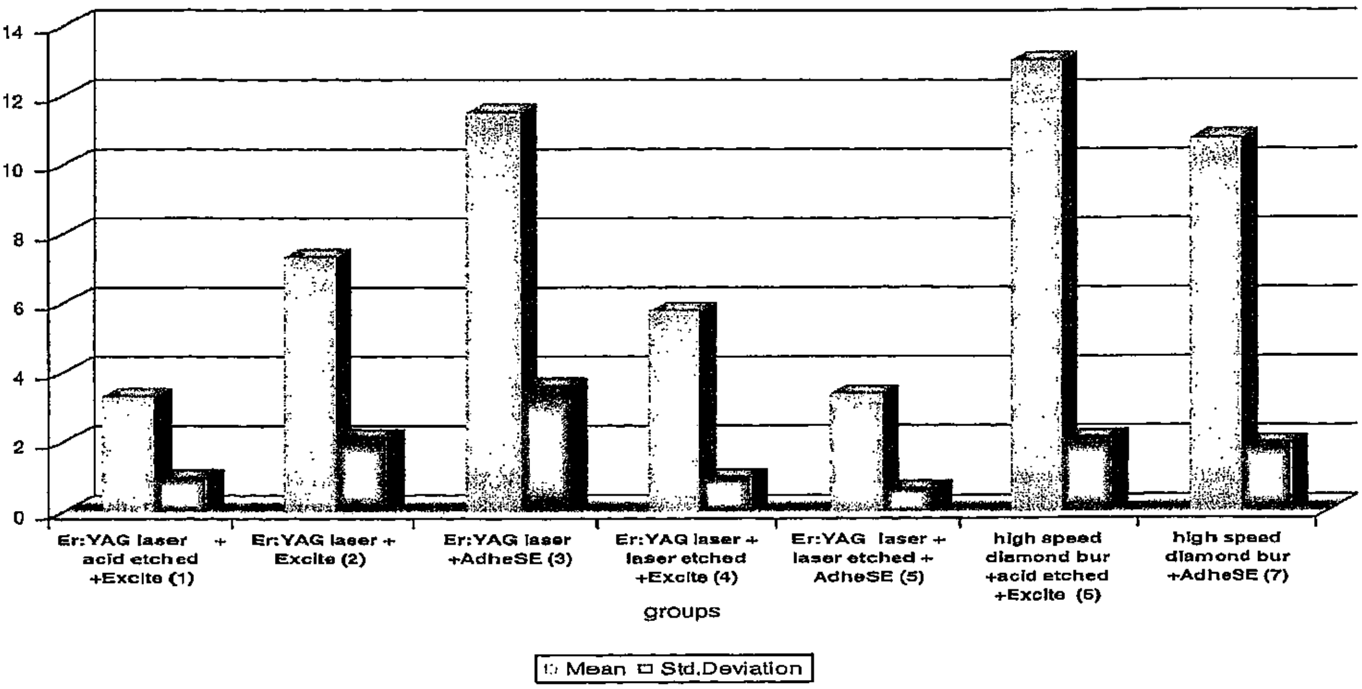

Fig. 1 Shear bond strengths (in megapascals) of resin composite bonded to dentin

Therefore, for bonding of these resins to be achieved, it is necessary for one to alter the topography of the tooth surface and use hydrophilic resins [1, 2, 9]. In this study, we modified the surface morphology by cutting the tooth surface with an Er:YAG laser or a bur and conditioning the surface with phosphoric acid or with self-etching primer and with laser in order to alter the chemistry of the dentin surfaces, so that they were able to bond with the composite.

Preparation of dentin with rotary instruments leaves a smear layer on the surface. The smear layer consists mainly of pulverized enamel and dentin and caries debris and bacteria, which are created by the bur. The low surface energy of this layer hinders impregnation of the enamel and dentin with the adhesive agent and, thus, prevents adequate adhesion [18]. The standard approach to this problem has been acid etching, first proposed by Buonocore [18] and later applied to dentin by Fusayama [19].

On the other hand, it was postulated that the lased dentin surface possessed an advantage because of an apparent enlarged surface area for adhesion, based on the scaly and flaky surface appearance following laser irradiation [20]. This is caused by the micro-explosions during the laser procedure, due to its thermo-mechanical ablation [21]. The erbium laser initially vaporizes water and other hydrated organic components of the tissue. On vaporization, internal pressure increases in the tissue until explosive destruction of inorganic substance occurs. Since intertubular dentin contains more water and has a lower mineral content than peritubular dentin, it is selectively ablated more than the peritubular dentin, leaving protruding dentinal tubules with a cuff-like appearance [21, 22]. This may also contribute to an increase in the adhesive area. Patent tubules and the absence of smear layer are additional factors that may enhance bonding to laser-treated dentin. Adhesion to laser-treated dentin could be explained by the mechanical retention provided by resin tag formation and the infiltration of adhesive resin into the micro-irregularities in laser-demineralized dentin.

In this study, although there were no significant differences among them, the highest bond strength was achieved by diamond bur preparation, acid-etching and application of Excite, followed by Er:YAG preparation and application of AdheSE and by diamond bur preparation and application of AdheSE. Excite is a two-step, etch-and-rinse system, where the primer and adhesive resin are combined into one solution. Generally, an etch-and-rinse procedure involves the use of phosphoric acid. The main objectives of acid conditioning are to remove the smear layer (and smear plugs) and render enamel and dentin surfaces more receptive to bonding. With the introduction of self-etching adhesives, the use of separate acid etching step was eliminated. AdheSE is a two-step, self-etching, adhesive system that uses an etching–priming solution followed by a separate adhesive. Self-etching priming-adhesive systems dissolve the smear layer and partially demineralize the underlying dentin surface. The dissolved smear layer is incorporated into the bonding process. We used the adhesive systems with the manufacturer's composite (TetricEvo

Ceram) to avoid incompatibilities with the bonding agent. Special attention was given to correct application procedures, in particular to the application of both adhesives to tooth substrates that were prepared in both ways.

Many researchers have suggested the use of different types of lasers as an alternative to dentin conditioning [7, 23–25], and several reports have compared bond strengths of erbium lasers. In general, there is variability among the dentin bond strength values reported by various studies [26, 27]. This may be attributed to different testing methods and conditions, the varying nature of dentin as a substrate, the composite–adhesive used, and also to laser energy parameters. Er:YAG laser irradiation promotes structural and morphological changes in dental hard tissues that depend on fluence, repetition rate, beam spot size and water presence [3, 7].

With regard to the settings of the Er:YAG laser, the technique utilized in this study was first to irradiate the dentin surfaces at the setting of 200 mJ/20 Hz. As the preparation was completed, the surface for bonding was then prepared with a setting of 120 mJ/10 Hz for better efficiency, the minimal number of induced changes, and favorable surface characteristics.

There are serious doubts about which energy density is the most appropriate to obtain a suitable micro-retentive pattern for adhesion procedures. Some clinicians have preferred to prepare the bonding surface by utilizing lower energy settings. de Sousa et al. [28] used the setting 80 mJ/2 Hz, whereas Eguro et al. [29] used 100 mJ/4 Hz, and De Munck et al. [30] used 80 mJ/10 Hz.

Visuri et al. [13] compared the bonding of composite resin to dentin following the preparation of the dentinal surface with either an Er:YAG laser with 350 mJ/6 Hz or a standard dental bur and with or without a subsequent acid-etching treatment (10% phosphoric acid applied for 30 s) and reported a significantly higher shear bond strength of composite to dentin prepared with an Er:YAG laser. In contrast, Dunn et al. [12] (using energy of 140 mJ/30 Hz) and Ceballos et al. [11] (180 mJ/2 Hz) reported a decrease in bond strength to laser-irradiated dentin.

Bertrand et al. [8] showed that the values of shear bond strength of bur-prepared dentin surfaces with acid applied; with Er:YAG laser applied (500 mJ/10 Hz) or Er:YAG laser and acid applied, did not differ significantly, whereas Trajtenberg et al. [9] (160 mJ/10 Hz) reported highest bond strengths when the tooth surfaces were acid- etched after preparation with either the laser or bur prior to the application of the bonding agent.

Data from our study demonstrated that higher bond strengths were achieved when the dentin surfaces were prepared with a diamond bur and were acid etched prior to the application of Excite, and prepared with an Er:YAG laser prior to the application of AdheSE, and prepared with a diamond bur prior to the application of AdheSE. Bond strengths were significantly weaker when dentin surfaces were prepared with an Er:YAG laser and acid-etched prior to application of Excite and prepared with Er:YAG laser and Er:YAG laser-etched prior to application of AdheSE. Although Er:YAG laser has been flagged up as a promising technology, there is still a need for more research to determine the best adhesive protocol and appropriate parameters of Er:YAG laser for its application in restorative dentistry. With regard to the bond strength to dentin with Er:YAG laser and the constant development of adhesive materials, studies are always necessary to consolidate new concepts.

Conclusion

Within the limitation of this in vitro study, it may be concluded that:

1. The highest bond strengths were obtained when dentin specimens were prepared with a diamond bur, then etched with 37% phosphoric acid, and Excite (an etch and rinse adhesive) was used.
2. Application of acid and Excite after Er:YAG laser preparation using power settings 20 Hz/200 mJ with 100 µs pulse duration decreased the bond strengths.
3. Application of AdheSE (two-step, self-etching adhesive) after Er:YAG laser preparation showed higher bond strengths, but Er:YAG laser etching (10 Hz/ 120 mJ) after Er:YAG laser preparation showed lower bond strengths.
4. Improvements in laser technology, and the increased interest in their potential for hard tissue application, warrant further investigations of Er:YAG laser-prepared teeth and adhesion with resin-based composites.

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COMPARISON OF ER:YAG AND ER:YSGG LASER ABLATION OF DENTAL HARD TISSUES

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ABSTRACT

To compare ablation quality of Er:YAG and Er:YSGG laser the surface quality, crater shape, mass loss, and temperature development were determined using the same fibre transmission system and handpiece.
Similar crater depths for both lasers but greater diameters for the Er:YAG laser were measured. Also mass loss per pulse of the Er:YAG laser exceeds that of the Er:YSGG laser. Temperature development while ablation of dentin is more pronounced for the Er:YSGG laser. The observed minor ablation quality of the Er:YSGG laser can be explained by the lower absorption coefficient of dental hard substances compared to the Er:YAG laser.

KEY WORDS: Erbium:YAG laser, Erbium:YSGG laser, laser, dental hard substances, ablation quality

1. INTRODUCTION

The Er:YAG laser ($\lambda = 2.94\ \mu m$) has been well investigated for ablation of dental hard tissues. Ablation efficiency was evaluated by crater shape and mass loss measurements. the surface quality was observed by light and scanning electron microscopy. [1,2] Now several comercial Er:YAG laser systems for treatment of dental disease are available and many studies deal with extension of applications. So the Er:YAG laser was evaluated for removal of subgingival calculi in periodontal treatment.[3,4] Also the use of this laser for sterilisation and for soft tissue surgery was investigated.[5,6]
In the recent years a further pulsed Erbium laser, the Er:YSGG laser was proposed for treatment of dental hard tissue. Its wavelength of 2.79 μm shows also a strong absorption in water (μ_a = 7000 cm^{-1}) but about 55 % compared to the Er:YAG laser (μ_a = 13000 cm^{-1}). Only few investigations about the application of this laser in dental treatment are published. D´akonov et al. measured the resulted crater depths in dentin and enamel as a function of pulse number and radiant exposure.[7] Belikov et al. made spectral measurements in the middle infrared region of natural and desiccated human dentin and enamel.[8] The biocompatiblity of Er:YSGG laser radiated root surfaces was investigated by Benthin et al.[9]
It is quite difficult to compare these lasers on the basis of already published examinations, because not only wavelength differs but also other laser parameters like energy, pulse duration, or spatial beamprofile are not comparable.

In this study we took care to use the same laser parameters for both lasers. In order to achieve the same beam profile the same fiber transmission system and same handpiece was used. Then extracted human teeth were irradiated by Er:YAG laser and Er:YSGG laser. Then we evaluated the achievable surface quality and determined crater depth and diameter. Also we determined the ablation efficiency by mass loss measurements, and temperature development during treatment.

2. MATERIALS AND METHODS

The used Er:YAG laser system was a commercially available device with fiber delivery system (KEY 2, KaVo GmbH, pulse energy ≤ 500 mJ, repetitionrate ≤ 15 Hz). The Er:YSGG laser was an laboratory laser system with adjustable pulse duration. The laser light of both systems was coupled into the same fiber delivery system with focal handpiece for caries therapy. To get a constant temporal and spatial beam profile the pump energy was fixed and the pulse energy was varied by attenuation with glass slides at the proximal fiber end. Handpiece and sample holder were mounted on an optical bank system for good alignment of the distance between handpiece and sample surface. A glass slide was inserted to provide the handpiece window against ablation products. We changed this slide always after ten pulses to get a constant laser energy at the sample surface.

For irradiation we choosed a base pulse energy of 300 mJ, which was attenuated to lower values. Pulse repetition rate was 4 Hz, and total pulse duration was 400 μs for both lasers with more pronounced temporal spiking for the Er:YSGG laser pulse. At the sample surface we measured a cylindrical beam profile with a $1/e^2$ - diameter of 760 μm. The amount of water spray if used was 2 ml/min.

As samples we used slices of extracted human teeth stored in Formalin.

The surface quality was examined by light (Axiophot, Zeiss) and electron scanning microscopy (Phillips SEM 500). For examination by SEM samples were dried in a desiccator and sputtered. Crater depth and diameter also were measured under light microscope.

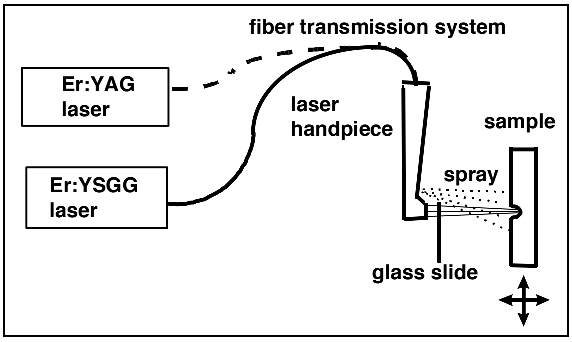
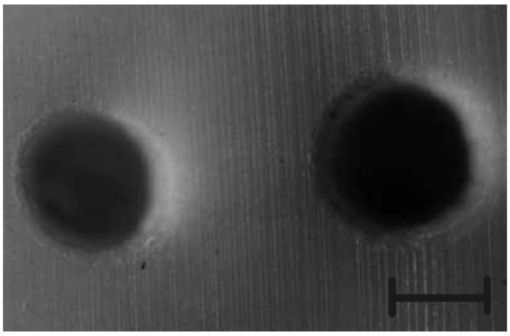


figure1: Experimental setup for comparative study of dental hard substances ablation with Er:YAG and ER:YSGG laser.

To determine the mass loss in dentin and enamel resulting from laser ablation the samples were weighted before and after laser irradiation by a precise balance (Research, Satorius). 10 craters per sample were drilled, each by 10 pulses of 300 mJ, applied with 4 Hz. No water spray was used, because the fluctuations of the samples weight caused by the water spray are to strong. For enamel, after first weighting loosely bound material was removed by a tooth brush and the samples were additionally weighted again.

For evaluation of thermal side effects temperature development was measured during perforation of 1.5 mm dentin of human tooth slices. At first 500 μm deep holes with an diameter of 400 μm were drilled into the backside of the 2 mm sample. Then a paste with good thermal conductivity was filled into the hole and a thermocouple was inserted. We made sure that the laser beam hit the thermocouple when the sample was perforated from the front side. The voltage level of the thermocouple was converted and computerized with a sample frequency of 50 Hz. Also the laser flashlamp was recorded by a photodiode. So it is possible to determine exactly the moment of perforation, when the voltage signal of thermocouple rises during or immediately after the laser pulse. As laser parameters 300 mJ and 4 Hz were used. The examination was only made in dentin, because the size of enamel is not enough for acceptable measurements. It is also difficult to measure the temperature when using water spray, because the water in the deep holes reduces the ablation rate per pulse down to zero.

a)



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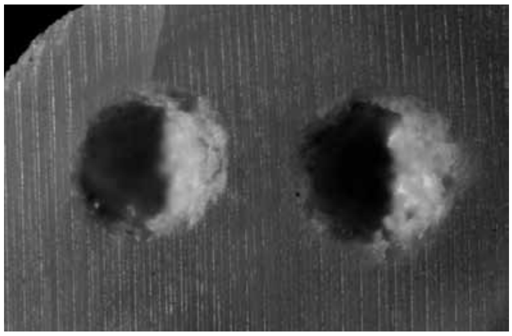
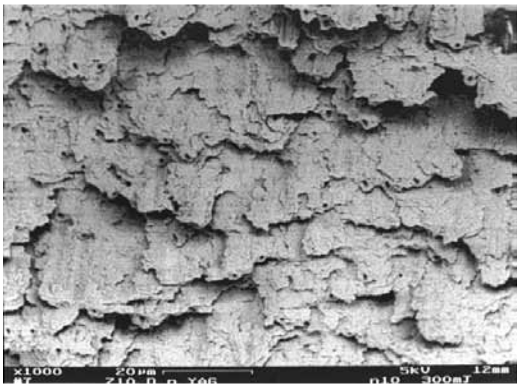


Figure 2: Optical microscope view of craters drilled in dentin (a) and in enamel (b). Left holes in the figures are drilled with Er:YSGG laser right holes with Er:YAG laser using 300 mJ, 5 Hz, 10 pulses, water spray (bar = 500 μm).

a)



b)

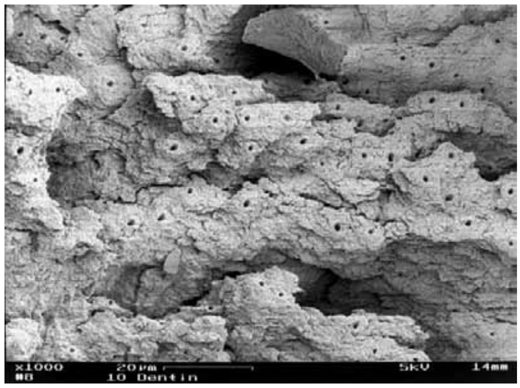
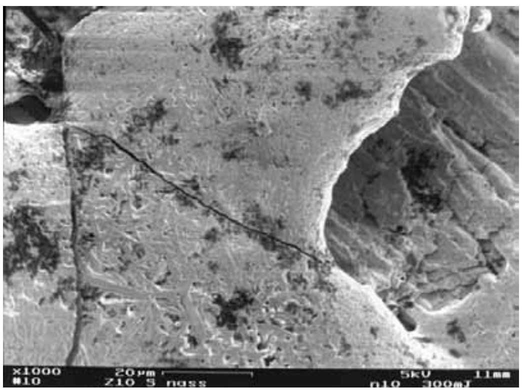


Figure 3: SEM view of crater bottom drilled with Er:YAG laser (a) and Er:YSGG laser (b) in dentin using 300 mJ, 5 Hz, 10 pulses, and water spray.

a)



b)

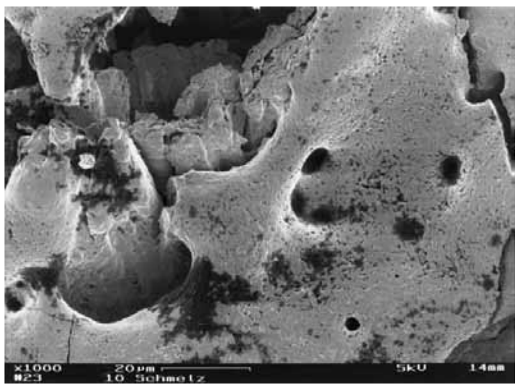


Figure 4: SEM view of crater bottom drilled with Er:YAG laser (a) and Er:YSGG laser (b) in enamel using 300 mJ, 5 Hz, 10 pulses, and water spray.

3. Results

Figure 2 shows craters drilled in dentin and enamel with 10 pulses using a pulse energy of 300 mJ and water spray. The shape and surface quality of the craters are similar for both lasers. There is no thermal damage like carbonisation or fractures discernible. Remarkable is the larger diameter of the Er:YAG laser induced hole in dentin. The same craters observed by SEM are shown in figure 3 and figure 4. The holes in dentin have a rough and flaky surface without signs of serious thermal injuries. For both lasers the dentinal tubules are open. In enamel there is a large amount of molten material in the crater bottom, also with similar appearance for both lasers. Especially using water spray we observed more material remaining in the craters produced by the Er:YSGG laser.

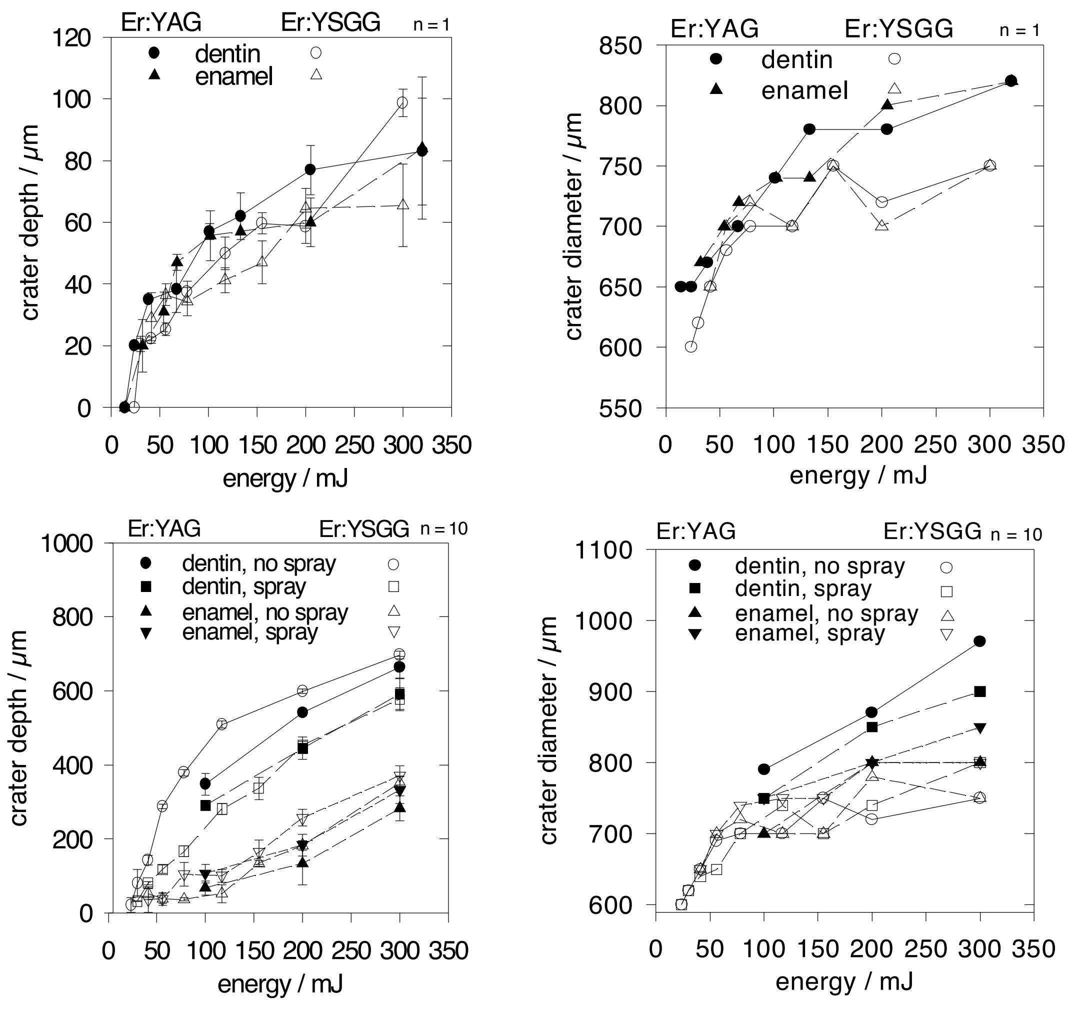


figure 5: Crater depths and diameters vs. pulse energy drilled with Er:YAG and Er:YSGG laser in dentin and enamel.

The measured crater depths and diameters are plotted over the pulse energy in figure 5. For both lasers and both in dentin and enamel the crater depth does not increase proportional to the pulse energy. For both lasers the crater depths are about the same especially when water spray is used. For single pulse irradiation the craters made by Er:YAG laser are slightly deeper, with 10 pulses irradiation and without water spray the craters of Er:YSGG laser are slightly deeper. The diameters of craters produced by the Er:YAG laser are larger for all parameters.

In Figure 6 the mean values of measured mass loss per pulse are depicted. For both lasers the mass loss in dentin is higher than in enamel. For the Er:YSGG laser mass loss per pulse in dentin is about 30% less than for the Er:YAG laser. In enamel also the Er:YSGG laser causes a slight minor mass loss. Loosely bound and still remaining material which can be removed by a tooth brush is about 25% of the ablated enamel.

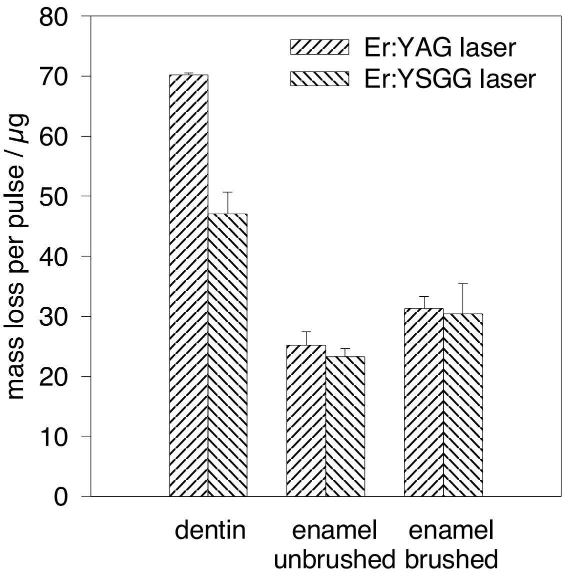


figure 6: Mass loss per pulse of Er:YAG and Er:YSGG laser in dentin and enamel at E_P=300 mJ.

For temperature measurements the mean number of necessary laser pulses for perforation of the slices are 21 for the Er:YAG laser and 33 for the Er:YSGG laser. The temperature rises with a delay time of about 4 sec after the beginning of irradiation and then increases with the number of laser pulses. Just before perforation the temperature begins to oscillate with the repetitionrate. After perforation when the probe was directly irradiated we obtained a very high and sudden temperature increase. When we shut down the laser the temperature decreases to its initial value in few seconds. The temperature increase is always more pronounced for the Er:YSGG laser. In figure 7 the mean values of obtained maximum temperature increase at perforation time are plotted. The maximum temperature increase is about 40 K for the Er:YAG laser and 65 K for the Er:YSGG laser, which means a difference of about 40%.

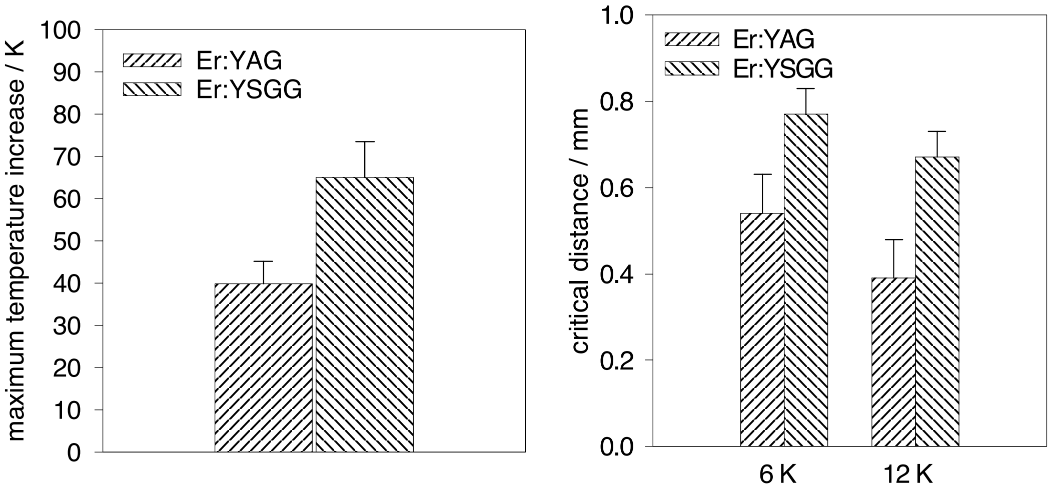


figure 7: Maximum temperature while perforating of 1.5 mm dentin slice with Er:YAG and Er:YSGG laser (300 mJ, 4 Hz, no water spray) and there from calculated critical distances not to exceed temperature increase of 6 K or 12 K.

4. Discussion

The light microscopic and SEM pictures from the holes of both laser show similar results like the pictures of Er:YAG laser holes obtained from prior investigations.[2]
To explain the results of ablation efficiency measurements one has to consider the optical data of dentin and enamel in the infrared region. Tab. 1 shows the absorption coefficients at 2.79 μm and 2.94 μm, measured from Belikov et. al. on natural and desiccated dental hard substances.[8] The absorption peak of water at 2.94 μm leads to the stronger absorption in natural dentin and enamel compared to 2.79 μm. After desiccation the absorption of dentin decreases dramatically and the difference between both lasers is less pronounced. In dry enamel the absorption at 2.79 μm is higher than at 2.94 μm caused by the stronger absorption of hydroxyapatite. For the ablation products we suppose also a stronger absorption at 2.79 μm because both the vapour and the hydroxyapatite are more absorbing at this wavelength. This difference in product absorption which was confirmed in our study, where we observed a stronger attenuation by the ablation products on the protective glass slide at 2.79 μm.

Tab. 1: Absorption coefficients of natural and desiccated (heating 600°C, 20 min) dental hard substances, normalised to the values for 2.94 μm in natural dentin and enamel (from Belikov et. al.)[8].

	Dentin		enamel	
	natural	desiccated	natural	desiccated
Er:YAG (2.94 μm)	1	0.07	1	0.77
Er:YSGG (2.79 μm)	0.68	0.055	0.96	0.96

The ablation mechanism of these lasers is a continuous process which starts when the absorbed energy per volume exceeds a certain value H_{abl}. Assuming H_{abl} is the same value for both lasers, the ablation threshold increases with decreasing absorption coefficient. So the observed larger diameter of the Er:YAG laser hole can be explained by the optical data of tab. 1. Assuming same spatial beam profile for both lasers that part of the spatial beam profile where the radiant exposure exceeds the ablation threshold is larger for the Er:YAG laser corresponding to the higher absorption coefficient. In enamel the observed difference in diameters is small, correlating to the less pronounced difference in absorption coefficient.
The crater depth d can be described by the formula:

$$d = 1 / \mu' \cdot \ln (\mu' / \mu_a * (F_0 / F_S - 1) + 1),$$ [10]

where: μ_a = absorption coefficient of the material [cm^{-1}]
μ' = attenuation coefficient of the ablated material [cm^{-1}]
F_0 = radiant exposure of the laser beam [J / cm^2]
F_S = ablation threshold [J / cm^2]

As one can see from the formula the crater depth depends not only on the absorption coefficient of material and the ablation threshold but also on the attenuation coefficient of the ejected material, which shields the incoming laser beam. So the slightly deeper holes drilled with Er:YAG laser using single pulse irradiation also correlates to the absorption and attenuation coefficients. For 10 pulses desiccation takes place, which leads to slightly deeper Er:YSGG-laser drilled holes in dentin. Using water spray desiccation can be partly prevented and the crater depths are at about the same.
The mass loss measurements for investigation of ablation efficiency show values for the Er:YAG laser similar to those obtained from prior investigations.[1] The Er:YAG laser values exceed those for the Er:YSGG laser, which can be attributed to the larger crater diameters. Using water spray we suggest the difference in mass loss between both lasers is more pronounced, because in this case we observed greater diameters and similar depths of holes.
The results for temperature increase correlates well to the obtained values of crater diameter and mass loss measurements. On the one hand the observed smaller diameters for the Er:YSSG lasers caused by the minor ablation

coefficient leads to the observed minor ablation efficiency. On the other hand the greater part of beam profile of the Er:YSGG laser where the radiant exposure does not exceed the ablation threshold leads to the observed major heating. If we suppose a proportional increase of crater depth with the number of laser pulses, the remaining distance to the thermocouple at each time can be calculated. So temperature to time courses can be converted to temperature to distance courses. From these courses the distances can be deduced where the temperature increase exceeds 6 K and 12 K. These values correspond to an in vivo temperature of 43° and 49° Celsius which are declared as the limits of reversible and irreversible pulp damages.[11] In figure 7 the mean values for minimum critical distances for reversible and irreversible pulp damages are depicted. As expected from the temperature courses the necessary distance to the pulp for safe treatment is larger using the Er:YSGG laser (about 0.75 mm) than for the Er:YAG laser (about 0.5 mm). One has to consider that these values are only true for the used laser parameters (300 mJ, 4 Hz). Especially for higher repetition rate the accumulation of temperature increase will be more pronounced. As known from other investigations with water spray the heating and therefore the critical distance is reduced.

5. Conclusions

In this study we have shown a comparable and good surface quality for both lasers. We also obtained craters with similar depths but larger diameters for the Er:YAG laser. Also mass loss per pulse of the Er:YAG laser in dentin exceeds that of the Er:YSGG laser. During perforation of dentin slices the temperature increase is more pronounced for the Er:YSGG laser.

In summary the presented results show a minor ablation quality for the Er:YSGG laser. This can be explained by the minor absorption coefficient at 2.79 μm in dental hard substances.

6. Aknowledgements

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