

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 ($\lambda = 2.94 \mu\text{m}$) 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 commercial 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 $2.79 \mu\text{m}$ shows also a strong absorption in water ($\mu_a = 7000 \text{ cm}^{-1}$) but about 55 % compared to the Er:YAG laser ($\mu_a = 13000 \text{ cm}^{-1}$). 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 biocompatibility 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 μ s 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 μ m. 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.

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 μ m deep holes with an diameter of 400 μ m 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.

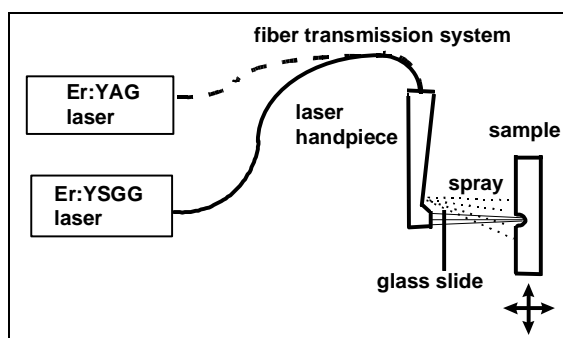


figure1: Experimental setup for comparative study of dental hard substances ablation with Er:YAG and ER:YSGG laser.

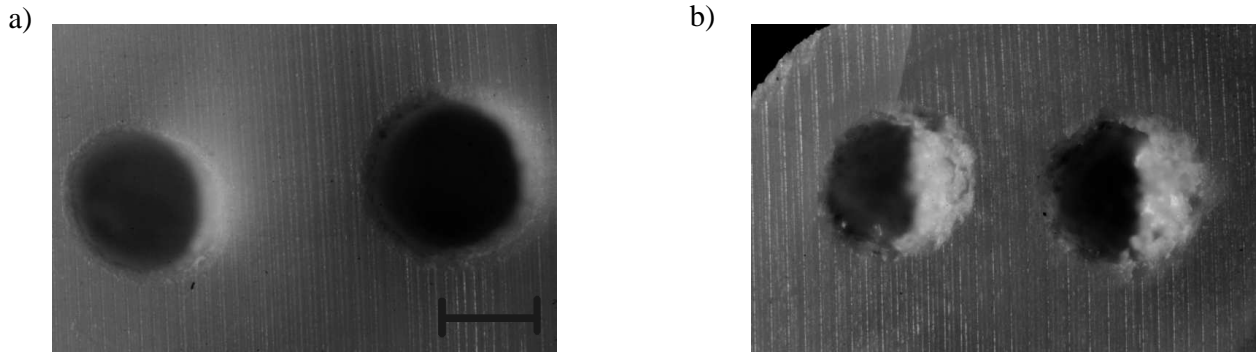


Figure 2: Optical microscope view of craters drilled in dentin (a) and in enamel (b). Left holes in the figures are drilled with Er:YSGG laser right holes with Er:YAG laser using 300 mJ, 5 Hz, 10 pulses, water spray (bar = 500 μ m).

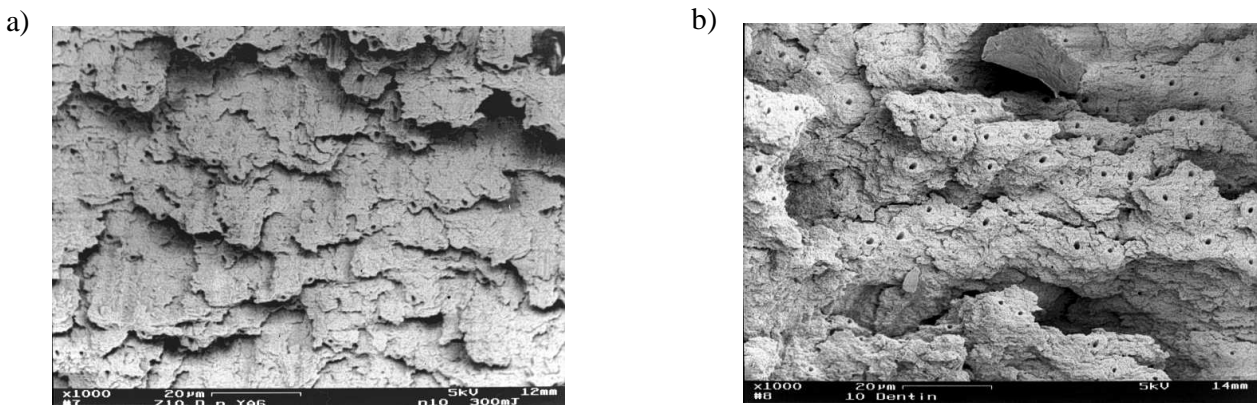


Figure 3: SEM view of crater bottom drilled with Er:YAG laser (a) and Er:YSGG laser (b) in dentin using 300 mJ, 5 Hz, 10 pulses, and water spray.

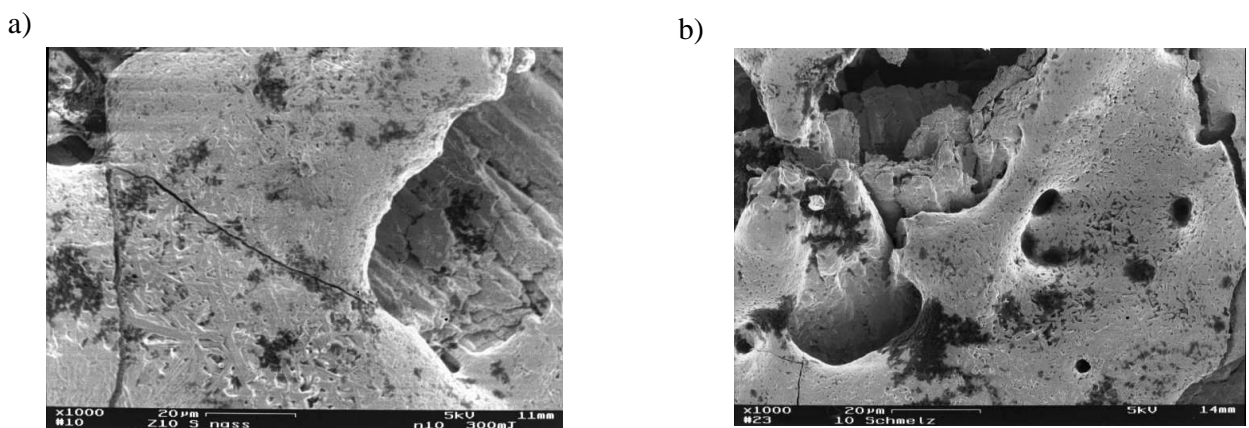


Figure 4: SEM view of crater bottom drilled with Er:YAG laser (a) and Er:YSGG laser (b) in enamel using 300 mJ, 5 Hz, 10 pulses, and water spray.

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.

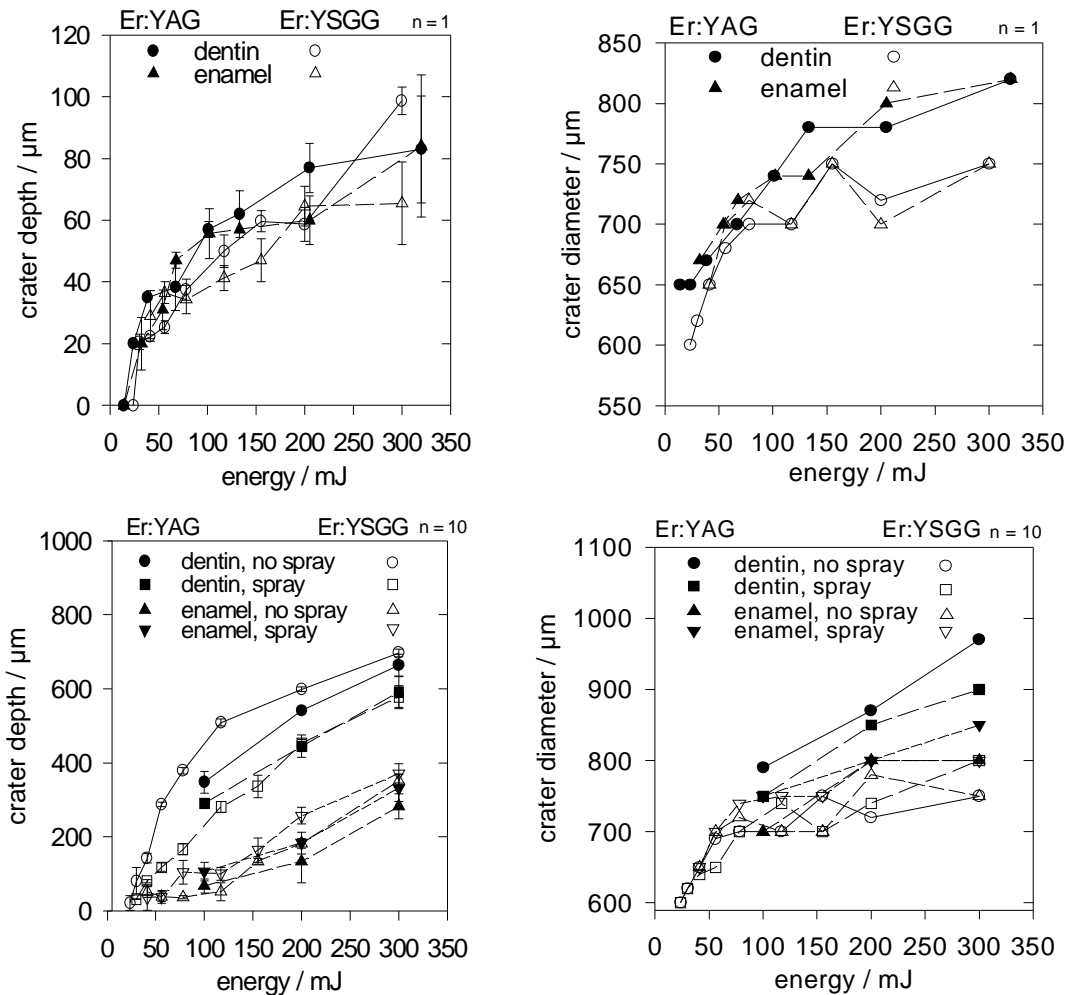


figure 5: Crater depths and diameters vs. pulse energy drilled with Er:YAG and Er:YSGG laser in dentin and enamel.

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

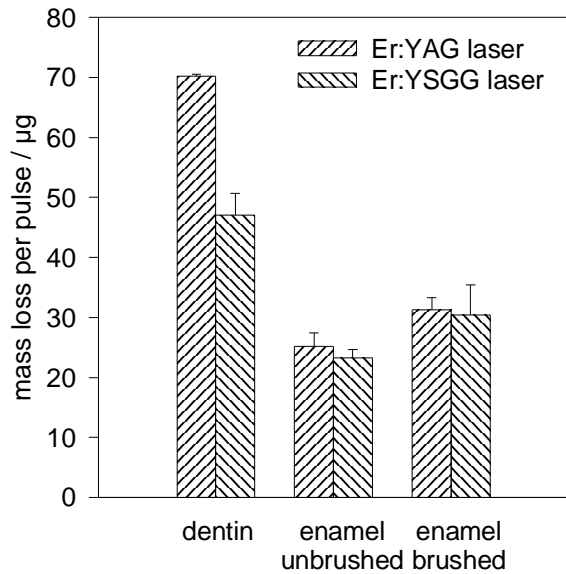


figure 6: Mass loss per pulse of Er:YAG and Er:YSGG laser in dentin and enamel at $E_p=300$ mJ.

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 repetition rate. 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%.

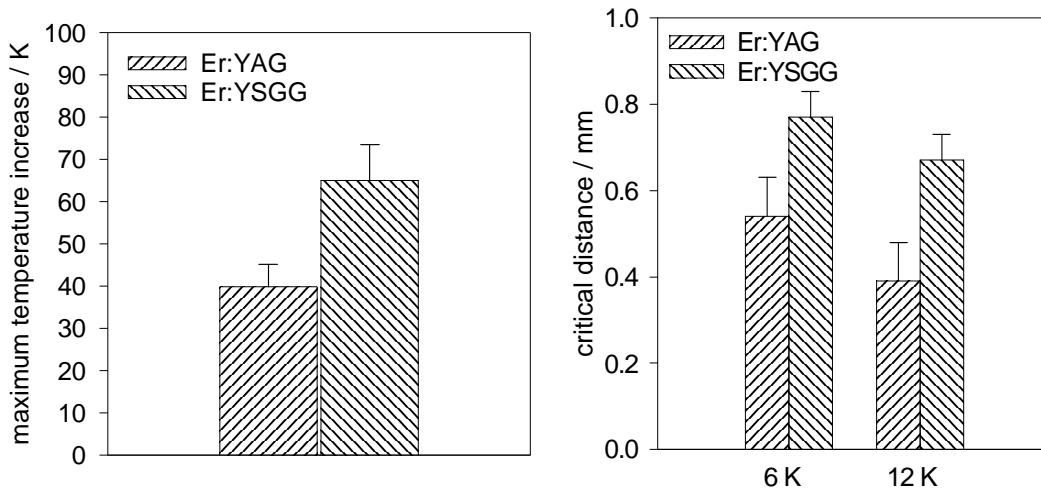


figure 7: Maximum temperature while perforating of 1.5 mm dentin slice with Er:YAG and Er:YSGG laser (300 mJ, 4 Hz, no water spray) and there from calculated critical distances not to exceed temperature increase of 6 K or 12 K.

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. Acknowledgements

The authors want to thank Mr. S. Rapp for his technical assistance and Mrs. A. Böhmler for preparation of the photographs.

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