ISSN 1855-9913

Journal of the Laser and Health Academy
Vol. 2012, No.1; www.laserandhealth.com

Quantum Square Pulse Er:YAG Lasers for Fast and Precise Hard Dental Tissue Preparation

Matjaz Lukac[1], Nina Malej Primc[2], Samo Pirnat[2]
[1]*Institute Jozef Stefan, Ljubljana, Slovenia*
[2]*Fotona, Ljubljana, Slovenia*

ABSTRACT

A highly significant difference has been reported in the adhesion strength between dental surfaces prepared with Er:YAG lasers and those prepared using conventional burs. The beneficial effect of Er:YAG laser cavity preparation is particularly pronounced when the laser is set to operate at super-short-pulse duration (SSP, 50 μs) and low energy (<90 mJ). However, when a VSP Er:YAG laser is set to operate in this regime, it's average output power is limited, making this treatment modality relatively slow. In this paper, we report on the use of a novel quantum-square-pulse mode (Fotona QSP) for higher bond strength cavity treatments that overcomes the above power limitation of Er:YAG lasers.

SEM micrographs of the surfaces prepared using the QSP mode are compared with those prepared with standard SSP and MSP pulse modes. The surfaces prepared with the QSP mode reveal the same surface quality as those prepared with the previously studied SSP pulses of low intensity. The QSP mode is thus indicated as an ideal treatment modality for fast, high quality, cavity preparations.

Key words: Er:YAG laser, cavity preparations, bond strength, quantum square pulse, QSP.

Article: J. LAHA, Vol. 2012, No.1; pp. 14-21.
Received: April 10, 2012; Accepted: May 04, 2012.

I. INTRODUCTION

The Erbium (Er:YAG) laser has become a standard tool in dentistry for minimally invasive removal of carious tissue containing bacteria without removing any sound hard-dental tissue. As opposed to the use of classical mechanical burs, the Erbium laser's removal of hard dental tissue is enabled by contact-less, optically induced micro explosions within the tissue. Substituting rotary instruments with Erbium laser technology has several advantages, such as reduced pain, and decreased noise and vibrations during cavity preparation. The Erbium laser is also partially selective in caries removal because of its higher absorption in the more humid carious tissue, compared to the surrounding healthy tissue [1-7].

When performing classical cavity preparations, the pre-treatment of dental tissue surfaces with acid-etching prior to adhesive restorative procedures is an extremely important step in the bonding protocol and determines the clinical success of restorations. Nevertheless, a disadvantage attributed to acid etching is the demineralization of tooth tissues, which make them more permeable and prone to acid attacks, especially if the demineralized substrates are not completely filled by adhesive resins. For this reason, an important additional potential advantage of the Erbium laser cavity preparation is that the Erbium laser is capable of creating a surface without a smear layer, similar to acid-etched surfaces, which should be favorable for bonding procedures [8,9].

The use of the Er:YAG laser for enamel and dentin pretreatment was reported to yield a microretentive surface and open dentin tubules, both apparently ideal for adhesion [10]. However, bond strengths to Er:YAG-irradiated tooth substrate that had been initially reported in the literature were confusing and even contradictory. This can be at least partially attributed to the fact that insufficient attention had been paid to the decisive role that the Er:YAG pulse duration and pulse energy play in the surface conditioning for better restorative adhesion. Only recently has it become understood that the pulse duration and pulse energy of the Er:YAG laser are very important factors influencing the bond strength of an adhesive to enamel and dentin [8,9]. This understanding has re-motivated research efforts towards elimination of the acid-etching step of an etch-and-rinse adhesive.

a) Er:YAG pulse energy and duration considerations

Most Erbium lasers use a standard PFN (Pulse Forming Network) technology to generate high-energy light pulses. This conventional method of energizing a flashlamp consists of discharging a pulse forming network (PFN) through the flashlamp [11]. PFN pulses have a typical temporal shape with a slow rise time and a long declining tail; the pulse power is not constant during the pulse and the exact pulse duration is not defined. Even more importantly, the pulse duration is not adjustable as it is determined by the hardware component values used in the PFN. However, as research has shown, control of the Er:YAG pulse duration is critical for the success of laser dental treatments. This has been made possible in recent years by the development of Variable Square Pulse (VSP) pumping technology [3]. This technological solution provides nearly square-shaped power pulses, the duration of which can be conveniently controlled over a wide range of pulse durations. The versatility and instantaneous power control enabled by VSP technology can be seen in Fig. 1, which shows different pulse durations and corresponding pulse shapes.

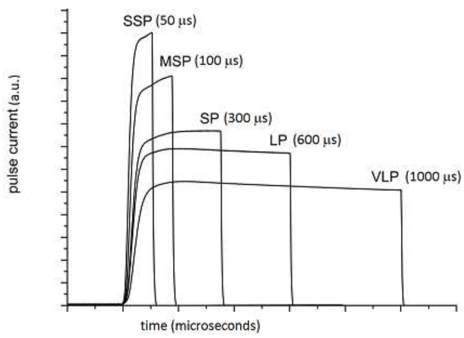


Fig. 1. VSP pulse shapes for different pulse durations (with a Fotona dental laser). Note that the rise and fall times are approximately the same for all pulse durations. Also, the pulse durations have no relationship with the rise and fall times. Data is from ref. 11.

Furthermore, the pulse shape in VSP technology should also be considered, as it has a strong influence on the pulse width and power. The pulse profile is controlled and allows the power within the pulse to remain approximately constant. This ensures that the pulse modality does not uncontrollably shift during a pulse from cold to warm and hot ablation, reducing the ablation and increasing the heating of hard dental tissue [12].

An Er:YAG laser based on VSP technology enables the selection of short pulse durations, which allow the speed of ablation to be faster than the diffusion of heat into the tissue, so that all of the laser energy is used for hard-dental-tissue ablation. This effect is less pronounced for longer pulses, during which ablation efficiency is reduced because of thermal effects [13-21]. In one of the most recently published studies [10], the measured ablation rates with Fotona SSP (50 µs) Er:YAG pulses (Fotona SSP pulse mode) was significantly higher in comparison with the longer Fotona MSP (125 µs) and Fotona SP (275 µs) Er:YAG pulses, as well as in comparison with the ablation speed of a steel bur (see Fig. 2).

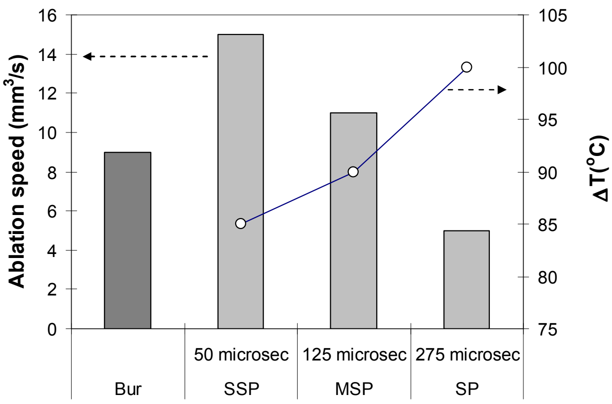


Fig. 2. Clinical ablation rate (in mm³/sec) of caries in dentin for different Er:YAG pulse duration modes of a Fotona Fidelis laser and for a steel bur. Ablation values are based on data from ref. 10. Published hard-tissue surface temperatures 2.5 ms following a laser pulse for different Fotona Er:YAG pulse durations are also shown. Temperature data is taken from ref. 17. Shorter pulse durations result in lower heat deposition and consequently higher ablation rates.

In the above study, the bur-treated group showed a dentin surface with a smear layer and closed dentinal tubules on SEM micrographs. In the VSP Er:YAG laser group with SSP, MSP, and SP pulse durations, the SEM micrographs revealed a dentin surface clean of a smear layer and with open dentinal tubules.

The absorption and scattering of a laser beam in tissue that has been removed in micro-explosions during laser irradiation also influence the ablation rate and the optical quality of the laser beam. Scattering lowers the ablation rate of hard dental tissue. Even more importantly, the scattering in the ablation cloud leads to the spreading of the laser beam, with the laser intensity at the edges of the beam coming close to or below the ablation threshold [12]. This results in an undesirable and uncontrolled heating of the hard tissue in this area (see Fig. 3).

The biggest “cloud” made of ablated particles of tissue is formed when longer pulses are used. However, scattering also affects shorter pulses when they contain high energy. This is due to the fact that at high pulse energies, i.e. high instantaneous pulse powers, the dynamics and the density of the ablation cloud are high [12].

Based on the above, the preferred Er:YAG laser pulses for surface modification during restorative procedures should be pulses of short duration (in order to reduce thermal deposition and scattering effects) and low pulse energy (in order to even further reduce scattering effects) [12]. This dependence was not fully appreciated in the early studies of bond strengths to Er:YAG-irradiated tooth substrate.

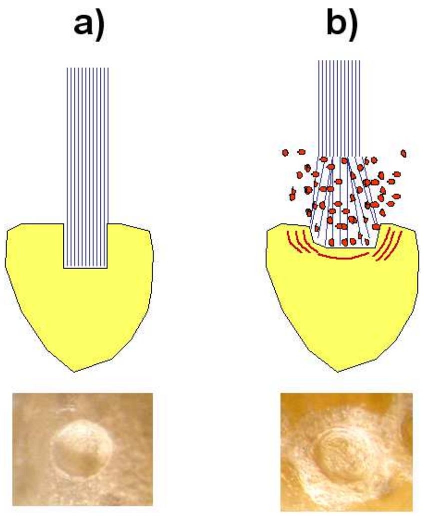


Fig. 3: a) During short Er:YAG laser pulses the ablation cloud does not have time to develop and the effects of scattering is small. Thermal effects are minimal, and the ablation is in the cold regime; b) During long pulse durations, the ablation cloud has sufficient time to develop and scatter the incoming laser beam. The laser intensity, particularly at the edges of the beam is sub-optimal, leading to heat deposition within the tooth. Ablation is reduced, and thermal effects are high.

b) Results of recent bond strength studies

The influence of pulse duration on the microtensile bond strength to Er:YAG-irradiated tooth substrate has been systematically examined in a recent study by Firat et al. (see Fig. 4) [9].

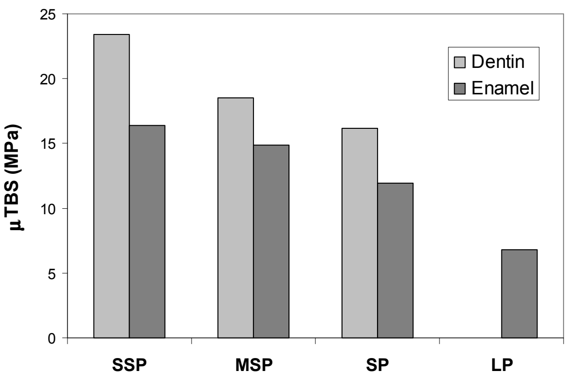


Fig. 4: Microtensile bond strength (µTSB) following hard-tissue preparation with Fotona SSP, MSP, SP and LP Er:YAG laser pulses. Values are based on data from ref. 9.

The µTBS of laser-pretreated teeth was observed to significantly increase with shorter pulse durations. Additional acid etching following laser treatment was shown to improve the µTBS for all pulse durations. However, the µTBS test results of enamel specimens showed that laser pretreatment of enamel with SSP pulse durations prior to acid etching significantly improved the bond strength in comparison to acid etching alone. In addition, the dentin group which was pretreated with 80 mJ (SSP) Er:YAG laser pulses exhibited a µTBS that can provide clinically sufficient adhesion without the application of acid etching [9].

The additional increase in the bond strength when short pulses with lower laser energies are used has been confirmed in a study by Bahrami et al. [8]. In this study, super-short (Fotona SSP) Er:YAG laser pulses were used for dentin conditioning. The first group (the control group) was prepared with a bur. The second group was prepared with Fotona Er:YAG SSP laser pulses at a relatively high pulse energy of 200 mJ. And one of the remaining groups was additionally surface conditioned with SSP laser pulses with a reduced pulse energy of 80 mJ. Composite resins (CeramX Duo, DENTSPLY, Germany) were placed on the treated surfaces, and the resulting shear bond strength tests were performed on a force sensor machine. The results are shown in Fig. 5.

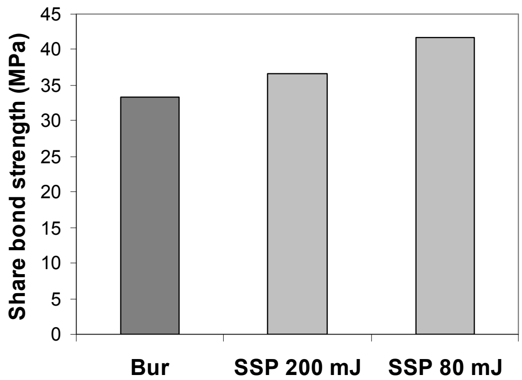


Fig. 5: Restorative shear bond strength following dentin preparations with standard bur vs. Fotona SSP Er:YAG laser pulses with energies of 200 mJ and 80 mJ (based on data from ref. 8).

The results demonstrated a highly significant difference in adhesion strength between the SSP 80 mJ Er:YAG laser-prepared group and the group prepared using the conventional bur. The application of a low-energy laser beam with a super-short pulse duration time (50 µs) markedly improved the strength of adhesion of the composite resin to the dentin.

Based on the above recent studies, laser pretreatment with SSP, low-energy Er:YAG pulses, especially in combination with acid etching, is the pretreatment modality of choice for enhanced adhesion to tooth tissues.

c) Quantum Square Pulse (QSP) technology for hard-tissue conditioning

In general, Er:YAG lasers are very inefficient when operating in the short duration, low-pulse-energy regime. This is due to the fact that a laser rod generates a laser beam only above a certain energy threshold, which must be overcome through pumping by means of a flashlamp. At very short pulses of low energy, a significant portion of the pumping energy is required for overcoming this energy threshold before a usable quantity of laser energy is even made available. Therefore, short pulses of low energy have poor efficiency and are extremely difficult to generate at sufficiently high repetition rates [12].

For the above reason, it is now a commonly accepted protocol, employed also in the study by Bahrami et al. [8], to first prepare the cavity with longer (MSP, for example) pulses of sufficiently high energy, and then in the second step to condition the surface by treating it with SSP pulses of sufficiently low energy (below 90 mJ). While this protocol is effective it requires more time than if the whole procedure was performed in one single step.

Recently, the range of treatment parameters of VSP Er:YAG lasers was significantly extended with the latest quantum square pulse (QSP) technology (Fotona, Slovenia). In the QSP mode, a longer laser pulse is divided, i.e. quantized, into several short pulses (pulse quanta) that follow each other at an optimally fast rate. This enables the QSP mode to deliver short, low-energy pulses with the efficiency of long duration, higher energy laser pulses without sacrificing the efficiency and precision that is provided by short duration pulses. One of the major advantages of the QSP mode is that it significantly reduces the undesirable effects of laser beam scattering and absorption in the debris cloud during hard-tissue ablation [12].

With the latest QSP technology, fast hard-tissue cavity preparation has been made possible without the necessity for the additional step of surface conditioning with short, low-energy pulses. In this paper, we report on a comparative study of the hard-tissue surface morphology following: i) high energy cavity preparation; ii) a dual step, high-energy cavity preparation + low energy surface conditioning, Er:YAG treatment, and iii) a single-step, high-energy QSP-mode Er:YAG cavity preparation.

II. MATERIALS AND METHODS

In this study, we used an Er:YAG dental laser (LightWalker AT, manufactured by Fotona d.d., see Fig. 6) that operates in a QSP (Quantum Square Pulse) mode that improves the efficiency of Er:YAG lasers in a high-finesse treatment regime. The laser system was fitted with a tip-less (non-contact) H02 handpiece (beam spot size in focus: 0.6 mm).

Fig. 6: LightWalker AT dental laser system with the QSP modality that was used in the study.

The novel quantum square pulse (QSP) technology improves the efficiency of short Er:YAG pulses in the following way. A standard laser pulse of a longer duration is divided (i.e. quantized) into several, short duration individual "pulselets" (quanta) that are separated by sufficiently short temporal pulselet spacing (see Fig. 7). For the same overall pulse energy, the pulse power of individual quanta is thus higher compared to the pulse power of the original long pulse.

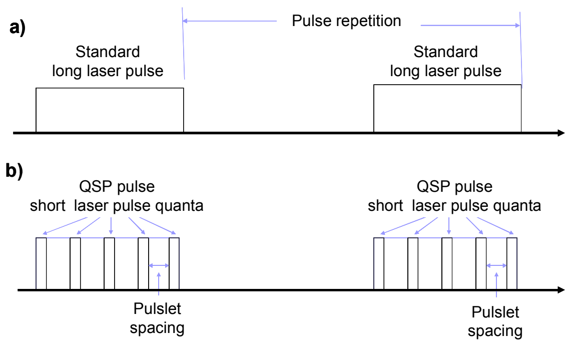


Fig 7: a) Standard laser pulse; b) QSP pulse: a long laser pulse is quantized into several pulselets (pulse quanta). Figure reprinted with permission from ref. 12.

The sufficiently short temporal pulselet spacing is required because there is some inversion population of the laser energy status remaining after the end of the laser pulse. When a laser material is supplied with energy by pumping, the individual erbium ions are successively moved into a higher laser-enabling energy state. A significant share of the atoms remains at this higher energy state for a short period of time after termination of the pumping process and even after termination of the laser emission. This period of time is limited by the inversion population remaining time (the time within which, in the absence of pumping, the remaining inversion population of the laser energy status is reduced to 10% of the initial value). In cases where the pumping for the second pulselet starts early enough, the threshold is reduced as the laser has already been pre-pumped from the previous pump pulse. From this viewpoint, the temporal pulselet spacing should be shorter than the inversion population remaining time. The shortening of the pulselet spacing utilizes this effect, in that after termination of a very short individual pulselet and after completion of the very short temporal pulselet spacing within the inversion population remaining time, there is still residual energy in the laser material that is available for the subsequent individual pulselet. This significantly enhances the efficiency of QSP laser pulses as compared to standard short laser pulses.

In the experiment, cavity preparations were made in dentin and enamel with the Er:YAG laser at a 15 Hz repetition rate, and using water spray with settings of water 6 and air 4. The H02-C handpiece was fixed at the focal distance from the tooth surface. Each cavity was made with 20 laser pulses.

Dentin samples were divided into the following three treatment groups:
a) D-standard: cavity preparation with MSP at 200 mJ.
b) D-conditioned: cavity preparation with MSP at 200 mJ, followed by surface conditioning with SSP at 80 mJ.
c) D-QSP: cavity preparation with QSP at 200 mJ.

Similarly, enamel samples were divided into the following three treatment groups:
a) E-standard: cavity preparation with SSP at 450 mJ.
b) E-conditioned: cavity preparation with SSP at 450 mJ, followed by surface conditioning with SSP at 80 mJ.
c) E-QSP: cavity preparation with QSP at 450 mJ.

The treated samples were cleaned, dried and mounted on a scanning electron microscope (SEM) holder (see Fig. 8). Each sample was observed at the original magnifications of x2000 and x10000.

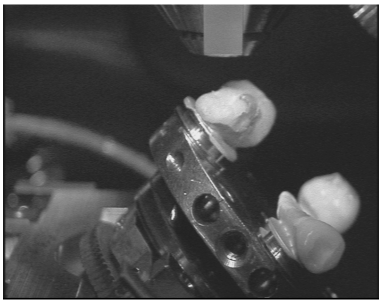


Fig 8: SEM sample chamber.

III. RESULTS

Under the same pulse energy conditions of 450 mJ, the ablated cavities made with QSP pulses were observed to be 75% deeper and 18% narrower compared to those made with SSP pulses (Fig. 9). The scattering effect is much more pronounced in the case of a high energy SSP mode, leading to wider and shallower cavities. QSP mode cuts much faster and deeper into the tooth.

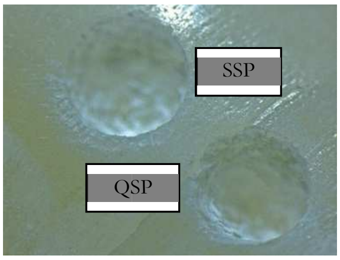


Fig 9: Cavities made from 20 Er:YAG pulses with 450 mJ at SSP and QSP pulse modes.

a) Dentin

Figure 10 shows a typical dentin surface from the D-standard group. The surface is irregular, but without a smear layer and with opened dentinal tubules. We attribute the observed irregularity of the surface to the effects of laser beam scattering.

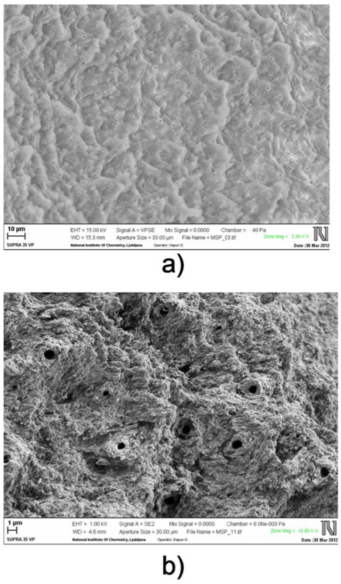


Fig 10: SEM pictures for the dentin group D-standard. a) magnification x2000; b) magnification x10000; The surface is irregular, but without a smear layer and with opened dentinal tubules. The irregularity of the surface is attributed to the effects of laser beam scattering.

The dentin surface which was post-conditioned with low energy SSP pulses (the D-conditioned group) shows a much more regular and flat surface, with wider open dentinal tubules (Fig. 11). This observation is in agreement with previous reports [10]. The effects of scattering following high-energy MSP pulses are "erased" by the subsequent low-energy SSP pulses.

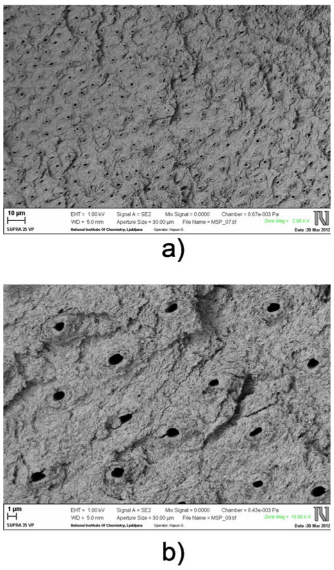


Fig 11: Typical SEM pictures for the dentin group D-conditioned: a) magnification x2000; b) magnification x10000; The surface is flat, with very wide open tubules Scattering effects were "erased" by the post-conditioning low-energy SSP pulses.

A regular and flat surface and wide open tubules were observed also for the D-QSP group (Fig. 12). The dentin surfaces from group D-QSP are extremely clean, with no difference between inter-tubular and peri-tubular dentin. This indicates that cavity preparation using the QSP mode eliminates the need for post-conditioning of the dentin surface to improve bond strength. It is important to note that, as opposed to cavity preparation using a steel bur [10], no smear layer was observed.

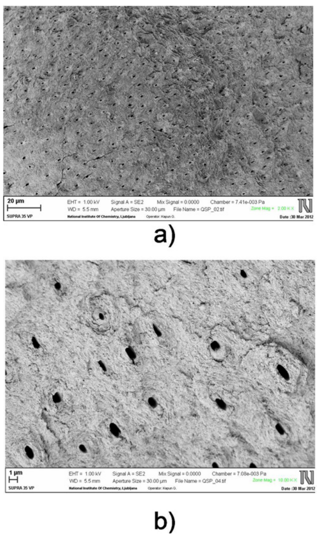


Fig 12: Typical SEM pictures for the dentin group D-QSP: a) magnification x2000; b) magnification x10000; The dentin surface is perfectly clean and flat, showing wide open dentinal tubules.

b) Enamel

Figure 13 shows a typical enamel surface from the E-standard group. The enamel surface prepared with a standard 450 mJ SSP Er:YAG setting is clean and without any smear layer. However, the surface is very rough, and with non-homogenous scaly zones.

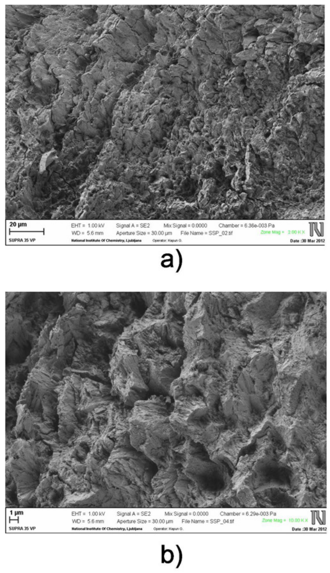


Fig 13: Typical SEM pictures for the dentin group E-standard: a) magnification x2000; b) magnification x10000; Scaly zones with a high degree of roughness can be observed.

A typical enamel surface from the E-combined group ("conditioned" with low energy SSP pulses following a high-energy cavity preparation) is shown in Fig. 14. The enamel surface appears homogeneous, and a well-defined micro-roughness can be seen.

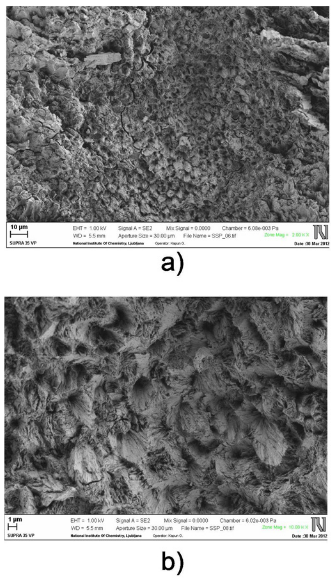
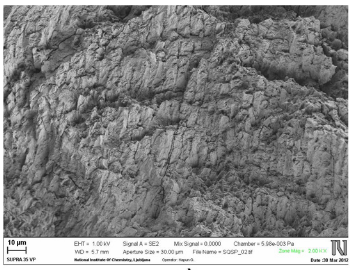
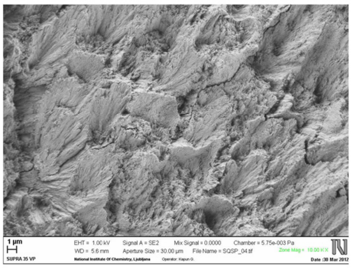


Fig 14: Typical SEM pictures for enamel group E-conditioned: a) magnification x2000; b) magnification x10000.

In the E-QSP group, the preparation and surface modification of enamel was accomplished in a single cavity preparation step using QSP pulses. Figure 15 shows the enamel surface is clean, sites for resin tags are created and this structure appears to fit the requirements for improved adhesion of dental materials [9]. The surface is very similar to the surface from the E-conditioned group, which required an additional surface conditioning step.



a)



b)

Fig 15: Typical SEM pictures for the enamel group D-QSP: a) magnification x2000; b) magnification x10000.

As opposed to the treatments with a steel bur [22], no SEM picture of laser-prepared enamel surfaces revealed any smear layer or etching of inorganic content from the enamel.

IV. DISCUSSION

Recently published studies have demonstrated a highly significant difference in adhesion strength between the Er:YAG laser-prepared dental surfaces and those prepared using the conventional bur.

The beneficial effect of the Er:YAG laser cavity preparation is particularly pronounced when the laser is set to operate at super-short pulses (SSP, 50 μs) and low pulse energies (<90 mJ). In this regime, the combined thermal and scattering effects are minimal. Since Er:YAG lasers are relatively inefficient when operating in the short-duration, low pulse-energy regime, their average output power is limited to relatively low levels in this regime. Since this may lead to prolonged treatment times, it is now a commonly accepted practice to first prepare a cavity using laser-efficient, high-intensity laser pulses, and then finish the procedure using super-short pulses of lower intensity. While this protocol is clinically effective it requires more time than if the whole procedure was performed in one single step.

Recently, a special mode of operation has been developed for Er:YAG lasers. This, Quantum Square Pulse mode (QSP, Fotona d.d.) overcomes the power limitation of the Er:YAG lasers at low-intensity, short pulses. This is due to the fact that in the QSP mode a longer laser pulse is divided (quantized) into several super-short pulses (pulse quanta) that follow each other at an optimally fast rate. This enables the QSP mode to deliver super-short, low-energy pulses with the efficiency of long-duration, higher energy laser pulses without sacrificing the efficiency and precision that is provided by super short duration pulses. Since the QSP mode consists of a series of optimally spaced super-short pulses, it can be viewed also as a super-short pulse mode "on steroids". The QSP mode is therefore a setting of choice when fast treatment and high precision are required. Preparation speed is of great importance in pediatric dentistry and with anxious patients. In addition, the noise generated by the QSP pulses is much lower than with other pulse modes.

Our *in vitro* study demonstrated the advantages of the new QSP mode. Due to the special operating regime of QSP pulses, the speed and precision of cavity preparations are increased when compared to currently used "single" (non-quantized) laser pulses at the same total energy setting. This is mainly due to the fact that the QSP mode effectively avoids the negative effects of scattering in the ablation cloud, which usually leads to decreased ablation effectiveness and lower precision. Preparations made using the QSP mode eliminate the need for post-conditioning of the dentin or enamel surface to improve bond strength. A two-step laser procedure is effectively optimized to just a single step, therefore shortening the procedure time. According to SEM micrographs, QSP-treated surfaces appear to have the high quality required for high bond strength, in addition to being free of a smear layer. The dentin surface appears clean, regular and flat with wide-open tubules with no difference between inter-tubular and peri-tubular dentin. The enamel surface also appears clean and homogeneous with a well-defined micro-roughness.

Recently, several clinical cases using the QSP mode were also reported [23], confirming the versatility and benefits of this latest technology in a clinical setting.

V. CONCLUSIONS

In this paper we demonstrated that with the QSP technology, high surface quality as required for high bond strength can now be achieved without sacrificing the speed of laser cavity preparations.

Acknowledgment

This research was carried out in a collaboration with the EU regional Competency Center for Biomedical Engineering (www.bmecenter.com), coordinated by Laser and Health Academy (www. laserandhealthacademy.com), and partially supported by the European Regional Development Fund and Slovenian government.

REFERENCES

1. Gutknecht N. State of the Art in Lasers for Dentistry, J Laser Health Acad., Vol. 2008; No3/2; www.laserandhealth.com.
2. Hibst R. Lasers for Caries Removal and Cavity Preparation: State of the Art and Future Directions. J Oral Laser Appl. 2002; 2:203-211.
3. Lukac M, Marincek M, Grad L. Super VSP Er:YAG Pulses for Fast and Precise Cavity Preparation. J Oral Laser Appl. 2004; 4:171-173.
4. Lukac M, Marincek M, Grad L. Dental Laser Drilling: Achieving Optimum Ablation Rates with Latest Generation Fidelis Laser Systems, J Laser Health Acad, Vol. 2007; No7/3; www.laserandhealthacademy.com.
5. Baraba A, Miletic I, Jukic Krmek S, Perhavec T, Bozic Z, Anic I. Ablative Potential of the Erbium-Doped Ytrrium Aluminium Garnet Laser and Conventional Handpieces: A Comparative Study, Photomedicine and Laser Surgery, 2009.
6. Gurkan S, Gutknecht N, Kiremitci A, Cakir F, Yazici E, Gorucu J, Tasar F, Bayramov I, Usubutun A. Pulpal Inflammatory Response to Er:YAG and Er,Cr:YSGG Laser Cavity Preparation, Lasers Med Sci 2009; 24: 492.
7. Gutknecht N, Gurkan S, Kiremitci A, Cakir F, Yazici E,[2] Gorucu J, Tasar F, Bayramov I, Usubutun A. Evaluation of Safety of High Speed MAX mode Er:YAG Laser Cavity Preparations, LAHA J. Laser and Health Academy, Vol. 2011, No. 1; www.laserandhealthacademy.com.
8. Bahrami B, Askari N, Tielmans M, Heysselaer D, Lamard L, Peremans A, Nyssen-Behets C, Nammour S (2011) Effect of low fluency dentin conditioning on tensile bond strength of composite bonded to Er:YAG laser-prepared dentin: a preliminary study. Lasers Med Sci 26: 187-191.
9. Firat E, Gurgan S, Gutknecht N (2012) Microtensile bond strength of an etch-and-rinse adhesive to enamel and dentin after Er:YAG laser pretreatment with different pulse durations. Lasers Med Sci 27: 15-21.
10. Baraba A, Perhavec T, Chieffi N, Ferrari M, Anic I, Miletic I (2012) Ablative potential of four different pulses of Er:YAG lasers and low-speed hand piece. Photomedicine and Laser Surgery, ahead of print.
11. Diaci J, Gaspirc B. Comparison of Er:YAG and Er,Cr:YSGG lasers used in dentistry, JLAHA Vol. 2012, No.1: 1-13.
12. Gutknecht N, Lukac M, Marincek M, Perhavec T, Kazic M (2011) A novel quantum square pulse (QSP) mode erbium dental laser. JLAHA Vol. 2011, No.1: 15-21.
13. Majaron B, Sustercic D, Lukac M, Skaleric U, Funduk N. Heat Diffusion and Debris Screening in Er:YAG Laser Ablation of Hard Biological Tissues. Appl Phys B 1998; 66(4):479-487.
14. T. Perhavec, J. Diaci. Comparison of Er:YAG and Er,Cr:YSGG dental lasers. J. Oral Laser Appl. 2008:8:87-94.
15. J. Diaci. Laser Profilometry for the Characterization of Craters Produced in Hard Dental Tissues by Er:YAG and Er,Cr:YSGG Lasers. J. Laser Health Acad, Vol. 2008; No2/2; www.laserandhealthacademy.com.
16. Meister J, Franzen R, Forner K, Grebe H, Stanzel S, Lampert F, Apel C. Influence of the water content in dental enamel and dentin on ablation with erbium YAG and erbium YSGG lasers. J Biomed Opt 2006; 11(3):034030 1-7.
17. Perhavec T, Diaci J. Comparison of Heat Deposition of Er:YAG and Er,Cr:YSGG Lasers in Hard Dental Tissues, J Laser Health Acad, Vol. 2009; No2/1; www.laserandhealth.com.
18. K. Nahen and A. Vogel. "Plume dynamics and shielding by the ablation plume during Er:YAG laser ablation," *Journal of Biomedical Optics* 7, no. 2 (2002): 165-78.
19. J. T. Walsh and T. F. Deutsch. "Measurement of Er:YAG laser ablation plume dynamics," Applied Physics B: Lasers and Optics 52, no. 3 (1991): 217-224.
20. Meister J, Apel C, Franzen R, Gutknecht N. "Influence of the spatial beam profile on hard tissue ablation." Part I: Multimode emitting Er:YAG lasers. Lasers in medical science, vol 18(2) (2003): 112-8.
21. Meister J, Franzen R, Apel C, Gutknecht N. "Influence of the spatial beam profile on hard tissue ablation," part II: pulse energy and energy density distribution in simple beams. Lasers in medical science vol. 19 (2) (2004): 112-8.
22. Luddin N, Ngo H, McIntyre J, Abbott J. Comparative study of the ultrastructure and adhesive properties of enamel prepared by Er:YAG laser and conventional bur. J Oral Laser Applications 2006; 6: 89-94.
23. Mironov E. Clinical Experience with Quantum Square Pulse (QSP) Er:YAG Laser. JLAHA Vol. 2012, No.1: 80-85.