

Indications and limitations of Er:YAG laser applications in dentistry

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ABSTRACT: Purpose: To describe the development, indications, and limitations of Er:YAG lasers in the dental field. **Methods:** A review based on the literature search in PubMed and completed by other documents was performed. **Results:** Based on the synthesis of the reviewed literature different topics concerning the Er:YAG effects and applications in dentistry are discussed and recommendations for the use of this type of laser are given. (*Am J Dent* 2006;19: 178-186).

CLINICAL SIGNIFICANCE: This literature review allows the practitioner to better decide on the proper indications and limitations of Er:YAG lasers in dentistry.

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Introduction

Since the early 1960s, lasers have been used in medicine and dentistry. Research and studies have prepared the pathway for cavity preparation without pain and discomfort. Different wavelengths have been tested with variable results and several lasers have shown serious side-effects which could cause damage to dentin and enamel while insufficiently cutting dental hard tissues.¹ Stimulated emission from Er³⁺ ions in crystals of yttrium, aluminum and garnet was presented in 1975, preparing the pathway to a new type of laser called Er:YAG.² Its emitted wavelength of 2940 nm matches exactly the maximal absorption in water, being about 15 times higher than the absorption of a CO₂ laser and 20,000 times that of a Nd:YAG laser.³ Also well absorbed in hydroxyapatite, this laser seems to have been made for effective removal of dentin and enamel with only minor side-effects such as thermal damage. The potential of Er:YAG lasers (ERL) for the ablation of hard tissue in dentistry was demonstrated already in 1989.⁴ Since its first introduction for dental use in 1992, Er:YAG lasers have been increasingly used in dental practice and are becoming more and more a comfortable method for caries removal for patients, as conventional cavity drilling may cause noise and pain. An increasing number of manufacturers have marketed Er:YAG lasers (ERL) since 1997, when this type of laser received FDA approval for caries removal and cavity preparation in the United States.

Overview of Erbium:YAG lasers for dental use

The first available system on the market, the Key Laser 1, was introduced by KaVo^a in 1992 and was further developed in Key Laser 2 and Key Laser 3. Nowadays many manufacturers are marketing Er:YAG lasers with important differences in their technical specifications (Table). The available maximum pulse energies range from 300 mJ (DELIGHT^d), over 600 mJ (Key Laser 3), 700 mJ (Smart 2940D^e), up to 1000 mJ (Fidelis Plus II^c and Opus Duo^b). The output power, which is the product of pulse energy times repetition rate, goes up to 12 W (Opus Duo) or even 15 W (Fidelis Plus II). For minimally invasive dentistry with an Er:YAG laser as an alternative to conventional mechanical drill a power of 10-12 W seems to be sufficient.⁵ Consequently, there seems to be no real need for the development of more powerful Er:YAG lasers, because when

Table. Main representatives of Erbium:YAG (Wavelength: 2.94 μm) lasers currently available on the market.

Opus Duo, Opus Dent ^b
Power up to 12 W
Pulse energy 100 - 1000 mJ
Pulse repetition rate 7 - 20 Hz
Pulse duration 250-400 μs
Flexible hollow fiber
Spot size up to 1.3 mm
Aiming beam with red diode laser, 3 mW, 635 nm
Contact, near-contact and non-contact
Sapphire tips: conical 200 - 1000 μm (contact and non-contact) and 1300 μm non-contact tips
Hollow metal contact tips for soft tissue cutting
Combined with a CO ₂ laser
Fidelis Plus II ^c
Power up to 15 W
Pulse energy - 1000 mJ
Pulse repetition rate 2 - 50 Hz
Pulse duration 100 - 1000 μs
Articulated arm with mirrors
Focusing handpiece, Sapphire tips
Combined with a Nd:YAG laser
DELIGHT ^d
Power up to 6 W
Pulse energy - 300 mJ
Pulse repetition rate up to 30 Hz
Pulse duration 200 μs
Fiber with bare fiber applicator, max 400 μm
Sapphire tips/hollow tips, bare fiber
Key Laser ^a
Power up to 6 W
Pulse energy 10 - 600 mJ
Pulse repetition rate 1 - 25 Hz
Pulse duration 250 - 500 μs
Focusing handpiece
Smart 2940 D ^e
Pulse energy up to 700 mJ
Pulse repetition rate up to 20 Hz
Pulse duration between 80 and 450 ms
Articulated arm with 7 mirrors
Aiming beam laser diode 5mW 680 nm

speeding up treatment by increasing pulse energy and/or repetition rate, more side effects such as leaflets and cracks may appear, especially in enamel. Ablation is already sufficient at a power of around 6 W in dentin and a very fast ablation, especially in deeper dentin layers, is possible with a power of around 10 W. Recently, an increased effectiveness using the so-

called very short pulse (VSP) is discussed, pretending that the typical debris cloud formation above the ablated surface negatively influences ablation speed by partially absorbing energy of the following laser pulses. According to Lukac *et al.*,⁶ the most effective ablation is reached with pulse lengths less than 100 μsec , but this study used vertical irradiation of the tooth surface, which did not allow a flush of the debris cloud by the spray device.

The laser beam is transferred to the operation field by water-free glass fibers (KaVo, DELight), articulated arms with mirrors (Smart 2940D, Fidelis Plus II) or flexible hollow fibers (Opus Duo). Although a glass fiber delivery system is very easy to handle, there is a limitation in maximal power transmission at about 6 W. Therefore, more powerful Er:YAG lasers need a hollow transmission system for their light. Among them, the flexible hollow fiber from Opus Duo is more suitable for the daily use because of its better handling than the articulated arms used for example by Fidelis Plus II or Smart 2940D. With the exception of Opus Duo, all systems deliver a focused beam and this specification may be of much importance for an even distribution of the power density on the working surface, especially during smoothing and conditioning of the enamel structure that is superficially destroyed during cavity access and preparation with high energy densities. The spatial beam profile after transmission through the flexible hollow fiber has not been reported in the literature. A water-free glass fiber has a quasi-Gaussian shape, whereas articulated arms achieve a distribution of even higher orders with an important maximum around the central peak, or a ring-shaped intensity distribution.⁷ However, even if different beam transfer technologies may have different advantages and disadvantages, it is impossible to compare different laser systems based on this property or on their parameter settings. Many factors, such as pulse formation, pulse width, beam profile and others have to be brought in relation to each other to allow an accurate comparison of their clinical efficiency.⁷

Most manufacturers propose sapphire contact tips for tooth preparation, with similarly looking handpieces. The range of tip diameters goes from 400-700 μm (DELIGHT) up to 200 μm -1300 μm proposed by Opus Duo. A non-contact focusing handpiece used for hard tissue preparation by the Key Laser 3 (the sapphire tips of Key Laser 3 are exclusively designed for periodontal applications) is also proposed by some other manufacturers, but a precise working, especially in the means of minimally invasive dentistry where aiming accurately with the beam is of high importance, is very difficult. As a complementary tool to the Er:YAG laser, two manufacturers have included in their system a second laser emitting another wavelength, as Nd:YAG (Fotona) or CO₂ (Opus Duo). The Nd:YAG may offer wider indications in endodontology, whereas Er:YAG in combination with CO₂ may allow a complete coverage of almost all dental indications assisted by a laser, except bleaching.

Ablation mechanism and ablation speed

Due to its wavelength of 2.94 μm , which matches exactly the absorption peak of water and which is also absorbed by hydroxylapatite, erbium laser radiation is very efficient in removing both dentin and enamel, limiting the laser effect on these tissues to a superficial layer of a few micrometers. This superficial layer can rapidly be heated up so that the pressure

within the irradiated volume increases until the material's strength is surpassed. The overheated water abruptly vaporizes and the so released vapor carries away surrounding broken tissue fragments in a thermomechanical ablation process. Increasing the power, especially when q-switching the laser, accelerates the ablation process, decreasing simultaneously the thermal side effects but resulting in higher mechanical side effects.^{5,8} Efficient removal of dentin and enamel by using Er:YAG lasers could be demonstrated from the very beginning in 1989, while sparing the surrounding tissue.⁴ The shorter the pulse length, the lower the energy density needed for ablation. The ablation threshold of Er:YAG lasers ranges between 6 J/cm² for 100 μsec pulses and 10 J/cm² for 700 μsec pulses.⁹ This means that the Er:YAG laser is the most efficient of all known systems for hard dental tissue removal. The Er:Cr:YSGG laser, for example, needs more energy density, ablation starting at 10 to 14 J/cm.^{2 10}

Carious dentin is removed at the same speed with Er:YAG lasers as with the classical bur method.¹¹ When associated to Carisolv^f pre-treatment, the ablation speed in carious dentin is higher than with the laser only.¹²

To increase ablation speed in enamel, a laser-abrasive method using sapphire powder in the water spray, accelerated by laser irradiation, was investigated. The aqueous suspension of sapphire particles increased three times the efficiency of enamel removal when compared to Er:YAG with water spray alone, approaching those of a high-speed turbine.¹³ However, as the spreading of the sapphire particles may cause side effects to the surrounding tissues, this method may not be further pursued.

In general, there is a linear relationship between crater depth or removed volume and applied energy density.¹⁴ Water mist is needed to avoid thermal side effects and for pain control. However, it only has a minimal effect on the ablation speed up to an energy of approximately 400 mJ.¹⁵ If using energies of 400 mJ and above, increased water flow increases ablation efficiency in enamel. In dentin, no significant difference was observed with a higher water flow rate at higher energies due to dentin's higher water content compared to enamel.¹⁶

When surrounded by enamel, certain selectivity for the ablation of composites was shown, as enamel ablation is slower than ablation of composites. However, this selectivity is compromised in dentin because of a higher ablation rate of dentin compared to some composite brands, due to the higher water content of dentin.¹⁷ No quantitative information is available on the ablation rate of dental ceramics, glass-ionomer cements and gold. Crater formation was reported after the application of Er:YAG laser beam on amalgam surfaces associated with a substantially increased release of Hg vapor.¹⁸

Morphological changes

Cavity walls and borders disclose typical morphological aspects after ablative Er:YAG laser treatment. Only minimal, if any, damage of surrounding dental hard tissues can be detected by use of optical and SEM microscopes.¹⁹ The smear layer is efficiently removed. In fact, in comparison to Nd:YAG or argon lasers, Er:YAG is the most effective for smear layer removal.²⁰ Neither Knoop hardness nor Ca/P ratio evaluations on the cavity floor revealed any significant difference between laser and bur treatment. If any, only minimal thermally induced

changes of dental hard tissue composition is produced by Er:YAG²¹ and only minimal local thermal damage follows Er:YAG irradiation.²² A difference is seen in the basophilic layer which is deeply stained on Er:YAG treated sites compared to bur-treated dentin. Less odontoblastic processes remain after Er:YAG treatment, related to a probable denaturation of the dentin organic matrix.²³

By comparing pulse duration times of 100 to 1000 μsec using the same energy, different results were found for chemical and structural modifications of dentin. Treatments with very long pulses of up to 1000 μsec resulted in a dentin surface with chemical and morphological characteristics very similar to that obtained with conventional methods; while with very short laser pulses (VSP), a strong modification of collagen aliphatic chains was observed.²⁴ Affecting the surface morphology and the chemistry of dentin may influence the bond strength to dental restorative materials and may necessitate the development of specific dentin adhesive systems for VSP laser-treated surfaces.²⁴ At the present time, no information is available on subsurface damage in enamel after the application of VSP.

Enamel acid etching after laser treatment increases the etching depth if evaluated with the help of X-ray tomography.²⁵ If the Er:YAG was water cooled, occlusal enamel fissures were debris-free and etching-like patterns were detected. On the other hand, when only air cooling was used and the enamel was treated in contact, melting and re-crystallization of enamel fissures occurred.²⁶

Pulp response

The thermal danger of any new cavity preparation procedure has to be investigated, as classical techniques line up with a high level of security in their application. Overheating of teeth, especially pulp damage and inflammatory response of the pulpal tissue during or after laser-treatment must be avoided.

Very low to slight temperature rise in the pulpal chamber has been reported, ranging from an initial decrease due to the water-spray cooling²⁷ to a rise of 3°C.^{28,29} Highest temperature increases in the pulpal chamber were measured at a maximum of 4°C³⁰⁻³² and 5°C,³³ under different treatment parameters. An important increase in temperature was only recorded in case when the laser beam hit directly the measuring probe after pulp exposure.²⁷ A difference between occlusal and cervical cavity preparation was found: the highest values were found during Class I preparations, followed by Class V in enamel. The lowest temperature increase occurred during caries removal or preparation in cementum.³³

No significant difference to classical preparation methods in respect to inflammatory reaction of the pulp was found as odontoblasts remained of spindle-like or star-like shapes³⁴ and immuno-histochemical analyses demonstrated similar effects to those after conventional bur methods.²⁰ The pulpal tissue directly exposed to laser treatment displayed no bleeding but some blood extravasations were found near the exposure site. After direct pulp exposure with 34 mJ/pulse, no inflammation or resorption was found and a potential for pulpotomy with the Er:YAG laser was claimed.³⁵ However, a good healing capacity of laser exposed pulp tissue was demonstrated, with formation of dentin bridges and reparative dentin.³⁶ Under long term *in vivo* observation, distinct tertiary dentin apposition, with cu-

boidal cells on its pulpal aspect were found.³⁷ Both sufficient wetness of the treated tissue and appropriate water-spray cooling and tissue re-hydration seem to be important parameters to avoid symptoms of pulpal damage.²⁹

Desensitizing effect

Cervically exposed hypersensitive dentin reportedly reacts positively to the application of many different kinds of desensitizing liquids.³⁸ The difficulty remains in the maintenance of the positive effect on even short or mid-term time periods. When applied with appropriate parameters, Er:YAG laser light seems to become an alternative for desensitization of hypersensitive cervical dentin. Applied with subablative 80 mJ/pulse at 3 Hz, the discomfort immediately improves, and remains even after a 6-month period at the same level, whereas conventional methods resulted in a gradual return to the original level of discomfort.³⁹

Caries prevention

Controversial results can be found in the literature regarding demineralization and acid-resistance of enamel and dentin after Er:YAG laser treatment. If after subablative Er:YAG irradiation a decline of 20% in calcium solubility in enamel was found, the effect was not judged sufficient to prevent caries.⁴⁰ In addition, subablative Er:YAG radiation seemed to produce fine cracks in the enamel surface.⁴¹ If using ablative laser energies of 400 mJ, lowest acid demineralization in enamel and dentin was found after dry laser treatment. However, on the micromorphological level, this treatment method induced thermal damages.⁴² Higher demineralization to a depth of 133.9 μm was found at restoration margins in enamel, when lased samples were subjected to a pH-cycling model, compared to unlased samples with a demineralization depth of 77.4 μm .⁴³ In a model using lactic-buffer solution, dissolved calcium and phosphate and their Ca/P ratio was not different in lased and unlased samples on bovine dentin, which suggests that Er:YAG laser irradiation does not increase nor decrease any acid resistance of dentin.⁴⁴ In an *in vivo* pilot study, the caries resistance following subablative erbium laser irradiation was determined by analyzing the demineralization before and after wearing for 1 week *in situ* (in the volunteers' mouths) treated and untreated enamel samples. Whenever a tendency towards increased caries resistance was described, it failed to reach statistical significance.⁴⁵

On the enamel surface, Er:YAG laser treatment combined with APF (acidulated phosphate fluoride) resulted in the lowest decrease of surface microhardness and the Er:YAG laser influenced the deposition of CaF_2 on the enamel.⁴⁶ If a superficial anti-cariogenic action can be induced, it is not possible in depth.⁴⁶ A laser-induced caries preventive effect is substantiated according to the "organic matrix blocking theory", whereas laser treated enamel confirms laser-induced blocking of the organic matrix in the micro-diffusion pathway in enamel.⁴⁷ In an artificial caries model, a significant reduction of secondary caries formation was demonstrated, with an important reduction of 56% of primary enamel surface lesion depth and a 39% reduction of root surface lesion depth, compared to classical bur and acid etch technique.⁴⁸

Bactericidal effect

Very early in laser-therapy, the bactericidal effect of laser

light was advanced to be one of the beneficial side effects associated with this kind of treatment. It is especially interesting to mention that wavelengths well absorbed in water have a good bactericidal effect even at low energy density output levels, starting at 0.3 J/cm², without excessive temperature elevation.⁴⁹ This may be one of the reasons why Er:YAG laser seems to be an efficient alternative for non-surgical periodontal treatment: Er:YAG laser treatment significantly reduces probing depth (PD) and bleeding on probing (BOP) and improves clinical attachment level (CAL) compared to the classical treatment strategy with scaling and root planning.⁵⁰ Even a decrease of endotoxins and lipopolysaccharides on root surfaces were observed, with a reduction ranging from 61% up to 93%, with the effect starting already at subablative energies of 60 mJ. Similar to these results on dental root surfaces, a bacterial reduction on implant surfaces can be reached up to 99.51% with 60 mJ and 99.94% with 120 mJ, without excessive temperature elevation and without morphological changes of the implant surfaces.⁵¹

In endodontics, a mean bacterial reduction exceeding 99% was observed, similar to the one after Nd:YAG and Ho:YAG laser treatments.⁵²⁻⁵⁴ Due to its complete absorption in water and dentin, Er:YAG acts on the surface of canal walls only.⁵⁵ This effect avoids uncontrolled light penetration into the surrounding tissues that may for example be observed with diode, Nd:YAG and Ho:YAG lasers and makes the laser very efficient.⁵⁶ The disadvantage of this effect is that if the Er:YAG cannot reach to the working length and is for example 3 mm short, 70% of the root canal specimens irradiated remain infected.⁵⁷

A dependency of applied power specific for the different bacteria species was demonstrated.⁵⁸ Though therapeutic, subablative laser light doses can lead to one-step disinfection including anaerobic micro organisms.⁵²

Pain perception

As Er:YAG lasers can be used to prepare cavities without thermal damage and the systems available on the market offer a high ablation efficiency, it was of interest to investigate the patients' subjective perception of this treatment method: cavity preparation with the help of Er:YAG laser was found to be more comfortable in the patients perception than mechanical treatment, in at least 80% of the cases.^{59,60} Only in exceptional cases local anesthesia was needed for cavity preparation and this was always limited to patients who complained of cervical dentin hypersensitivity before treatment. No or little pain response, which was reported as a feeling of a brief pressure to the tooth, was felt in 93% of the laser-treated teeth.⁶¹

One of the parameters partly explaining the absence of pain perception is the difference in tooth vibration speed caused by Er:YAG laser *versus* the high-speed drill. Mean vibration speed during laser cavity preparation reaches 166 +/- 28 µm/second, at a characteristic frequency of 230 Hz, whereas the high-speed drill induces a 100 times higher vibration speed of 65 +/- 48 mm/second, at 5 kHz. In addition, this much higher frequency has its spectrum near the peak sensitivity of hearing, as a potential factor of discomfort and pain provocation.⁶²

Another explanation for mechanisms of pain reduction in Er:YAG cavity ablation might be the disruption of nerve terminals in the dentin tubules, combined with a degeneration

of nerve terminals between the odontoblasts and the disruption of the myelin sheath in the pulp core, which were demonstrated by using transmission electron microscopy.⁶³

Tensile bond strength (TBS)

Contradictory results and conclusions may be found on tensile bond strengths after laser treatment in the literature, may be because of the fact that many different experimental setups have been used.

If no difference was found between Er:YAG lased or turbine drilled dentin,⁶⁴ best results were found with a self-etching primer (Clearfil Liner Bond 2V[®]) regardless the surface treatment.⁶⁵ The effect of acid conditioners on resin bonding to dentin differed according to whether the dentin had been laser irradiated or not⁶⁶ and for Optibond FL,^h (etch & rinse) etching of the lased dentin surface was found to be mandatory.⁶⁷ TBS for single bottle bonding systems, such as Excite,ⁱ and Gluma One Bond,^j were negatively affected by laser irradiation.⁶⁷ When combined with phosphoric acid and air powder treatment, better results were found than for Er:YAG alone,⁶⁸ but other authors found worse results in lased samples after citric acid and HEMA treatment compared to unlased samples.^{69,70} For Clearfil SE,^g and Optibond FL with Z100^k composite, TBS was always lower for Er:YAG than in bur-treated samples.⁶⁷ Contradictory results and conclusions were found for Bond 1,^l with Alert,¹ where Er:YAG treatment preceding phosphoric acid treatment improved tensile bond strength compared to acid treatment alone.⁷¹ In the same model, Optibond Solo,^h with Prodigy,^h and Single Bond,^k with Z100, behaved worse, regardless if pre-lased or not. Other authors found indications that laser-irradiated samples had improved bond strengths compared to acid-etched and handpiece drilled controls. Their conclusion was that preparation of dentin with Er:YAG treatment leaves a suitable surface for strong bonding.⁷² If TBS to superficial dentin is compared to deep dentin (at 2 mm distance to the dentin-enamel junction), results showed that it was mandatory in both cases to use a conditioning agent, such as a self-etching primer system, when Er:YAG laser was used. In deep dentin, best results were achieved with a combination of Er:YAG laser treatment and conditioner.⁷³

Many authors found similar TBS after Er:YAG-only treatment compared to acid-etched samples.^{74,75} If Er:YAG treatment was combined with acid etching, higher bond strengths were found than with laser treatment alone.⁷⁶ After a complementary treatment with an ultrasonic scaler, TBS was doubled if compared to lased-only samples.⁷⁷ With self etching systems (Clearfil SE) or etch and rinse systems (Optibond FL), lower TBS were found than in diamond bur samples.⁶⁷ Some authors, using low energy levels (maximum 120 mJ), found higher TBS for orthodontic brackets in lased enamel samples,⁷⁸ while others, using energy of 200 mJ, found the opposite.⁷⁹ An interesting study compared different water cooling flow rates during laser treatment on dentin and enamel. If TBS on dentin was not adversely affected by different water flow rates, it was of importance to optimize the water flow on enamel to prevent the formation of non-apatite CaP phases on the enamel surface, which may compromise adhesion. Relatively high TBS were realized without acid etching when a copious water flow was applied during the Er:YAG laser treatment.⁸⁰

For composite repairs, Er:YAG laser as the conditioning

method, showed a significant improvement in TBS in comparison to classical methods such as air-abrasion, silanization, hydrofluoric acid and their combinations, reaching mean values of 22.92 MPa.⁸¹

Microleakage and marginal adaptation

As Er:YAG lasers work in a "mechanical" way, with micro-explosions due to instant vaporization of the water contenting tissues, it is not the same for the very fragile and brittle enamel structure if high or low energies are applied, comparable to drilling with different diamond grain sizes.⁸² Most of the studies available on microleakage and marginal adaptation used Er:YAG with high energies, over 300 mJ. These energies induce subsurface damages into enamel. It is thus not surprising that many publications reported poor marginal adaptation with a high degree of microleakage⁸³⁻⁸⁷ and that acid etching of enamel following Er:YAG, as a kind of finishing of enamel, gave much better results.^{83-85,88} As soon as low energies were used for cavity preparation, microleakage of laser and bur-treated cavities was not significantly different.⁸⁹⁻⁹⁴ Some studies using dye penetration even presented less microleakage.^{19,95} The problem is that the preparation with low energies requires a very long treatment time, compromising the use of Er:YAG laser in the routine clinical setup. It seems to be necessary, the same as after classical bur treatment, to smoothen the cavity surfaces and margins after the efficient cavity preparation using high energy settings. Using ultrasonic scalers,⁷⁷ air-abrasion techniques⁶⁸ and laser finishing, even when combined with acid etching^{83-85,88} have already been tried out as adequate finishing methods to improve marginal adaptation with less microleakage present.

Primary teeth

Compared to the smooth appearance of the cavity walls after bur preparation, cavity margins and walls are irregular but without any smear layer after ablative Er:YAG irradiation.¹⁹ Dye penetration in restorations where cavities were prepared by Er:YAG and filled with composite in primary teeth was less than by mechanical bur.¹⁹ Other studies found no difference between microleakage of resin composite restorations after laser treatment only or after bur preparation and phosphoric acid etching.⁹⁶ In Class II restorations with composite or compomer, dentin bonding remained a problem with or without laser treatment, whereas in Class V compomer or composite restorations in primary teeth, good results with over 90% of perfect margins were found after thermal cycling.⁹⁷

Due to its bactericidal effect combined with the reduced pain sensation during its application, the Er:YAG laser was a very promising tool for cavity preparation in primary teeth. However, detailed parameters and clinical treatment protocols have to be defined in the future.

Pits and fissures

The bactericidal effect of Er:YAG laser irradiation could boost the interest in the already widely accepted pits and fissures sealing procedures. A simultaneous cleaning, conditioning and decontamination in hardly accessible depths of fissures would open a new perspective to this preventive treatment.

As the prismatic structure of enamel is very sensitive to mechanical stress, a precise range of correct conditioning parameters for pits and fissures by erbium lasers must be estab-

lished, in order to allow an at least equal sealing quality to conventional methods, with the advantage of cleaning and decontamination in only one step and with a single device only.

Occlusal fissure sealings treated exclusively by Er:YAG provided poor marginal adaptation compared to acid-etched groups. Er:YAG pretreatment and subsequent acid etching with highly concentrated phosphoric acid was equivalent to etching only.⁸⁴ No significant difference in microleakage was reported between extended fissure sealing with a bur and phosphoric acid-etching or Er:YAG and phosphoric acid-etching. Laser irradiation did not eliminate the need for etching enamel as the laser only group showed the highest microleakage values.⁹⁸ Most of the available studies used ablative parameters for enamel conditioning. A testing of low energy levels for fissure decontamination exclusively by Er:YAG, at a maximum of 100 mJ would be of interest.

Acid etching after laser treatment of the enamel margins increased the etching depth under microtomography control.²⁵ Fissures were debris-free and etching-like patterns were found in Er:YAG treated occlusal fissures when the tooth was water cooled during laser application. When only air cooled and treated in contact, melting and re-crystallization of fissure enamel occurred.²⁶

Further investigations, using parameters preventing from scattering and leaflet-producing on the enamel surface, are needed for secure and predictable results.

Endodontics

A comparison of conventional root canal preparation with Er:YAG laser using 200 to 400 μm microprobes showed that in straight root canals, enlarging, shaping, and cleaning is faster and more efficient with the laser and that no residual pulp tissue was present after laser application.⁹⁹ Canal walls free of debris, evaporated smear layer and open dentin tubuli were reported after Er:YAG laser application,^{100,101} under some specific conditions even near the apical orifice.¹⁰² Er:YAG efficiently removed the smear layer in the root canal if water was used as the irrigating medium¹⁰³ and its bactericidal effect in root canals is well documented.^{52-55,58} However, in spite of the absence of smear layer, no significant difference in respect to leakage of classical root canal obturations between laser treated and conventionally treated root canals has been detected so far.¹⁰⁴

Periodontology

Based on its good absorption in water and in dental hard tissues, the Er:YAG laser suggested itself for evaluation in the field of periodontology. In comparison to ultrasonic scaling, a similar removal of calculus can be obtained but superficial structural and thermal micro-changes in the form of micro-roughness were found on root cementum.¹⁰⁵ An important parameter to define was the threshold level for cementum ablation, being 10.6 J/cm² per pulse.¹⁰⁶ So it is not surprising that adversary results are obtained, *e.g.* in comparison to classical scaling and root planing (SRP) *in vivo*. While the Er:YAG is capable of removing calculus, its effectiveness is lower than the SRP method, but without removing cementum, especially if an active selectivity feedback system is built in, as is for example the Key Laser 3. However, if Er:YAG was less invasive than the conventional method, it needed twice the time of SRP.¹⁰⁷ Using low radiation energies, calculus removal can

be done with a certain selectivity, comparable to that of conventional root surface instrumentation. It is possible to remove calculus with a significant selectivity of more than 4.5 times than for root surface material.¹⁰⁸ Compared to a treatment with a diode laser, which is not sensible for calculus removal and alters the root surface in an undesirable manner, Er:YAG combined with a calculus detection system can remove calculus on a level equivalent to SRP.¹⁰⁹

After Er:YAG treatment of periodontal pockets *in situ* on corpses, thermal changes on root surfaces with ultra structural irregularities at the apical end of Er:YAG scaling tracks were found, with energies ranging from 60 to 180 mJ.¹¹⁰ Copious water spray minimized thermal effects and led to cleaner and less porous surfaces.¹¹¹ Angulation had an important influence on the amount of root substance removal, reaching from very slight at a tip angulation of 15°, to severe ablation of more than 400% at (clinically impossible) angulation of 90°.¹¹²

Most probably as a result of the elimination of bacteria and endotoxins on root surfaces, human gingival fibroblasts adhere and grow significantly faster on a 60 mJ Er:YAG pretreated surface than after SRP.¹¹³ After incubation with human fibroblasts, cell count in the Er:YAG group was 1.5 times higher than with an ultrasonic treatment, 2.7 times higher than with SRP and 4.5 times that of the control group.¹¹⁴

Clinical parameters as plaque index (PI), gingival index (GI), probing depth (PD), bleeding on probing (BOP) and clinical attachment level (CAL) improve more after Er:YAG laser treatment than after SRP. It is also of interest that Er:YAG alone reached the same scores than combined treatment using ERL and SRP, and that these two groups scored clearly better than the SRP method alone.¹¹⁵ A follow-up study on periodontal conditions over 2 years showed better long term prognosis for Er:YAG treatment alone than for SRP. Results of CAL improvement in comparison to the attachment level at the beginning was 28.5% after 1 year for Er:YAG and 13.8% for the SRP group. After 2 years, still 22.2% improvement was found compared to 10.7% for the SRP group. Clinical attachment level improvement after Er:YAG laser treatment was twice the one of the classical approach.¹¹⁶

Bone tissue and implantology

The Er:YAG laser is able to cut bone tissue. Compared to mechanical bur and CO₂ laser groups, Er:YAG irradiated bone tissue showed a more pronounced inflammatory cell infiltration, fibroblastic reaction and a faster revascularization adjacent to the irradiated bone surface. In addition, a significantly greater and more rapid bone neo-formation was observed.¹¹⁷

Even after a long irradiation period of up to 120 seconds, temperature rise at an implant-bone interface was low¹¹⁸ allowing postulation that peri-implantitis therapy with Er:YAG is clinically safe. After direct Er:YAG treatment and ablation of bone, the chemical composition of the remaining bone was similar to that following bur drilling.¹¹⁹ It was also possible to create smear layer free grooves with well defined edges, representing an alternative method for safe oral and periodontal osseous surgery.¹¹⁹ A layer of only 30 µm thickness presented a changed ultrastructure with microcracking, disorganization and slight re-crystallization of the original apatite and a reduction of the surrounding organic matrix.¹²⁰ On the implant side, surface alterations such as partial melting, cracking and crater forma-

tion became obvious under certain conditions, but with clinically inadequate high power output and always less pronounced than after Nd:YAG or Ho:YAG irradiation.¹²¹ As a consequence of these findings, power output must be limited to avoid surface damage, but already with low output energies under water spray, Er:YAG is able to effectively remove plaque and calculus on implant abutments without injuring their surfaces.¹²² The instrumentation of titanium implants resulted *in vivo* in effective removal of subgingival calculus without any thermal damage¹²³ and showed a high bactericidal effect on implant surfaces, with a bacterial reduction of up to 99.94%.⁵¹ Even the second stage implant surgery with Er:YAG was safe and minimized intra- and postoperative pain. An already complete tissue healing by Day 5 *in vivo* speeded up prosthetic rehabilitation compared to classical methods.¹²⁴

Conclusions

Since the first publication dealing with Er:YAG application in dentistry in 1989 by Hibst & Keller,⁴ numerous articles concerning the use of Er:YAG lasers in dentistry have been published. These publications answer many questions, but leave many questions open.

There seems to be a general consensus on the fact that Er:YAG is one of the best suited laser types for cavity preparation because its efficiency, especially in dentin, is very good without any danger of pulpal damage if working under sufficient water cooling. In addition, important pain reduction in comparison to bur-assisted preparation has clearly been demonstrated making it possible to work without local anesthesia in most instances. Together with its suitability for minimally invasive dentistry, this point predestines the Er:YAG to be an ideal tool for cavity preparation in both primary and permanent teeth in the field of pediatric dentistry. Another advantage is its bactericidal effect and the possibility of desensibilization of dentin with subablative energies. It is important to realize that after a coarse cavity preparation with high energy pulses a finishing of enamel margins has to be done with reduced energy density to avoid subsurface damage and to optimize marginal adaptation of adhesive restorations. The necessity of finishing enamel after cavity preparation with high energies is in analogy to enamel finishing with fine grit diamond burs after classical bur excavations.

As laser-treated dentin and enamel surfaces may have other properties than bur drilled enamel and dentin, specifically laser-optimized adhesive systems and restorative materials may be one of the next steps of the development of restorative systems.

Er:YAG is also efficient in removing composite restorations, however, little is known on its ability to ablate dental ceramics, glass-ionomers and gold. Ablation of amalgam should be avoided, because it is not efficient and because it leads to mercury evaporation. Further research in the field of cavity preparation may focus on optimizations in pulse morphology, application systems and caries selectivity.

Pits and fissure sealings might become one of the important indications to treat with Er:YAG if, besides sterilizing the fissure, a perfect marginal quality of the sealing material can be realized. More research is needed to find optimal laser parameters and materials for this indication.

Er:YAG can cut bone. Open questions in this field are the definition of optimal laser parameters, if the use of a spray

system can be safely recommended and if the adjunction of physiological saline solutions does not affect the laser systems.

The decontamination of root canals by Er:YAG has been well documented. The excellent absorption of Er:YAG radiation by water and dentin prevents damage of the surrounding tissues, such as periodontium or bone. However, its limitation is the fact that if the working length cannot be reached by the delivery tip, no disinfection will occur. Further research is needed to extend the action of the Er:YAG laser beyond decontamination of root canals. The development of new devices allowing complete elimination of the smear layer on the entire canal length and on the entire wall surface would be highly welcome because it would allow for tight root canal obturation and/or cementation of posts.

The advantages of Er:YAG application in periodontology are based on the efficient elimination of bacteria and endotoxins on root surfaces in combination with the selective feedback, where the laser arrives to differentiate between calculus and tooth tissue. Further research is needed to optimize laser parameters, to improve treatment efficiency and to design optimal tips for periodontal indications.

Implantology may benefit from Er:YAG laser use for the decontamination of implant surfaces without injuring them and for second stage implant surgery.

- a. KaVo, Biberach, Germany.
- b. Lunenis Company, Yokneam, Israel.
- c. Fotona d.d., Ljubljana, Slovenia.
- d. Hoya ConBio, Fremont, CA, USA.
- e. DEKA-DLS, Florence, Italy.
- f. MediTeam Dentalutveckling AB, Sävedalen, Sweden.
- g. Kuraray, Osaka, Japan.
- h. Kerr, Orange, CA, USA.
- i. Ivoclar Vivadent, Schaan, Liechtenstein.
- j. Heraeus-Kulzer, Dormagen, Germany.
- k. 3MEspe, Minneapolis, MN, USA.
- l. Jeneric/Pentron, Wallingford, CT, USA.

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