Influence of the water content in dental enamel and dentin on ablation with erbium YAG and erbium YSGG lasers

Jörg Meister
René Franzen
Katharina Forner
Henning Grebe
RWTH Aachen University
Department of Conservative Dentistry, Periodontology, and Preventive Dentistry
Aachen, Germany
E-mail: jmeister@ukaachen.de

Sven Stanzel
RWTH Aachen University
Institute of Medical Statistics
Aachen, Germany

Friedrich Lampert
Christian Apel
RWTH Aachen University
Department of Conservative Dentistry, Periodontology, and Preventive Dentistry
Aachen, Germany

Abstract. The theory of the ablation of dental hard tissue with erbium lasers is based on a process of thermomechanical interaction, which is explained by the absorption of the radiation in the water component of the tissue. The abrupt evaporation of the water is the cause of tissue fragments being blasted out of the tooth structure. The aim of this study is to examine the effect of the water contained in dental hard tissues on the efficiency of ablation. 192 specimens of both bovine dental enamel and bovine dentin are irradiated with an Er:YAG and an Er,Cr:YSGG laser. Half of the specimens are dehydrated beforehand. Irradiation is carried out in subgroups: without water spray and with water spray at flow rates of 0.8 and 3 ml/s. The ablated volume is determined following histological preparation. Only in dentin, and then only with irradiation with the Er:YAG laser, is the water contained in the tissue found to have a significant influence ($p < 0.0001$) on the ablated volume. The water content has no effect on the efficiency of laser ablation in any of the other test groups. In contrast, the externally supplied water always has a significant influence on the effectiveness of the ablation process. [DOI: 10.1117/1.2204028]

Keywords: erbium laser irradiation; ablation; dental enamel; dentin; dehydration; water-mediated ablation.

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1 Introduction

Since erbium lasers were introduced in medicine and dentistry in the late 1980s and early 1990s, the understanding of the ablation of hard tissues using erbium laser wavelengths has essentially been based on the theory of thermomechanical interaction. Due to the high degree of absorption, the water component contained in the tissue is abruptly heated and evaporated. The pressure of the expanding steam blasts small particles of hard tissue out of the tooth structure.[1–3] The absorption in hydroxyapatite, the main component of the hard tissues, plays only a subordinate role. This is clearly illustrated by the fact that ablation begins in temperature ranges well below the melting point of biological apatites.[4–6]

However, it is also known that the theory described is fundamentally only valid for single pulses.[2] Application of a sequence of pulses leads to dehydration of the irradiated tissue.[7,8] The consequences are carbonization, cracking, and a loss of effectiveness due to thermally induced changes in the material.[9–12] Since pulse repetition rates of up to 30 Hz are currently used in clinical practice, an external water spray additionally has to be provided. Supplying water externally makes it possible to reduce the thermal stress on the surrounding tissues and rule out damage.[13–15] At the same time, however, the water spray also serves to maintain the ablation process, although the role played by the external water in ablation has still not yet been clarified.[3,16] Rehydration can be ruled out, since this process takes time that is not available in the sequence of pulses.[10] Moreover, it can be observed that a certain thickness of the superficial water film is necessary for effective ablation. It is surprising in this context that optically thick water films (approximately 1 mm) additionally promote the effectiveness of ablation.[10,17,18] Accordingly, other effects, such as channel formation, cavitation, and shock waves within the water film, must exert a decisive influence on the dynamics of ablation.[19–21]

The present work examines the contribution made by the water contained in the tissue to the effectiveness of ablation with the Er:YAG and Er,Cr:YSGG laser in enamel and dentin. The question as to the role played by the externally supplied water is also clarified.

2 Materials and Methods

The tooth specimens were irradiated with an Er:YAG laser (Deka-DLS, Smart 2940 D, Firenze, Italy) with a wavelength of 2.94 μm and an Er,Cr:YSGG laser (*Biolase*™, Waterlase™ Millennium®, San Clemente, California) with a wavelength of 2.78 μm.

Address all correspondence to Jörg Meister, RWTH Aachen University, Pauwelsstr. 30, Aachen, NRW 52074 Germany. Tel: +49 241 8089088; Fax: +49 241 8082468; E-mail: jmeister@ukaachen.de

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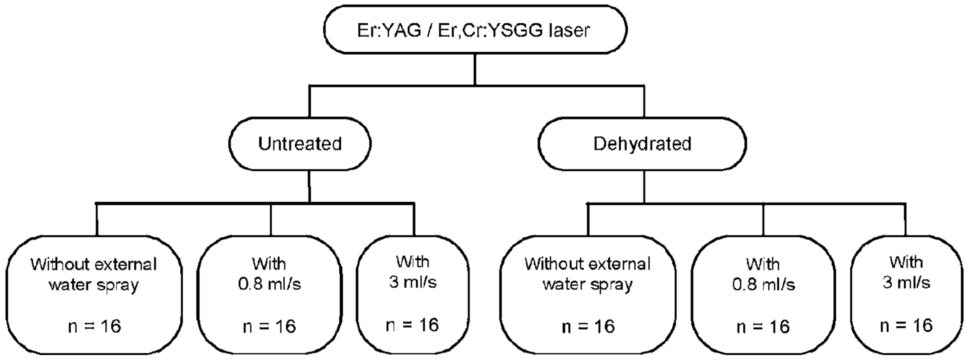

Fig. 1 Irradiation system for the enamel and dentin specimens. Identical numbers of specimens were irradiated with both the Er:YAG laser and the Er,Cr:YSGG laser. Each group was further subdivided into untreated and dehydrated teeth, where each subgroup was irradiated once without a water spray and twice with a water spray at different flow rates.

Bovine incisors were used as the specimen material. Following extraction, the teeth were cleaned and the roots cut off with a band saw (*Exakt* Apparatebau GmbH, Hamburg, Germany). The labial area of the enamel surfaces was smoothed and polished on a polishing machine (*Struers*, DP-U4, Ballerup, Denmark) with rotating abrasive paper from the same manufacturer with grain sizes of P 800 and P 2400 (waterproof silicone carbide paper). For better fixing in the test set-up, the dental crowns were given a rectangular shape using a Reco GMT 5350 trimmer manufactured by Ritter Sybron (Karlsruhe, Germany).

The size of the labial surface of bovine front teeth permits two irradiations per tooth. On the surface, distances of 6 to 8 mm between the two incisions were chosen in a way that the irradiated areas do not influence each other. Thus, with 192 teeth, this resulted in a total number of specimens of 384 for enamel and dentin. Half of the teeth (96 pieces) were stored in isotonic saline solution to prevent dehydration. Prior to irradiation, the other half were dehydrated under constant vacuum at a temperature of 100 °C for 24 h in a desiccator containing a desiccant.[22,23] This procedure makes it possible to observe the effect of the water content of the tissue on the enamel and dentin ablation process.

To investigate the influence of externally supplied water on ablation, one-third of the teeth were irradiated without a water spray. The remainder were wetted with a water spray during irradiation. Separate regulation of air and water permitted accurate metering of the spray. The effects of different flow rates on tissue ablation were examined on the basis of two different metering parameters (0.8 and 3 ml/s).

Figure 1 illustrates the system for grouping and irradiation of the enamel and dentin specimens.

The samples were irradiated with pulse energies between 100 to 150 mJ and moved perpendicularly through the laser beam on a computer-controlled linear micropositioner, so as to obtain a linear incision on the tooth surface. The selected pulse repetition rates of 5 and 10 Hz for the Er:YAG laser and 20 Hz for the Er,Cr:YSGG laser, in conjunction with the feed rates of the micropositioner (125 and 250 μm/s) and given beam diameters on the tooth surface of 474 μm for the Er:YAG laser and 668 μm for the Er,Cr:YSGG laser, result in a corresponding pulse overlap. Table 1 provides an overview of the irradiation and processing parameters.

The parameters were chosen in a way that the generated incisions on the specimens were suitable for histological analysis after irradiation. To analyze the profile of the laser-generated cuts, the band saw was used to cut a 1.5-mm-thick slice from each of the teeth, perpendicular to the laser cut. The slice was subsequently applied to a slide using a precision adhesive (Technovit 7210VLC *Kulzer Exakt* with precision adhesive press). Using an oscillating grinder manufactured by *Exakt*, the specimens were ground down to a thickness of 150 μm with abrasive paper and subsequently polished (grain size P 4000). The laser-cut surfaces were analyzed under the transmitted-light microscope (*Leica* DMRX with integrated *Hitachi* HV-C20A camera, Wetzlar, Germany) by means of a computer program [*Diskus* (Tech. Office Hilgers), Königswinter, Germany].

Based on the data given in Table 1 and the areas determined, the ablated volumes per pulse in mm^3 were calculated using Eq. (1)

$$V_{\text{pulse}} = A \cdot \frac{\omega}{n}, \tag{1}$$

where V_{pulse} is the ablated volume per pulse, A is the laser beam profile area, ω is the beam radius, n is the pulse overlap,

Table 1 Laser and processing parameters used for irradiation.

	Enamel		Dentin	
Laser	Er:YAG	Er,Cr:YSGG	Er:YAG	Er,Cr:YSGG
Wavelength	2.94 μm	2.78 μm	2.94 μm	2.78 μm
Energy density (integral)	56 J/cm^2	43 J/cm^2	56 J/cm^2	28 J/cm^2
Repetition rate	10 Hz	20 Hz	5 Hz	20 Hz
Average power	1 W	3 W	0.5 W	2 W
Beam diameter	474 μm	668 μm	474 μm	668 μm
Motor speed	125 μm/s	250 μm/s	250 μm/s	250 μm/s
Pulse overlap	19	26	5	26

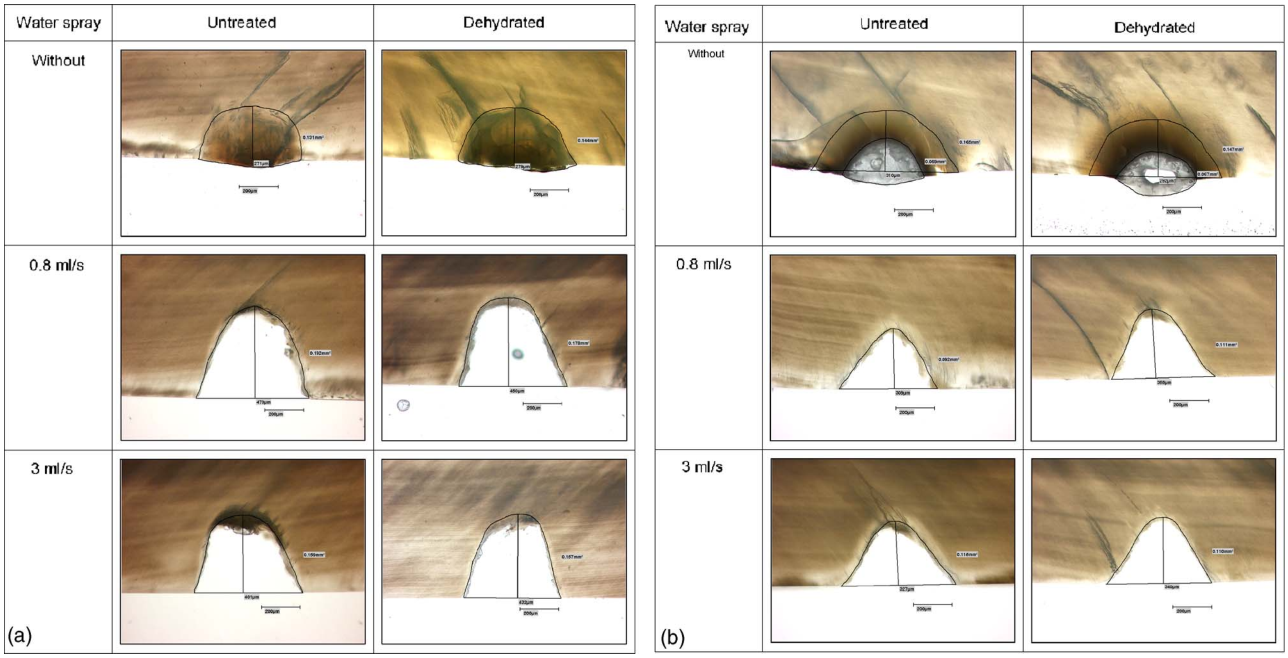

Fig. 2 (a) Effects in dental enamel when using an Er:YAG laser. The left-hand column gives information on the quantity of external water spray. The middle column shows the microsections in untreated enamel, the right-hand column containing those in dehydrated enamel. (b) Effects in dental enamel when using an Er,Cr:YSGG laser. The left-hand column gives information on the quantity of external water spray. The middle column shows the microsections in untreated enamel, the right-hand column containing those in dehydrated enamel.

and where n is a function of the repetition rate and motor speed.

Owing to the fact that irradiation was performed with different energy densities, an additional analysis was carried out regarding the ablated volume as a function of the applied energy in mm^3/J, which in the following is called ablation efficiency. This also eliminates influences arising from the different spatial and temporal beam profiles, thus ultimately permitting comparison of the two different lasers.

2.1 *Statistical Analysis*

Observed ablation efficiencies were summarized and displayed graphically by means and corresponding standard deviations.

Statistical evaluation was performed by fitting a two-way analysis of variance model to the observed ablation efficiencies with independent factors "water content" (two levels: untreated, dehydrated) and "amount of water spray" (three levels: no H_2O, 0.8 ml/s, and 3.0 ml/s), separately for each of the four study groups (dental enamel or dentin with each of the two erbium lasers). Statistical evaluation of the observed ablation efficiencies was based on the results (p-values) of the global F-tests investigating each of the earlier mentioned two factors.

For the three-level factor "amount of water spray," only in the case of a statistically significant test result in the corresponding F-test, post-hoc t-tests were carried out for pairwise comparison between any two out of the three water spray amount groups.

The significance level for the global F-tests was chosen to $\alpha=5\%$, i.e., a p-value of $p\leqslant 0.05$ indicates a statistically significant effect of the corresponding factor on the observed ablation efficiencies. The Bonferroni method was used for adjustment of p-values obtained from the post-hoc t-tests.

All statistical analyses were carried out using the SAS statistical analysis software package, version 9.1, SAS Institute, Cary, North Carolina.

3 Results

In total, 384 samples were irradiated with both erbium lasers. Nine samples were lost during cutting and grinding procedures and could not be examined. The losses predominantly occurred in the groups of dehydrated samples, two samples in dental enamel and seven samples in dentin, respectively. None of the subgroups had more than two samples missed.

The evaluation was made in two steps. The ablated volume per single laser pulse was first determined on the basis of the histological examination. Based on these data, the ablated volume per pulse energy (ablation efficiency) was calculated. Only this value allows a comparison of the different laser systems, since it excludes influences derived from different energy densities caused by differences in spatial light distribution (TEM modes). The values of the ablation efficiency depending on the endogenous water content (untreated versus dehydrated) in tooth material and the amount of added external water spray were used for statistical analysis.

3.1 *Dental Enamel*

The micrographs in Figs. 2(a) and 2(b) illustrate that no ablation could be achieved in enamel upon irradiation with the two erbium lasers, either in untreated condition, or in the dehydrated specimens without external water spray. Only superficial melting and deeper carbonization zones were to be observed. With both erbium lasers, ablation only occurred when

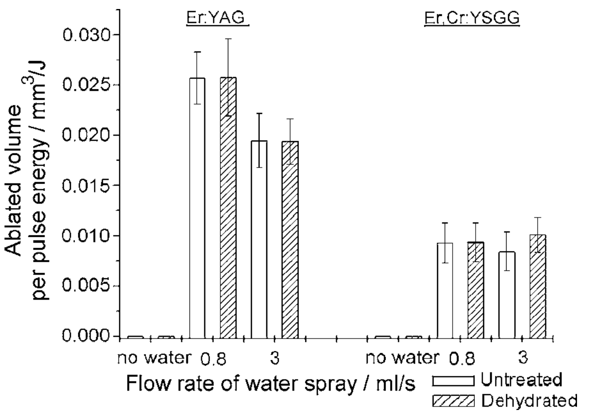

Fig. 3 Ablated volume in dental enamel as a function of pulse energy (ablation efficiency), plotted against the flow rate of the externally supplied water spray.

an external water spray was used. The ablated volumes of the Er:YAG laser in water-containing and dehydrated enamel were identical at the corresponding flow rates of the external water. At a flow rate of 0.8 ml/s, the mean ablated volume was $2.3 \cdot 10^{-3}$ mm^3 per pulse for both untreated and dehydrated dental enamel. At a flow rate of 3 ml/s, a value of $1.7 \cdot 10^{-3}$ mm^3 per pulse was calculated for both conditions.

The ablated volumes of the Er,Cr:YSGG laser were smaller than those of the Er:YAG laser. The mean ablated volume was $1.3 \cdot 10^{-3}$ mm^3 per pulse for the flow rate of 0.8 ml/s, and $1.28 \cdot 10^{-3}$ mm^3 per pulse for 3 ml/s.

When using the Er:YAG laser, it was found that the ablation efficiency was dependent on the flow rate of the external water supply. Greater ablation was observed at 0.8 ml/s than at 3 ml/s. This dependence could not be established for the Er,Cr:YSGG laser.

Taking into account the ablated volumes per pulse energy (Fig. 3), inferential statistical analysis confirms these results. No ablation could be observed without external water spray. Furthermore, for dental enamel, no influence of dehydration on the ablation efficiency of the two lasers was found (Table 2). The amount of externally supplied water had a significant influence on the efficiency of substance ablation with both erbium lasers (Tables 2 and 3).

Comparison of the influence of the individual flow rates of the external water spray (0.8 versus 3 ml/s) showed a statistically significant difference only for the Er:YAG laser, where greater ablation was obtained with the lower flow rate. No significant difference could be found between the different flow rates when using the Er,Cr:YSGG laser.

Table 2 Results (p-values) of the global F-tests for determining the influence of the water content in dental enamel and of the supplied water spray on ablation efficiency.

Laser	Water content in dental enamel	Flow rate of water spray
YAG	0.9985	<0.0001
YSGG	0.0800	<0.0001

Table 3 Results (Bonferroni-adjusted p-values) of the pairwise post-hoc t-tests comparing the influence of the individual flow rates on tissue ablation in enamel.

Laser	No H_2O versus 0.8 ml/s	No H_2O versus 3 ml/s	0.8 ml/s versus 3 ml/s
YAG	<0.0001	<0.0001	<0.0001
YSGG	<0.0001	<0.0001	1.0000

3.2 *Dentin*

In dentin, completely different behavior was observed for the Er:YAG laser radiation. In this case, ablation could be seen without an external water spray, both in untreated dentin ($14.6 \cdot 10^{-3}$ mm^3 per pulse) and in dentin in dehydrated condition ($10.1 \cdot 10^{-3}$ mm^3 per pulse) [Fig. 4(a)]. The quantity of the ablated volume was statistically significantly lower for the dehydrated condition. In addition, the different quantities of externally supplied water had an impact on the efficiency of tissue ablation. At 0.8 ml/s, the ablated volumes per pulse were $11.7 \cdot 10^{-3}$ mm^3 in the dentin containing water and $10.9 \cdot 10^{-3}$ mm^3 in dehydrated condition. The ablation determined for the higher flow rate of 3 ml/s was $7.6 \cdot 10^{-3}$ mm^3 (untreated) and $3.7 \cdot 10^{-3}$ mm^3 per pulse (dehydrated).

Without the external water spray, the Er,Cr:YSGG laser again caused only superficial melting and deeper carbonization zones in the dentin [Fig. 4(b)]. No ablation could be observed.

As with the enamel, ablation only occurred with the Er,Cr:YSGG laser when used in conjunction with the water spray. The ablated volumes per pulse were roughly equal for both material conditions (untreated and dehydrated) and each flow rate, amounting to $1.9 \cdot 10^{-3}$ mm^3 at 0.8 ml/s and $1.7 \cdot 10^{-3}$ mm^3 at 3 ml/s.

The inferential statistical analysis of tissue ablation in dentin revealed that the water content (untreated versus dehydrated) only had a significant influence on ablation efficiency at a wavelength of 2.94 μm (Er:YAG, Fig. 5). In contrast, no significant difference could be determined at the wavelength of 2.78 μm (Er,Cr:YSGG) (Table 4). Without the external water spray, no ablation occurred with the Er,Cr:YSGG laser.

The amount of external water spray had a statistically significant influence on tissue ablation with both lasers (Tables 4 and 5).

4 Discussion

The standard theory of ablation states that the endogenous water content of dental hard tissues (enamel: $3\%_{weight}$, $12\%_{vol}$; dentin: $12\%_{weight}$, $25\%_{vol}$)[23–25] is the dominant factor influencing the ablated volume.[2] The present study was able to demonstrate that the water contained in the tissue has no influence, or only a secondary influence, on the ablation efficiency of the erbium lasers. Without an external water spray, ablation could not be observed using the Er:YAG laser and the Er,Cr:YSGG laser in dental enamel, and the Er,Cr:YSGG laser in dentin. Melting and carbonated hydroxyapatite mineral occurred, which resulted in high surface temperatures.[8] Only in dentin and when using the Er:YAG laser, a statistically

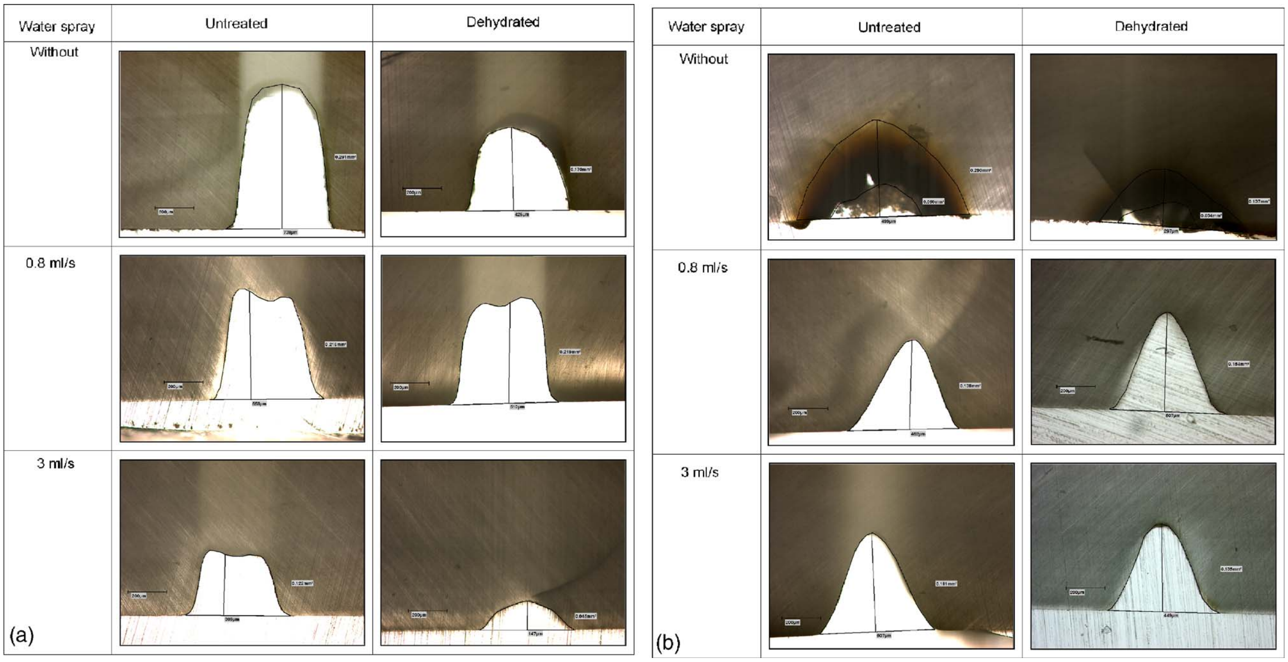

Fig. 4 (a) Effects in dentin when using an Er:YAG laser. The left-hand column gives information on the quantity of external water spray. The middle column shows the microsections in untreated dentin, the right-hand column containing those in dehydrated dentin. (b) Effects in dentin when using an Er,Cr:YSGG laser. The left-hand column gives information on the quantity of external water spray. The middle column shows the microsections in untreated dentin, the right-hand column containing those in dehydrated dentin.

significant dependence of the ablated volume on the endogenous water content was found. The results obtained thus permit the following conclusions to be drawn.

• The results of this study are not totally interpretable by the standard ablation theory. It does not provide an explanation for high-repetition-rate erbium laser applications and must be reconsidered.

• The role of the water spray is completely different from that of a classical absorber complying with Beer's law (Table 3).[10,12,17,26]

• The results do not indicate that the sole benefit of the water spray is that of a coolant, since, with the exception of the Er,Cr:YSGG laser in enamel (Table 3, 0.8 versus 3 ml/s: $p = 1.0$), the external water spray has a significant influence on the ablated volume.[27]

• Rehydration of the dental hard substance can likewise be ruled out, since, despite using an external water spray, a significant difference in the ablation efficiency between water-containing and dehydrated dentin (Table 4) could be observed with the Er:YAG laser.[10,25]

In the present study, only the Er:YAG laser applied to dentin behaved as expected.[28] In this case, the endogenous water content had a statistically significant influence on the ablated volume. That ablation was observed despite dehydration can be explained by the fact that the water contained in the tissue can only be partially eliminated from the dental hard substance. The drying method used only removes the free water component from the tissue. Interprismatically stored water or bound OH^- components cannot be expelled; this consequently ensures a high degree of ablation efficiency with Er:YAG laser radiation.[22,23]

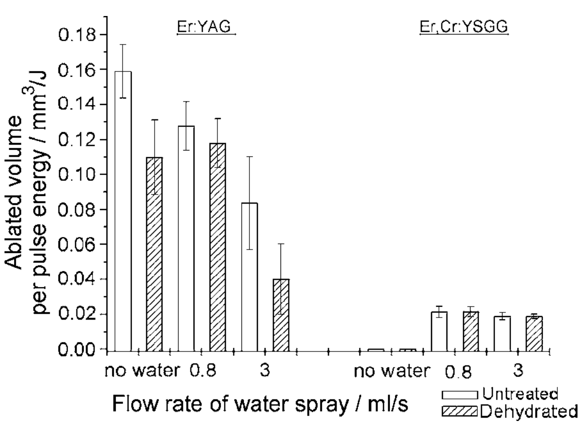

Fig. 5 Ablated volume in dentin as a function of pulse energy (ablation efficiency), plotted against the flow rate of the externally supplied water spray.

Table 4 Results (p-values) of the global F-tests for determining the influence of the water content in dentin and of the flow rate of the water spray on ablation efficiency.

Laser	Water content in dentin	Flow rate of water spray
YAG	<0.0001	<0.0001
YSGG	0.6030	<0.0001

Table 5 Results (Bonferroni-adjusted p-values) of the pairwise post-hoc t-tests comparing the influence of the individual flow rates on tissue ablation in dentin.

Laser	No H_2O versus 0.8 ml/s	No H_2O versus 3 ml/s	0.8 ml/s versus 3 ml/s
YAG	0.0031	<0.0001	<0.0001
YSGG	<0.0001	<0.0001	<0.0001

For the Er,Cr:YSGG laser ($2.78\ \mu m$), no statistical association was found between endogenous water content and ablation in dentin. Compared to the untreated teeth, irradiation of the dehydrated teeth yielded no statistically significant differences in the ablated volumes, not even when taking different flow rates into account (Table 4). This result may possibly be attributable to the different absorption constants of the two wavelengths in water. At $12{,}480\ cm^{-1}$,[29] the absorption constant μ_a of water at a wavelength of $2.94\ \mu m$ is three times higher than at $2.78\ \mu m$, where μ_a is $4180\ cm^{-1}$,[29] as a result of which the energies deposited in the tissue differ spatially, owing to the penetration depths. The small penetration depth of the Er:YAG laser generates a high spatial energy density, this making the tissue more sensitive to interaction with the radiation. The penetration depth of the Er,Cr:YSGG laser is greater, the corresponding spatial energy density being lower as a result.

When the absorption constants of the two erbium lasers are compared in the tooth mineral, where absorption of erbium radiation mainly takes place on bound OH^- components in hydroxyapatite, the differences of the laser-tissue interaction are explicable.[30] Er,Cr:YSGG laser radiation is stronger absorbed by the mineral of dental enamel than Er:YAG laser radiation, but in contrast, the volumetric content of hydroxyapatite is much higher than that of water. Therefore, the absorbed radiation of an Er,Cr:YSGG laser is distributed to a large volume in enamel, which leads to substantially lower spatial energy densities. The consequence is mainly a heat deposition into the mineral.[8] The light-tissue interaction is thus less sensitive, and this also explains the higher threshold for ablation.[30]

The influence of the amount of water spray on the ablated volume is statistically significant in every instance (Tables 2 and 4). In conjunction with a water spray, ablation was observed with both erbium lasers in enamel and in dentin. This permits the conclusion that the contribution of the endogenous water content alone is not sufficient for ablation. This statement is backed by the irradiation of the dehydrated specimens (no significant difference compared to the nondehydrated tooth specimens). The exception is dentin when irradiated with the Er:YAG laser. Ablation occurs as a result of the high absorption of the radiation in water and the high water content in dentin. The differences in ablated volume between untreated and dehydrated tooth substance display a statistically significant difference; this suggests that the endogenous water content in dentin plays an essential role with this type of laser.

The results of the present study indicate that physical phenomena occurring in the superficial water film are of far greater importance than previously believed. The nature of the interactions occurring can only be discussed at a very fundamental level on the basis of the available literature. For example, different hypotheses are described and favored, such as the formation of channels, the collapse of which causes cavitation bubbles, which in turn generate shock waves, or also so-called recoil-induced material expulsion.[21] It may also be that the combination of the two phenomena as a function of the quantity of water supplied leads to an adequate understanding of tissue ablation.

5 Summary

The results of the present study show that the water component contained in dental enamel does not contribute to the ablation process when using pulsed erbium lasers.

The tissue water component in dentin only has a statistically significant influence on ablation efficiency when using an Er:YAG laser.

The externally supplied water spray, or rather the water film applied by it, is the actual mediator of the ablation process. The consequence of this is a demand for revision or expansion of the model of erbium laser ablation in biological hard tissues.

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