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EVALUATION OF THE SURFACE CHANGES IN ENAMEL AND DENTIN DUE TO POSSIBILITY OF THERMAL OVERHEATING INDUCED BY ERBIUM:YAG LASER RADIATION

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Abstract

This study investigates the thermal danger of Erbium (Er):YAG laser ablation. Classical preparation techniques have many disadvantages caused by unfavorable changes of temperature, pressure, and by mechanical vibrations. The effect of mechanical vibrations and pressure is eliminated by use of laser ablation technique. The purpose of this study was to analyze the side effects resulting from thermal changes of enamel and dentin in extracted human teeth subjected to pulsed Er:YAG laser radiation using both wet and dry ablation methods.

The micrographs of the sections were checked and measured afterwards. The effect of the investigated laser irradiation on the origin of cracks was analyzed in the scanning electron microscope. The hard structures of the teeth were observed under transmitted and polarized light. The occurrence of cracks can be directly correlated to overheating during dry enamel ablation, because heat is generated by absorption of the laser beam by enamel and dentin. The addition of water mist during irradiation not only enables rapid ablation of enamel and dentin, but offers thermal protection to the pulp. The heat changes to the pulp caused by an energy level of 200 mJ from the tested laser system may be reduced by adding a fine water spray during the lasing procedure.

Key Words: Dentistry, laser therapy, Erbium:YAG laser, heat/adverse effects.

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Introduction

The widespread use of laser technology in dentistry has been restricted in part because of the inability of currently available lasers to remove particles of enamel effectively {lasers generating radiation in the visible part of spectrum are not so effective (Vahl and van Benthem, 1992)} and because of the thermal changes produced in the dental pulp (Burkes *et al.*, 1992).

Temperature changes during the preparation of dental hard tissue is one criterion for evaluation of the safety of the preparation technique with respect to tooth vitality (Seltzer and Bender, 1975). Classical preparation techniques have many disadvantages caused by unfavorable changes of temperature, pressure, and by mechanical vibrations (Seltzer and Bender, 1975). The effects of mechanical vibrations and pressure are eliminated by the use of a new laser preparation technique (Hibst and Keller, 1993). This method is based on tissue interaction with electromagnetic radiation.

The important factor in the tooth tissue preparation is to maintain the temperature increase below 5°C in the pulp chamber (Seltzer and Bender, 1975). From previous work (Zach and Cohen, 1965), it is evident that the dental pulp responds to measured increases in applied heat in a fairly constant, predictable manner. The threshold temperature related to complete destruction of pulp (overwhelming irreversible necrotic response) is 16°C (critical range is 6°C). From classical preparations, it is obvious that, under clinical conditions of the actual dental treatment, the pulp is subjected to severe thermal shock from procedures other than rotary-drill cavity preparation alone.

A similar, or even more dangerous, situation can be caused by laser ablation. In previous experiments, we have shown that uncooled long-term Erbium (Er):YAG laser preparation caused irreversible changes of the pulp: the intrapulpal temperature rose up to 10°C. This method is therefore dangerous and unacceptable (Dostálová *et al.*, 1993b). Alternately, if the tooth is cooled by an appropriate fine water spray, i.e., under the same conditions as in the classical preparation, the temperature during the preparation of the enamel, and the dentin is stable within 2°C up to the moment of the pulp perforation (Dostálová *et al.*, 1993b). The opening of the pulp chamber coincides with the rapid temperature increase. Results from Burkes *et al.* (1992) suggest that pulsed Er:YAG radiation used with water mist removes hard dental tissues, with intrapulpal temperatures rising an average of 4°C. Similar results were obtained by Hoke *et al.*, 1990: an average rise of 2.2°C was produced in the pulp chamber during Er:YAG laser ablation of extracted dry human tooth structures using a water mist. It is evident that thermal shock by Er:YAG laser ablation is minimal (lower than by classical preparation with air turbine or low-speed water-cooled operative technique).

Besides the temperature increase in the pulp, the thermal side effects are the most important question with regard to the applicability of a laser system in dentistry. Hibst and Keller (1989) investigated the ablation rate and degree of tissue damage during application of an Er:YAG laser on enamel and dentine. They found that, during ablation, the major part of the incident energy is consumed in an ablative process, and only a small fraction of the energy results in heating of the remaining tissue. The enamel and dentine are removed by continuous vaporization and by microexplosions (Hibst and Keller, 1994).

Thermal changes produced by the Er:YAG laser are directly related to surface changes, including crazing, cratering and glazing. The craters produced in enamel and dentin are cone-shaped with no melting and vaporization (Hibst and Keller, 1989).

The aim of the present study was to optically analyze the thermal changes caused by wet and dry ablation of enamel and dentin with an Er:YAG laser. We wanted to determine the damage to surrounding tissue after removal of enamel and dentin.

Materials and Methods

Laser equipment and experiment preparation

For the experiment, we designed and constructed in our laser laboratory the prototype of an Erbium:YAG laser ($\lambda = 2.94\ \mu m$) drilling machine (Jelínková *et al.*, 1992). The system has a laser head with an articulated arm, water cooler, and power supply with automatic control. The laser head consists of an Er:YAG crystal with diameter of 7 mm and length of 100 mm which is placed along with a xenon flashlamp into the silver-coated pumping cavity. The resonator design enables generation of an output energy up to 800 mJ in a free-running, long-pulse mode. The length of generated pulses was measured to be 200 μsec. By the articulated arm (seven total reflecting mirrors), the radiation is focused on the target specimens by a CaF_2 lens ($f = 30$ mm). Along with the articulated arm, the water and air are focused on the same place. It was proved experimentally that the Er:YAG laser is powerful enough to efficiently remove hard tissues such as enamel, dentin, or bone (Hibst and Keller, 1989; Jelínková *et al.*, 1994). For the preparation, we found the optimum energy equal to 200 mJ corresponding to 1000 W peak power. The repetition rate was 0.5 Hz. During the experiment, teeth were held steady in a special holder. The spot focus diameter was about 90 μm; energy density in focus was 3.2×10^3 J/cm^2. The duration of laser preparation was five minutes. The cavities on the buccal sides of teeth were ablated (one cavity per one tooth).

Water cooling

During our experiments, the continuous room temperature water flow (50 ml/min), the fine water mist (water, 50 ml/min at a pressure of 2 atm; air at a pressure of 3 atm), and the ablation without water cooling were used. The delivery system for this case was the same as in the classical high-speed drilling machine (two channels: one for water, one for air).

Preparation of the teeth

Ten extracted noncarious permanent human teeth were used for all parts of this study. The teeth were stored in 10% neutral formalin, cleaned and rinsed with water and stored in distilled water (room temperature). Prior to the laser preparation teeth were wiped clean with cellulose wool and allowed to dry in the air. Before the laser ablation, micrographs of each tooth were taken to record the cracks caused by extraction of teeth and immersion in the formalin (Dostálová *et al.*, 1994).

Analytical methods

Micrographs of each tooth before and after the laser ablation were compared. The effect of the investigated laser irradiation on the surface of the teeth, to determine the possible origin of cracks, was analyzed in the scanning electron microscope (SEM). The tested specimens were fixed onto specimen holders and covered with an approximately 30 nm layer of gold in a Fine Coat Ion sputter B 30.1 (FEB Hochvakuum Dresden, Germany). The specimens were studied in a BS 300 Tesla (Brno, Czech Republic) scanning electron microscope. The influence of the investigated laser irradiation was observed in crack formation.

For the second part of the experiment, the following polished longitudinal sections (30-50 μm) were prepared: the intact teeth, the teeth after Er:YAG laser ablation without water cooling, and with cooling by water flow or water mist. These samples were observed under the optical microscope using both ordinary transmitted and polarized light. The sections were embedded without dehydration (Dostálová *et al.*, 1993c).

Figure 1. Marginal defects: macrocracks and microcracks (arrow) in enamel only; dry laser ablation in SEM. Photo width (P.W.) = 1.65 mm.

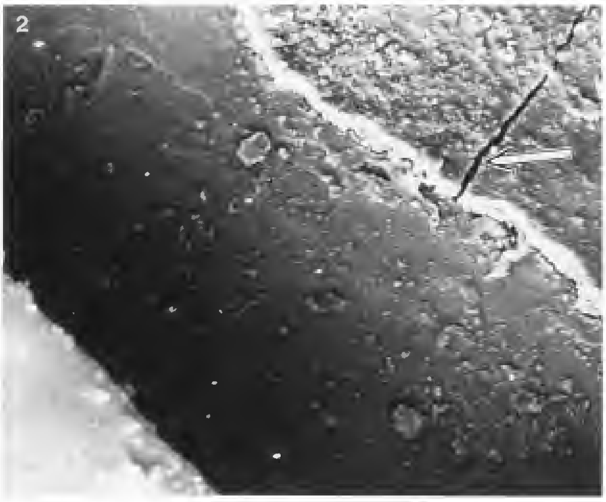


Figure 2. Detail of macrocracks in enamel (SEM); dry laser ablation. The arrow marks the edge of a cavity. P.W. = 1.04 mm.

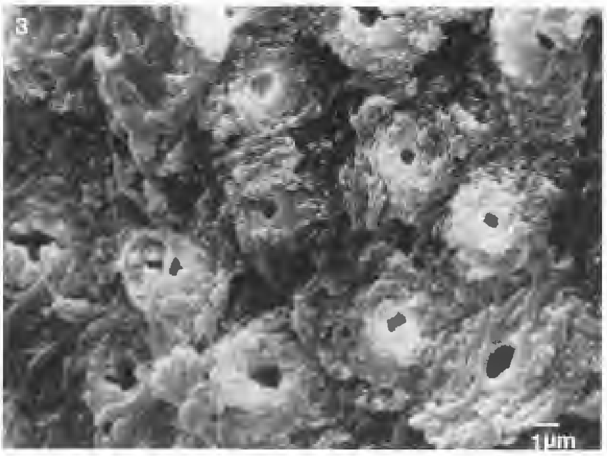


Figure 3. No sign of defects in dentin (SEM); dry laser ablation.

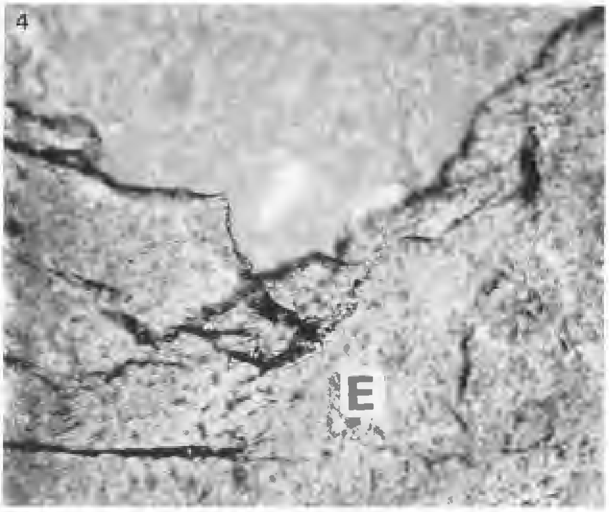


Figure 4. Cracks in enamel under polarized light; E: enamel; dry laser ablation. Part of lased cavity. P.W. = 650 μm.

Results

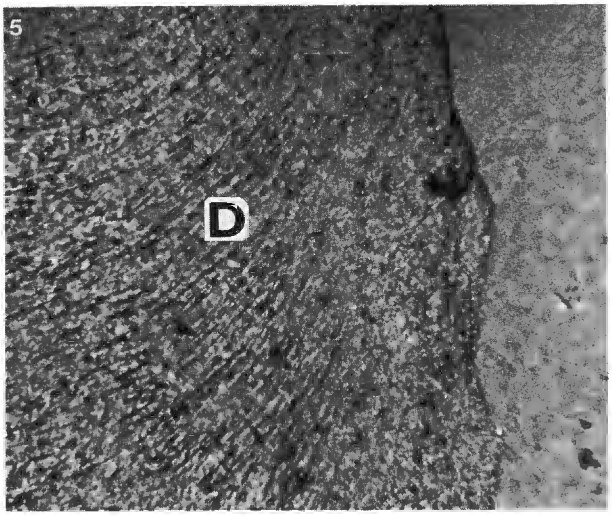
The cracks in the enamel due to the pressure exerted during extraction and immersion in the formalin were presented in our previous study (Dostálová *et al.*, 1994). These teeth were eliminated from our experiments.

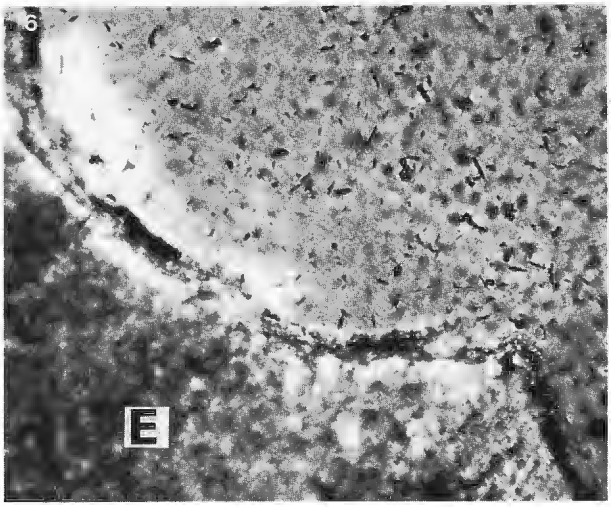
Laser irradiation without water cooling

Surface side effects after laser ablation without water cooling were detected in the SEM. Marginal defects around the cavities were formed in the enamel only (Fig. 1). Cracks (about 3.5 mm) (Figs. 1 and 2) and microcracks (about 300 μm) (Fig. 1) were observed. The dentin observed in the SEM did not show any defects (Fig. 3). Defects of mineralization were found in sections under the optical microscope with both ordinary transmitted and polarized light. Enamel appeared near the cavity margins. Irregular microcracks surrounding the cavity margin were observed in enamel only (Fig. 4). The layer of dentin was transparent, which was also a characteristic of the intact tooth (Fig. 5) (Dostálová *et al.*, 1993c).

Laser irradiation with water flow

Ablation of the hard dental tissues with water flow





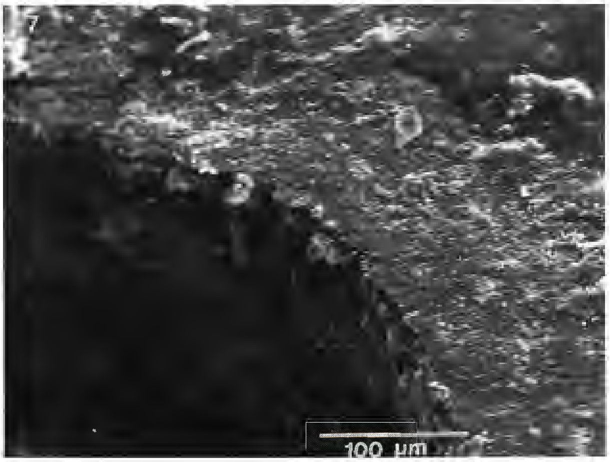


Figure 5. The layer of dentin is transparent under polarized light; D: dentin; dry laser ablation. Bottom of cavity in dentin. P.W. = 640 μm.

Figure 6. Water flow (50 ml/min) filled the cavity during laser ablation and for this reason the laser effect was reduced in enamel only (polarized light); E: enamel. P.W. = 640 μm.

Figure 7. Water mist Er:YAG laser ablation without morphological changes of enamel; SEM micrograph.

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cooling was not so effective as ablation with water mist cooling. Water flow (50 ml/min) filled the cavity during laser ablation and for this reason the laser effect was reduced in enamel only (Fig. 6). This phenomenon was related to the absorption of Er:YAG radiation in water (Dostálová *et al.*, 1993a).

Laser irradiation with fine water spray

Water mist was the optimal method to prevent the side effects, i.e., the cracks, during laser ablation. The cavity margins observed by SEM were smooth and lacked cracks and microcracks (Fig. 7). A SEM study of resulting surfaces in dentin showed smooth fractured projections and depressions corresponding to the dentinal tubules. The edges of the tubules were rounded, without cracks based on overheating of tissue (Fig. 8).

The enamel and dentin in cavities were observed without changes of mineralization (Fig. 9). The variations of the mineralization in teeth were checked with an energy-dispersive X-ray analysis system (Oxford Instruments eXL system, Oxford, UK), and appeared related to certain preformed structures (prisms, striae of Retzius and the bands between them) (Dostálová *et al.*, 1993c; Kostlán, 1962).

Discussion

Hibst and Keller (1989) found that with a pulsed 2.94 μm Er:YAG laser, removal of dentin and enamel tissue is very effective. One of the dangers of laser ablation is overheating by the laser energy with heat-related changes in pulp and side effects around the cavity margins.

During dry laser ablation, the temperature in the pulp chamber rose, and there is insufficient time for the tooth structures to dissipate the heat between the pulses. For this reason, not only irreversible changes in pulp but also thermal cracks near the cavity margins were found. From the literature (Niemz *et al.*, 1993), we can divide the morphological changes in enamel due to the laser radiation into 3 mm-long fractures {caused by Holmium (Ho):YAG laser} and smaller microcracks (about 300 μm, generated by Ho:YAG and Er:YAG lasers). Measurements of Paghdiwala *et al.* (1993) with thermocouples placed in the pulp while preparing teeth with an Er:YAG laser revealed, for constant irradiation conditions, a temperature increase which depended on the thickness of remaining tissue. Microscopical observation showed fine cracks on 33% of the dry teeth exposed for 1 second and 100% of the dry teeth. The cracks that could be attributed to the laser impact were arranged radially around the periphery of the laser-drilled holes, and spread out like sun rays. Paghdiwala *et al.* (1993) used this characteristic to differentiate laser-induced cracks from pre-existing cracks.

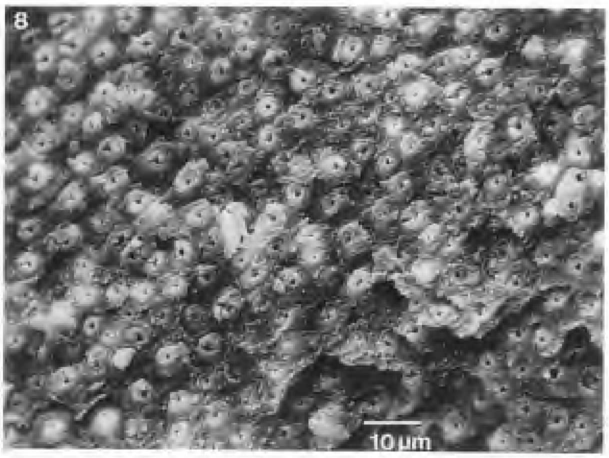
Our present study showed that the occurrence of cracks can be directly correlated to overheating only of highly mineralized enamel during dry ablation because the heat is generated by laser beam absorption in enamel, and as a consequence of heat conduction, also the temperature of the dentin is increased. It is possible to divide the cracks into two size groups: microcracks (about 300 μm) and macrocracks (about 3.5 mm). Both types of cracks were observed around the cavity margins. The same orientation of cracks was demonstrated by Paghdiwala *et al.*, 1993. The presence of the macrocracks appears to be related to the duration and number of pulses used during ablation.

Water flow absorbs the laser energy during ablation. The absorption depends on the laser wavelength (Vahl and van Benthem, 1992). Our results show that laser ablation with water flow is less effective than with water mist. The water flow on the tooth during the lasing process resulted in a marked decrease in structural alterations. Paghdiwala *et al.* (1993) showed that lasing in the presence of water flow resulted in a distinct parallel orientation of the enamel rods along the walls. The holes were relatively smoother with little flakiness or fragmentation of the enamel. The fragmentation of the tissues can be caused by a sudden evaporation of the water, which is contained in the enamel and dentine, resulting from rising internal pressure during ablation (Hibst and Keller, 1993).

The addition of water mist during irradiation can speed up ablation of enamel and dentin (Burkes *et al.*, 1992; Keller *et al.*, 1992). Water mist cools the surface sufficiently to prevent undesirable physical changes.

Combining the pulsed Er:YAG laser ablation with fine water mist produced encouraging results. The conduction of the heat is minimal. The ablation is only local with no apparent thermal damage to the surrounding enamel or dentin. It is postulated that the tooth structures dissipate the heat during the time between pulses.

The Er:YAG laser system with the fine water spray cooling (as in the classical preparation) prepares enamel and dentine without undesirable temperature changes in pulp (Dostálová *et al.*, 1993b) and without side effects such as cracks in enamel and dentin.



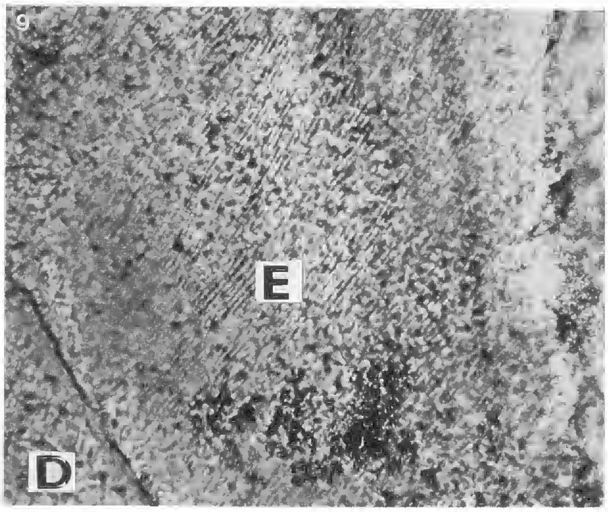


Figure 8. Detail of dentin cavity without cracks; SEM micrograph; water mist ablation). P.W. = 100 μm.

Figure 9. Transparent enamel and dentin under polarized light; water mist; E: enamel, D: dentin. P.W. = 640 μm.

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Discussion with Reviewers

Reviewer I: What is the influence of the water flow and the fine water mist on the morphological changes in enamel and dentin? How is heat generated in enamel and dentin?

Authors: We think that the morphological changes in enamel and dentin depend on the anatomical structure of hard dental tissues and their degree of mineralization. Enamel is a compact highly mineralized tissue with the inclination to crack. We observed this process not only in extracted teeth, which are brittle, but also when we checked the enamel surface in the patients. The structure of dentin and the water mist help to dampen the microexplosions.

H.E. Goodis: Please describe the laser equipment used in this study in more detail. In particular, how was it proven that the Er:YAG laser was powerful enough? To what depth were cavities prepared? What were the remaining dentin thicknesses?

Authors: The influence of the laser system described in this study on the depth and profile of the drilling cavity was recently presented at another meeting (Dostálová *et al.*, 1995), and therefore, did not form part of the present study. From our previous studies and clinical practice, we conclude that optimal and safe laser systems have energies from 200 to 300 mJ and repetition rates from 0.5 to 2 Hz. The preparation using a repetition rate of 0.5 Hz is slow, but not insufficient.

H.E. Goodis: How do your micrographs demonstrate cracking due to extraction or after laser exposure?

T.D. Myers: Please explain the significance of the micrographs taken before laser ablation.

Authors: We took photomicrographs before laser ablation, to have the possibility to investigate the tooth surface before preparation, and after laser ablation, to check for the occurrence of cracks before SEM. The procedure of making photomicrographs has been published previously (Dostálová *et al.*, 1994, text reference).

H.E. Goodis: The authors have not proved that heating by laser caused the cracks as no temperatures were taken. Please comment.

Authors: We do not think that it is possible to carry out an experiment that both measures temperatures and evaluates teeth in polarized light, because it would be necessary to install a thermocouple in the pulp cavity with the help of a classical drilling machine. This would cause us to observe the effect of mechanical vibration and temperature increase on the teeth.

A.F. Paghdiwala: The authors state that ablation of hard dental tissues with water flow was not as effective. Since this is a significant statement that can influence laser delivery systems, it should be mentioned that the rate of water flow was not measured. Also, only one energy level (200 mJ/pulse at 0.5 Hz) has been studied. It is possible that under different rates of water flow or different laser energy levels there might not be enough laser energy left to cause ablation in tissues in spite of the attenuation of the Erbium laser energy through absorption in the water, as shown by other researchers (Paghdiwala *et al.*, 1993, text reference).

Authors: Since we would like to explain the dependence of the ablation of the tissues, but also of the saturation of the laser system, on the focus, energy, and number of pulses, we carried out a new study which will be presented elsewhere. We agree that the effect of the water mist is not completely understood, but we think that the effect is connected with the microexplosions and saturation of the hard tissue during Er:YAG laser ablation. We do not agree with the explanation that the difference between wet and dry preparations is due to the absorption of energy in water because we found the same results also at higher energy (up to 500 mJ). If this explanation were correct, only water would be the optimal coolant, but water absorbs the laser energy, which makes the drilling effect insufficient.

J. Palamara: To what extent does the higher water content in the dentine, compared to that in the enamel, influence whether crack formation occurs at the edge of the crater?

Authors: Micro- and macrocracks were observed, in the absence of water cooling, in enamel but not in dentin. We think that this depends on the structure of the hard dental tissue and its degree of mineralization. The theory that the difference is due to the higher water content in dentin could well be correct. We think that the enamel as a whole is fragile. In control specimens, many cracks in the enamel, not only in extracted teeth but also *in situ* in patients before laser treatment, were observed.

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