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Er:YAG and CTH:YAG laser radiation: contact versus non-contact enamel ablation and sonic-activated bulk composite placement

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Abstract
Laser radiation can be used for effective caries removal and cavity preparation without significant thermal effects, collateral damage of tooth structure, or patient discomfort. The aim of this study was to compare the quality of tissue after contact or non-contact Er:YAG and CTH:YAG laser radiation ablation. The second goal was to increase the sealing ability of hard dental tissues using sonic-activated bulk filling material with change in viscosity during processing. The artificial caries was prepared in intact teeth to simulate a demineralized surface and then the Er:YAG or CTH:YAG laser radiation was applied. The enamel artificial caries was gently removed by the laser radiation and sonic-activated composite fillings were inserted. A stereomicroscope and then a scanning electron microscope were used to evaluate the enamel surface. Er:YAG contact mode ablation in enamel was quick and precise; the cavity was smooth with a keyhole shaped prism and rod relief arrangement without a smear layer. The sonic-activated filling material was consistently regularly distributed; no cracks or microleakage in the enamel were observed. CTH:YAG irradiation was able to clean but not ablate the enamel surface; in contact and also in non-contact mode there was evidence of melting and fusing of the enamel.

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser radiation can be used for effective caries removal and cavity preparation without significant thermal effects, collateral damage to tooth structure, or patient discomfort. Erbium (Er)-based laser radiation can achieve effective ablation at temperatures well below the melting and vaporization temperatures of enamel [1]. This type of laser radiation (wavelength 2940 nm) can produce clean, sharp margins in enamel and dentin. In addition, pulpal safety is not a significant concern, because the depth of energy penetration is negligible. When the Er:YAG laser is used for caries removal, the patient usually does not require local anesthesia. The laser radiation is antimicrobial when used within root canals and on root surfaces, and it removes endotoxins from root surfaces. Finally, no vibration related to the Er:YAG laser radiation effect is present, and therefore treatment using this system is less severe in comparison with the conventional high-speed drill. Also, it will be less likely to cause discomfort or pain. The laser has shown potential for removing calculus during root debridement. On the downside, the Er:YAG laser does not selectively remove calculus on root surfaces [2].

Chromium–thulium–holmium:yttrium aluminum garnet (CTH:YAG) lasers emit energy in the middle infrared region of the electromagnetic spectrum (2100 nm wavelength), where water has one of its absorption peaks [3]. Compared to the erbium lasers, interactions of the CTH:YAG laser with dental hard tissues have been less extensively examined. Initial studies of enamel and dentine ablation suggested that the wavelength is promising, particularly when compared to less well absorbed wavelengths in the near infrared region [4]. In these previous studies, the laser energy was delivered without an accompanying water mist spray, and thermal side effects were a concern. When CTH:YAG laser energy interacts with the water contained within the enamel and dentin, it causes ablation due to the process described as ‘spallation’, a photodisruptive effect with fragmentation of the substrate caused by the shallow penetration depth of the laser energy into hard tissue, and due to high peak power of the CTH:YAG laser, which results in an outwardly explosive process. The laboratory study indicates that the CTH:YAG laser is suitable for ablation of dentin, and that this process should be conducted with coaxial water spray providing cooling of the tooth in order to minimize its carbonization [5].

The Er:YAG laser generates photons with the strongest absorption by water in the enamel and dentin and, when combined with a water cooling spray, it produces extremely minor zones of carbonization, debris, and necrosis after irradiation. Furthermore, the Er:YAG laser wavelength can today be delivered via a special optical fiber, a hollow waveguide delivery system and a non-contact or contact sapphire tip. The hollow waveguide delivery system and contact sapphire tip are more flexible for the doctor and result in a more precise cavity preparation than other delivery systems [6]. CTH:YAG laser energy can be delivered effectively using flexible special quartz glass optical fibers [7].

The Er:YAG laser has been used in dentistry for several years, with advantages and disadvantages as against bur preparation of enamel and dentin. The removal of both the healthy and carious dental tissue with the Er:YAG laser is slower than with conventional high-speed rotary instruments, especially when cavity preparation involves deep and large carious lesions of enamel. On the other hand, the laser systems offer several advantages over the conventional high-speed handpieces. The bur-prepared teeth are unavoidably associated with the production of a metallic sound and bone-conducted vibration that might cause patient discomfort and anxiety. Patients have shown a greater tolerance to laser treatment and usually report minimal or no pain, which is due to the lack of noise and vibration [7]. For this reason laser treatment is popular in pediatric dentistry, and now, in combination with fluorescence control or a CCD camera, caries detection can be optimal for minimally invasive preparation [8].

Many studies have concluded that adhesion to laser-ablated or laser-conditioned dentin and enamel of permanent teeth is inferior to that of conventional rotary preparation and acid etching. However, it is necessary to acid-etch both the dentin and enamel surfaces after laser conditioning, and to monitor the laser energy output to avoid substructural damage [9]. The laser-treated dentin and enamel surfaces may have different properties to bur-prepared enamel and dentin. Therefore, adhesive systems and restorative materials specifically developed for laser-treated substrates may be an important next step in the development of restorative systems. Care must be taken regarding the choice of laser energy output [10]. The microleakage of a cavity prepared by laser radiation is less that caused by mechanical bur [11].

The main aim of the study was to compare the quality of tissue after contact or non-contact laser ablation from the point of view of the optimal shape of the cavity without a smear layer. The second goal was to prove the increase of the sealing ability to hard dental tissues by using sonic-activated bulk fill material with a change in viscosity during processing to allow perfect adaptation in the cavity.

2. Materials and methods

2.1. Laser irradiation source—Er:YAG

A Key III laser system (KaVo, Biberach, Germany)—lasing medium, erbium-doped yttrium aluminum garnet ($Er:Y_3Al_5O_{12}$), emitting 2940 nm radiation with a spot diameter of 0.63 mm—was used. The output settings for contact preparation were 250 mJ/pulse, and the pulse repetition rate was 15 Hz, i.e. the average power was 3.75 W. For non-contact ablation these values were 600 mJ/pulse, 6 Hz, and 3.6 W. Irradiation was performed by the non-contact handpiece 2060 and the contact handpiece 2063 (KaVo, Biberach, Germany) (figure 1). A sapphire fiber optic with a diameter of 1.1 mm was mounted on the handpiece 2063 for ablation of enamel in the contact mode. The irradiated area was continuously cooled by a water spray system (1 ml min^{-1}).

2.2. Laser irradiation source—CTH:YAG

The second laser system was a flashlamp-pumped CTH:YAG (Cr:Tm:Ho:YAG) laser operating at the wavelength of 2100 nm. The used output pulse energy was 300 mJ, pulse repetition rate 1 Hz, and average power 0.3 W. The radiation for the non-contact mode of treatment was focused on the tooth tissue by a CaF_2 lens ($f = 100$ mm), and for contact mode the radiation was delivered by a hollow cyclic-olefin-polymer (COP) waveguide (100 mm) with a quartz cap (figure 1).

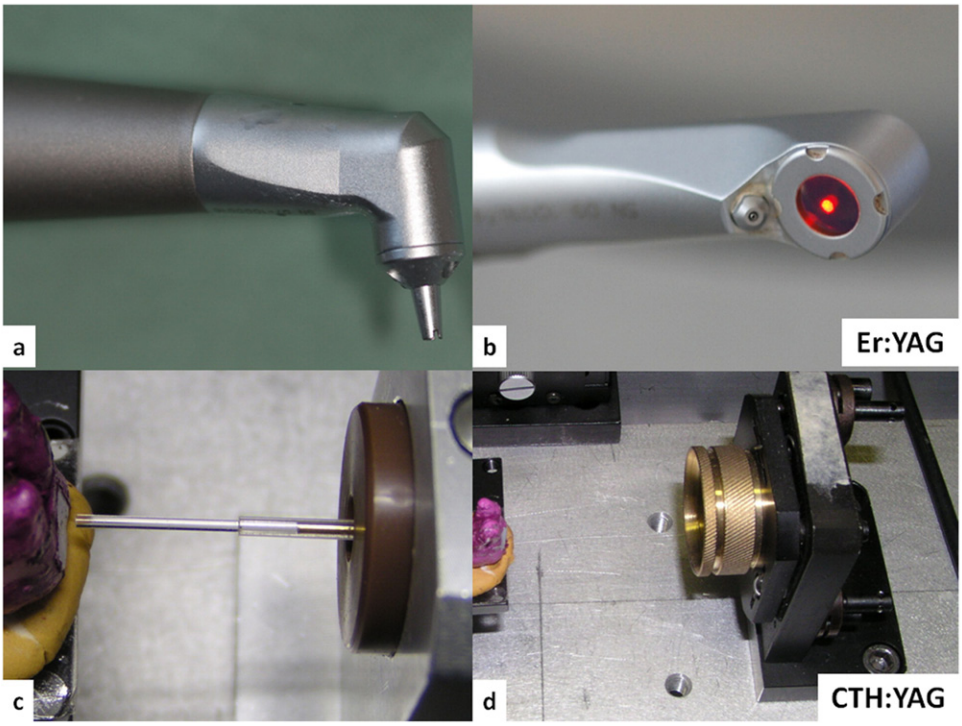

Figure 1. Contact and non-contact handpieces: (a) sapphire fiber-optic Er:YAG; (b) lens Er:YAG; (c) COP hollow waveguide (100 mm) with quartz cap; (d) CaF_2 lens.

2.3. Specimen preparation

Forty human third molars of young patients (age 15–25), extracted for orthodontic reasons, were used in the study. The teeth were stored for 48 h in chloramine dilute aqueous disinfectant solution, and then coated with acid-resistant nail varnish on the polished surface. Two comparable square windows with dimension ≈5 mm × 5 mm were left uncoated to be exposed and to form an artificial caries lesion (one for evaluation of the cavity, the other for insertion of filling material). To create the demineralization window in unprotected areas, the teeth were incubated for 48 h at 37 °C in a dematerializing solution containing lactic acid 0.1 M at pH level 4.5 [12].

2.4. Experimental procedure

The energy used in a particular laser irradiation was measured with a Molectron EPM 2000 energy/power meter with probe J25N. An oval cavity of size 6 mm × 8 mm was prepared and then rinsed with water. Etching, priming, and bonding in one material (OptiBond All-In-One, Kerr, Scafati, Italy) were applied (i.e. two consecutive coats of adhesive with disposable applicator for 20 s each; air-thin adhesive for 5 s with medium force stream of air; and light-activated adhesive for 10 s). Then the SonicFill tip (1.5 mm) was placed at the bottom of the cavity floor by using a foot pedal to activate the handpiece, and the cavity was filled with a steady, continuous stream of composite (SonicFill, Kerr, Scafati, Italy). From the occlusal surface the material was compressed to avoid gaps between the material and tooth. The margin was adapted and the excess was removed with finishing and polishing tools. Finally, the Elipar Freelight 2 (3M ESPE, St Paul, MN, USA) light cured the filling for 20 s from the occlusal surface and from the buccal and lingual aspects of the tooth for an additional 10 s each.

2.5. Analyzing methods and measuring instruments

To characterize the laser irradiation, the mean power, spectrum, time development, and spatial beam structure were measured. The following instruments were used for this purpose: Molectron energy/power meter EMP2000 with probe J25N (Molectron-Coherent, Portland, OR, USA); Oriel monochromator model 77 250 (50 mm wide slit) (Newport Corporation, Irvine, CA, USA); IR-sensitive Pyrocam III pyroelectric camera (Ophir-Spiricon, North Logan, UT, USA); and a TDS3052B Tektronix oscilloscope (500 MHz, 5 GS s^{-1}) (Tektronix, Portland, OR, USA) with an InAs/InAsSbP photodiode (model PD36-05, IBSG, spectral range 0.8–3.8 mm, rise time 150 ns) (Lambda Photometrics, Hertfordshire, UK). All teeth with laser cavities were photographed (before and after treatment) using a Nikon SMZ-2T (Osaka, Japan) stereomicroscope connected to a Mintron color video camera (MTV-73X11P-R, Mintron Enterprise, Fremont, CA, USA) and a computer; the surface of the enamel after laser ablation (one window) and the other with filling SonicFill material (second window of every tooth) were analyzed with a JSM 5510 LV scanning electron microscope (SEM; JEOL, Tokyo, Japan). Before evaluation in the SEM, the teeth were cut into two longitudinal sections, polished to have flat enamel and dentin surfaces, and stored in

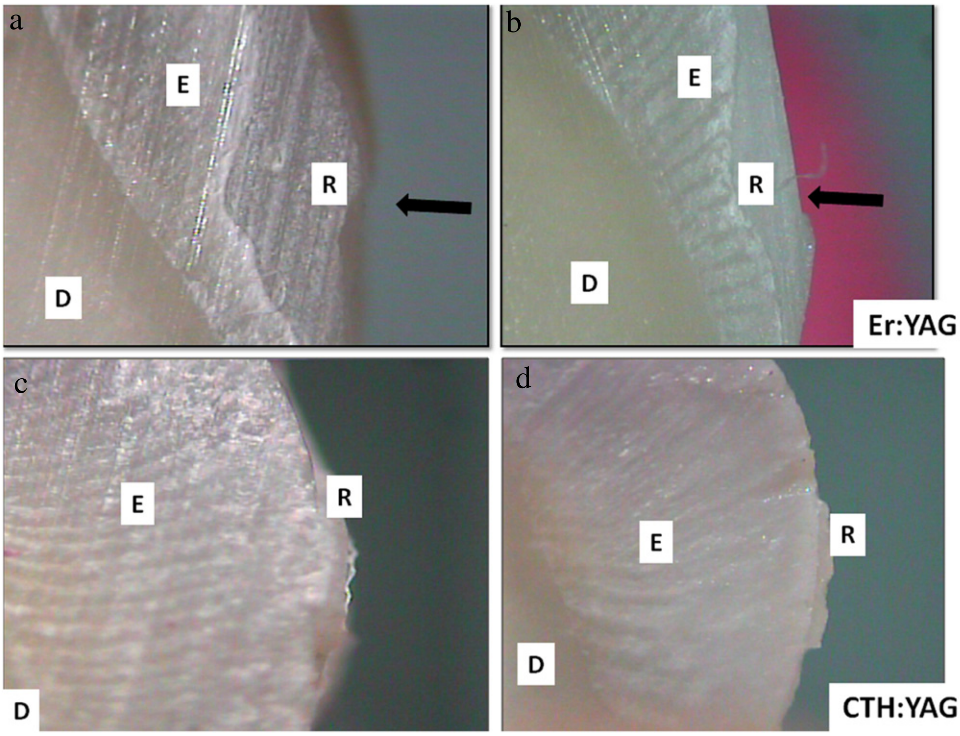

Figure 2. Photo of cavity with filling—microscopic image in longitudinal section (arrow composite filling material): (a) Er:YAG contact ablation; (b) Er:YAG non-contact ablation; (c) CTH:YAG contact ablation; (d) CTH:YAG non-contact ablation (E—enamel, D—dentin, R—resin).

a saline solution. The teeth were processed in a 'low vacuum' (10 Pa) regime without desiccation. Back-scattered electron images were recorded using this technique.

3. Results

3.1. Er:YAG ablation

The output settings for contact preparation were energy 250 mJ/pulse, pulse repetition rate 15 Hz, mean laser power 3.75 W; for non-contact ablation they were 600 mJ/pulse, 6 Hz, and 3.6 W, respectively. Contact ablation (handpiece 2063) in enamel was quick and precise (figure 2(a)); the cavity was smooth with a keyhole shaped prism and rod relief arrangement without a smear layer (figure 3(a)). The non-contact mode (handpiece 2060) ablated a less precise shape (figure 3(b)). SEM examination also showed honeycomb relief but with a revealed irregular shape with some undercuts, jagged margins, or pitting; however, no evidence of fissuring or fracturing of the surrounding enamel was seen (figure 3(b)).

3.2. CTH:YAG laser

The same delivery system (COP/Ag waveguide with inner diameter 700 μm) was used to deliver the radiation to the interaction location. The fluence used was 77 J cm^{-2}. The CTH:YAG laser displayed lower absorption in the enamel and could prepare only small cavities (figures 2(c) and (d)); in both the contact and non-contact modes there was evidence of melting and fusing of the enamel in both groups, particularly along the cavity base. No such alterations were seen on the walls in the enamel; however, closure of hydroxyapatite crystals was seen, signifying that some vitrification of the enamel had occurred (figures 3(c) and (d)).

3.3. Microscopic and SEM findings—sonic-activated bulk composite system placement

A stereo-microscopic view of the investigated interaction results together with the SEM record of the investigated tissue is seen in the following figures. Microscopically, Er:YAG cavities were deeper and also more regular in both groups (figures 2(a) and (b)). The shape of the cavity walls and base was seen to be consistent and its extent was proportional to the pulse energy, frequency, and also water absorption peak. Flat cavities for CTH:YAG radiation (figures 2(c) and (d)) were seen in longitudinal sections. In the Er:YAG ablation group, no visible charring occurred at pulse energies of 250 mJ (contact handpiece) and 600 mJ (non-contact handpiece), and the frequency was 15 or 6 Hz. For both modes a high-reliability connection with a sonic-activated bulk composite system was detected (figures 4 and 5). From comparing the filling pictures it follows that the SonicFill material was consistently and regularly distributed, and no cracks or microleakages in enamel were observed (figures 4 and 5).

CTH:YAG irradiation was able to clean but not ablate the enamel surface (table 1, figure 2). Under wet contact ablation

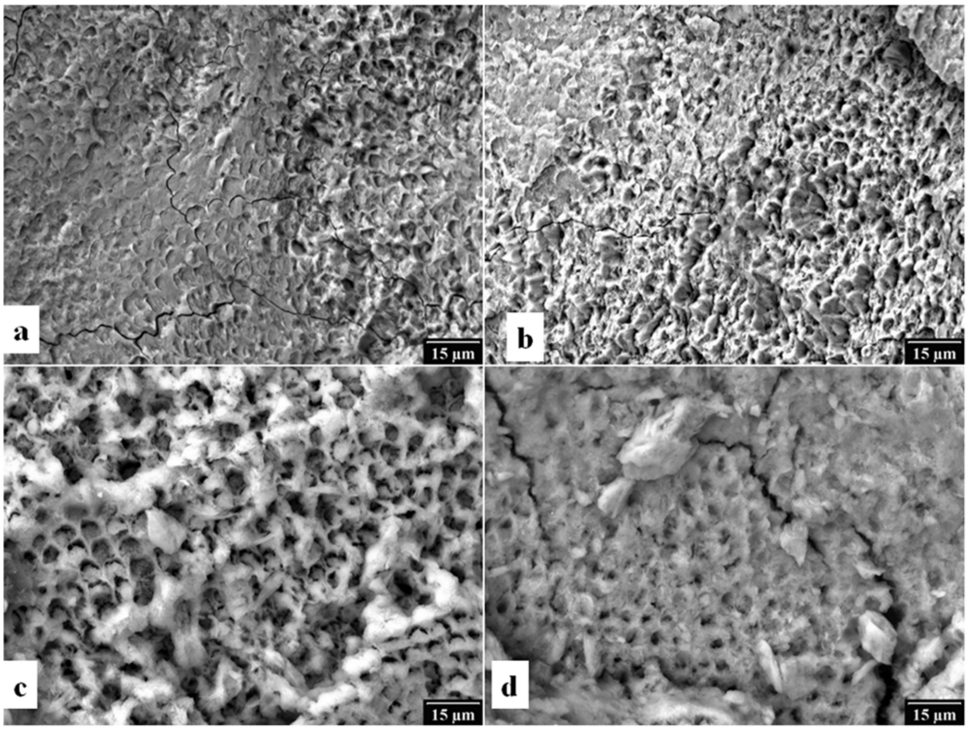

Figure 3. SEM examination of the bottom of laser ablated cavities with different results in cracking and cleanliness of the cavities: (a) Er:YAG contact ablation—keyhole shaped prism and rod relief; (b) Er:YAG non-contact ablation—irregular surface, non-precise shape; (c) CTH:YAG contact ablation—irregular shape with some undercuts, jagged margins or pitting; (d) CTH:YAG non-contact ablation—closure of hydroxyapatite crystals, some vitrification of the enamel.

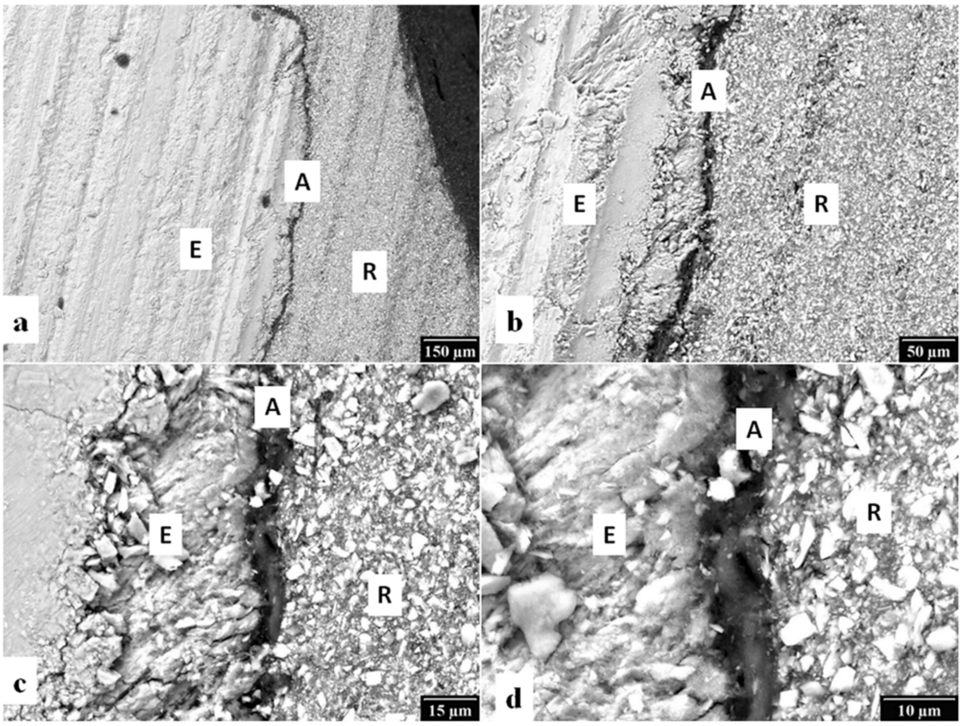

Figure 4. Er:YAG contact ablation with sonic-activated bulk composite material in the scanning electron microscope in four different magnifications—tooth longitudinal section—SonicFill material is regularly distributed; no cracks or microleakages in enamel are seen. (E—enamel, A—adhesive system, R—resin.)

conditions, only the initial surface layer of the enamel was ablated and the surface became irregular. The wet non-contact irradiation in the enamel has displayed a tendency towards a charring effect and the cavity formation was immediately reduced, which effect was not seen in sonic-activated bulk composite placement (figures 6 and 7). The seal ability of

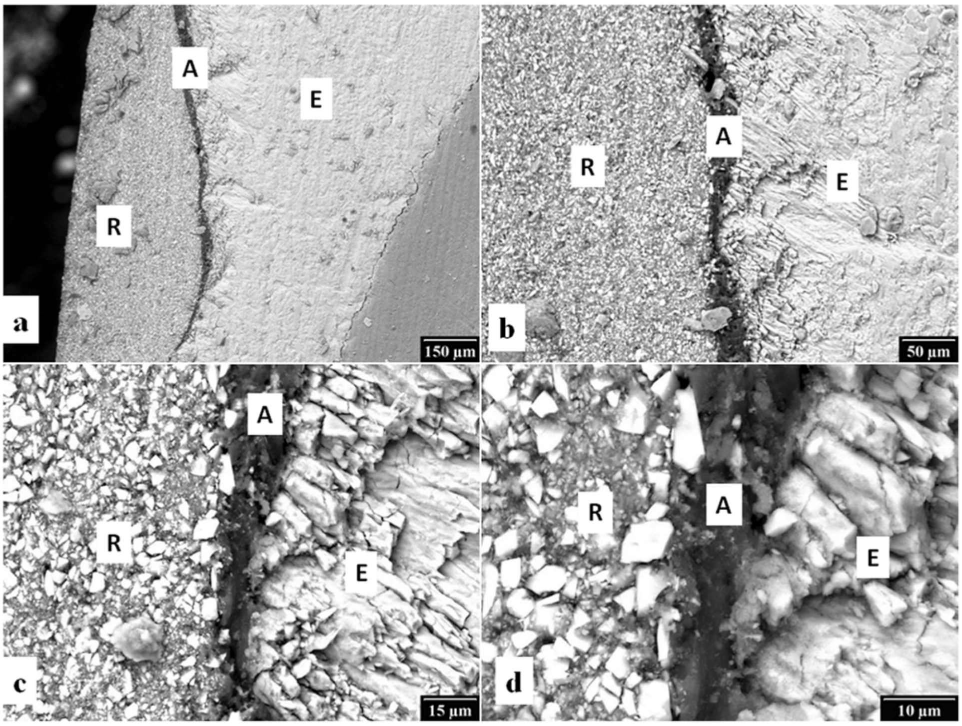

Figure 5. Er:YAG non-contact ablation with sonic-activated bulk composite material in the scanning electron microscope in four different magnifications—tooth longitudinal section—no microleakage between enamel and sonic-activated composite filling is detected. (E—enamel, A—adhesive system, R—resin.)

Table 1. Laser and interaction parameters.

Laser	Wavelength (nm)	Interaction energy per pulse (mJ)	Mean power (W)	Pulse length (μs)	Repetition rate (Hz)	Spot diameter (mm)	Fluence (J cm^{-2})
Er:YAG contact	2940	250	3.75	250	15	0.63	80
Er:YAG non-contact	2940	600	3.75	250	6	0.63	192
CTH:YAG contact	2100	300	0.3	300	1	0.7	77
CTH:YAG non-contact	2100	300	0.3	300	1	0.3	424

the bond system was reduced due to superficial ablation only. Wet contact or non-contact ablation at high energies and high frequencies did not prevent slight charring of the margins, since desiccation of the surface was seen to occur with each pulse in enamel (figures 3(c) and (d)). This structure had no effect on the connection with the sonic-activated bulk composite. The connection was also without cracks and microleakages (figures 6 and 7).

4. Discussion and conclusion

The scanning electron microscopy evaluation has shown the characteristics of Er:YAG-lased enamel and dentin surfaces: the irregular enamel surfaces with typical keyhole shaped prisms and rods, and protrusion of dentinal tubules with a cuff-like appearance. Laser conditioning rounded off the sharp edges on the enamel irregularities and dentin surface structures. The first signs of vitrification were seen at 250 mJ for enamel samples and 300 mJ for dentin samples. An increase in the pulse repetition rate from 5 to 10 Hz did not result in changes of surface morphology. The laser conditioning did not result in additional vitrification [13]. Our results have shown that the contact mode treatment had a direct influence on the shape, size, and structure of cavity preparation. The Er:YAG contact handpiece irradiation effect was similar to the classical drilling machine and burs, but no smear layer was observed [14]. The Er:YAG irradiation at 25 Hz for enamel and 30 Hz for dentin provided the best ablation rates, but laser efficiency decreased if the frequency was further raised. Greater tissue ablation was found with the water flow rate set to low and it dropped with higher values. Since ablation rates varied with different air pressure values, air pressure was found to interact with the other settings. Fine tuning of all parameters to obtain a good ablation rate with minimum surface damage seems to be the key in achieving optimal efficiency for cavity preparation with the Er:YAG laser [15]. In our study, for the contact mode the optimal parameters were 250 mJ/pulse, pulse repetition rate 15 Hz, and average power 3.75 W. The typical smooth keyhole shaped prism and rod relief was detected, and such a surface was ideal for sonic-activated bulk composite placement. The sonic activation significantly reduced the composite's viscosity so as to rapidly fill the cavity [16, 17].

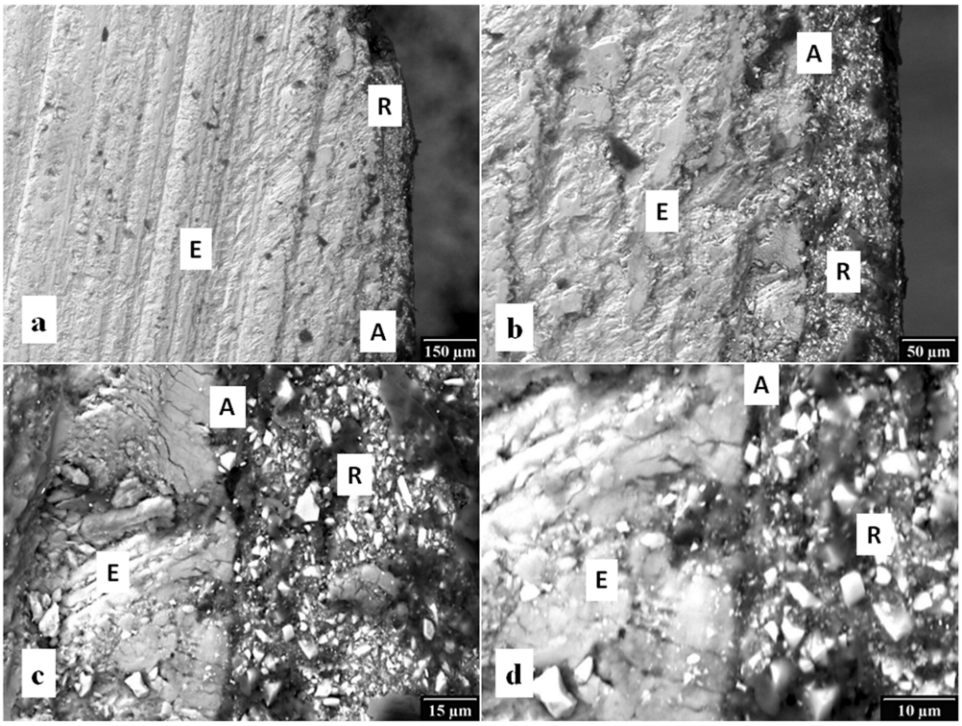

Figure 6. CTH:YAG contact ablation with sonic-activated bulk composite material in the scanning electron microscope in four different magnifications—tooth longitudinal section—only the initial surface layer of enamel is ablated and the surface is irregular. The wet non-contact irradiation in the enamel has a tendency to a charring effect and cavity formation is reduced. Melting of tissue has no effect on the sonic-activated bulk composite system placement. (E—enamel, A—adhesive system, R—resin.)

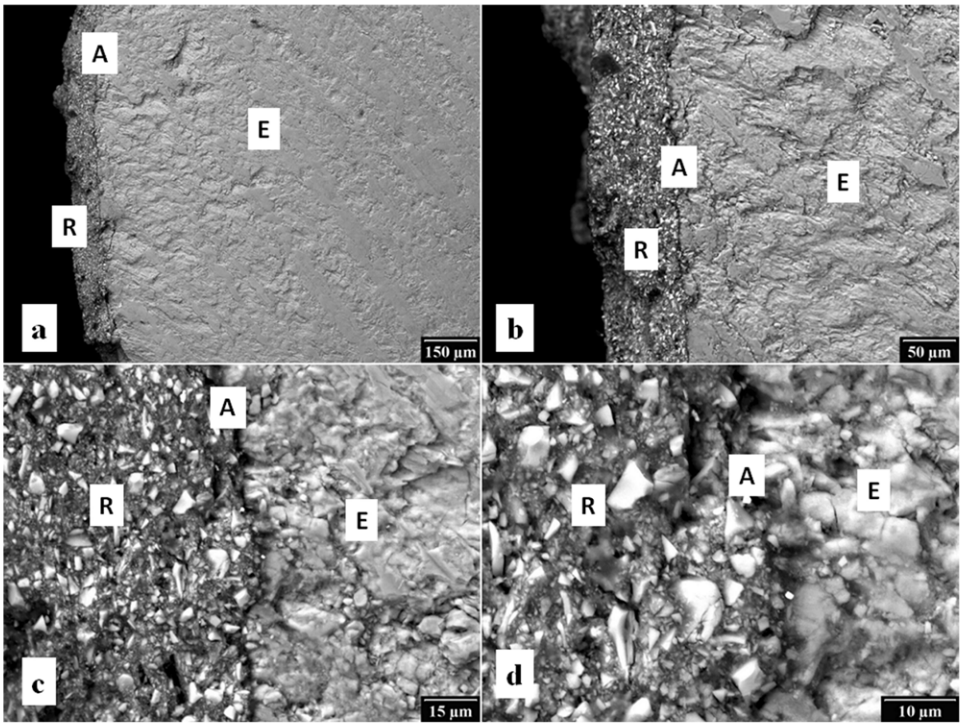

Figure 7. CTH:YAG non-contact ablation with sonic-activated bulk composite material in the scanning electron microscope in four different magnifications—tooth longitudinal section. The cavity is very shallow due to superficial laser ablation; the enamel has a tendency to a charring effect. (E—enamel, A—adhesive system, R—resin.)

Successful composite placement is exacting, tedious, and time consuming. The process includes achieving the necessary isolation, selecting and placing an appropriate matrix, precise execution of the adhesive steps, the placement of a flowable resin or resin ionomer liner, and finally the incremental placement, adaptation, and light curing of at least two layers of composite. In recent years, materials have been introduced in an attempt to reduce the time and effort needed for layering and adaptation when placing mainly posterior composites. One such composite resin material, Quixx (DENTSPLY Caulk), is advocated as a true 'bulk fill' composite. Nevertheless, because of its high viscosity, it still might be prudent to place a low viscosity composite resin or low viscosity resin ionomer liner to achieve intimate adaptation to the pulpal and gingival floors. The four-year clinical study showed an acceptable annual failure rate of 2.7% [18]. The sonic-activated material (SonicFill, Kerr) is capable of delivering an aesthetic composite restoration in one true 'bulk fill' increment. It is a high viscosity restorative composite which comes in tooth-colored shades (A1, A2, A3) and opacity, yet has a high depth of cure (5 mm). The customized composite is provided in a unidose tip. It is inserted into the cavity using a uniquely designed sonic handpiece. When the tip is placed into the cavity and the handpiece activated, liquefaction occurs, resulting in an 87% drop in viscosity. The cavity fills in seconds. When the activation is ceased, the material begins returning to a high viscosity to allow for sculpting [19]. The SonicFill system was comprised of a KaVo handpiece that enables sonic activation of a specially designed and conveniently delivered composite. Our results have confirmed that sonic-supported filling insertion protects the laser ablated cavity against cracks. A different situation has been found in the case of CTH:YAG laser ablation. Georg and Walsh [5] in their laboratory study indicated that the Ho:YAG laser was suitable for ablation of dentin and that this process should be conducted with coaxial water spray so as to minimize carbonization and provide cooling to the tooth. We found that wet contact or non-contact laser CTH:YAG irradiation does not fully protected enamel against overheating. This laser system is effective only for enamel cleaning, but with sonic activation the flow material had a strong bond to lased enamel.

Laser-treated dentin and enamel surfaces have different properties to bur-prepared enamel and dentin. Therefore, adhesive systems and restorative materials specifically developed for laser-treated substrates may be an important next step in the development of restorative procedures. Care must be taken regarding the choice of laser energy output [10]. It is known from the literature that microleakage with etch-and-rinse and self-etching adhesives is generally significantly higher in association with Er:YAG-lased enamel/dentin compared with conventionally prepared substrates [11]. Our study confirmed that the self-etching adhesives and sonic-activated bulk composite placement in association with the contact mode Er:YAG-lased enamel has an optimal influence on connection of the enamel and resin seal bond and could help to protect the laser cavity against cracks and microleakage. We found that wet contact or non-contact laser CTH:YAG irradiation does not fully protect enamel against overheating. This laser system is effective only for enamel cleaning, but with sonic activation the flow material had a strong bond to lased enamel.

Acknowledgments

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