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RESEARCH ARTICLE

Comparative Study of the Restoration Quality in Cavities prepared with Er:YAG Laser in Quantum Square Pulse Mode and Conventional Method

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ABSTRACT

Nowadays, dental treatment has been enriched by the use of lasers. The introduction of the novel treatment parameter of quantum square pulse (QSP) constitutes an additional challenge to older techniques, promising minimally invasive treatments. The aim of this study is to comparatively investigate the quality of cavity preparations using erbium-doped yttrium-aluminum-garnet (Er:YAG) laser with QSP technology as opposed to the conventional bur. The Er:YAG laser (2940 nm) has been used at 120 mJ energy level in QSP and medium short pulse (125 µs) modes. Subsequently, the dentin and enamel surfaces were examined using scanning electron microscopy techniques and compared with cuttings prepared with conventional bur. The laser-treated dentin samples exhibited relatively homogenous surfaces without smear layer and with open dentinal tubules. Laser-treated enamel showed scaly surfaces but again free of smear layer. In contrast, both dentin and enamel samples treated with the conventional bur showed abundance of smear layer, groove marks, small-scale cracks, and closed dentinal tubules.

Keywords: Er:YAG laser, Quantum square pulses, Scanning electron microscopy.

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INTRODUCTION

The evolution of esthetic restorative materials as well as the development of better adhesive systems altered the whole process of cavity preparation. GV Black's principle of "extension for prevention" has been reviewed and the modern approach of restorative dentistry focuses on:

- Ensuring access in order to control caries lesion
- Cutting hard dental tissues and removing caries
- Achieving suitable surfaces for the adhesion of restorative materials.

Understandably, contemporary research trend focuses in establishing alternative ways of cavity preparation with the scope of succeeding minimally invasive techniques and better adhesion characteristics. With that in mind, laser, ultrasound handpiece with suitable tips, and air abrasion have been introduced to the clinical practice. Therefore, the aim of using any of the above systems is to selectively remove caries lesion and to prepare the appropriate surfaces for optimal adhesion of the restorative material.

On that context, the application of laser systems seems to be very promising for achieving the goal of less-invasive dentistry.[1-4]

Following the development of the first laser by Theodor H. Maiman in 1960, many pioneers in the dental field tried to utilize laser systems for painless cavity preparation. The available laser systems around that time – Ruby, neodymium-doped yttrium-aluminum-garnet, and CO_2 – have been tried for their ability to cut hard dental tissues. The reported results were disappointing since cutting potential was insufficient and a great increase in temperature led to vast thermal side effects, such as melting, cracking, and carbonization of the hard tissues and damage to the pulp.[5-7] Many years later in 1988, erbium-doped yttrium-aluminum-garnet (Er:YAG) was introduced for dental applications. Er:YAG was a new solid-state laser with a wavelength of $\lambda = 2.94$ µm exactly where the maximum absorption in water is observed. It is this property of Er:YAG that gives it the ability to remove dentin and enamel with sufficient cutting speed and without excessive thermal damage.

Taking advantage of the knowledge of the composition of tissues and the known properties of the laser beam, several researchers tried to determine the most suitable parameters as well as other associated factors affecting the rapid and safe removal of hard dental tissue with minimal if any thermal damage. Deep knowledge of laser/tissue interactions, choice of suitable wavelength and settings, such as pulse duration, energy, frequency plus the adjustment of other influencing factors like water irrigation and handpiece design, constitutes the basis for applying laser therapies to patients and the introduction of additional indications.

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Maziar Mir in his study regarding the significance of water-layer thickness and its importance on Er:YAG laser ablation[8] showed that very short pulses (90–120 µs) may lead to the elimination of a possible thermal damage. On the same context, Apel examined the influence of pulse duration on the ablation threshold of dental enamel[9] and showed that the dependence of the ablation threshold on the laser pulse duration is statistically significant. A potential explanation for the observed relationship between the ablation threshold and the pulse duration is that the thermal loss mechanism is a function of time. This observation possibly means that with longer exposure times a larger amount of energy will be dispensed in the surrounding tissues.

Along with Er:YAG, another laser of the Er family has been developed making use of garnet crystals doped with Cr^{3+} ions. The Er,Cr:YSGG emits at 2.79 µm at a wavelength where the absorption by the water molecules is considerably lower but with an interesting secondary absorption by the OH^- group (2.80 µm) of the hydroxylapatite mineral.[10] Both Er:YAG and Er,Cr:YSGG have been proven to be effective and safe modern tools for hard-tissue ablation.[3,10] However, over the years, certain differences among the two Er laser systems have been pointed out by various researchers. In practice, Er,Cr:YSGG shows under the same circumstances higher ablation thresholds (10–14 J/cm^2 as opposed to 9–11 J/cm^2 for Er:YAG) and slightly lower ablation speed due to lower mass loss per pulse.[9,11] At the same time, occasional cracks in dentin have been reported even at energies lower than the ablation threshold.[9] Any analysis of the above observations requires a comprehension of the mechanism of ablation. At first, there was a notion that the absorption by OH^- should play an important role in the ablation process of Er,Cr:YSGG. Nevertheless, today the prevailing view is that both lasers actually share the same ablation mechanism since the absorption by OH^- is absolutely secondary.[4] The common ablation mechanism of both Er lasers can be summarized along these lines. The interstitially trapped water molecules in both enamel and dentin selectively absorb the laser energy causing a rapid phase change, and consequently, an abrupt expansion of the water within the mineral substrate. This explosive mechanism leads to a more or less linear ablation of dental tissue.[4,12] Both lasers require concurrent water spraying for the prevention of a temperature buildup and possible tissue desiccation.

Putting together all the above observations, it makes sense that the ablation mechanism of both Er laser systems is essentially the same. The absorption by the water is predominant and therefore more energy from every pulse of the Er:YAG system is utilized for ablation, while the excess energy required for every pulse of the Er,Cr:YSGG can dissipate to the surrounding tissue explaining the higher penetration in dental tissues[13] and the slightly more evident thermal side effects observed.[10] Considering the common ablation mechanism and the rather high difference in the absorption by the water (the absorption figures are on a logarithmic scale), the differences between the two Er lasers might be moderated by the observed dependence of absorption to the temperature increase.

Several studies have been published examining the ablation rate and the quality of the prepared surfaces when using Er:YAG laser at various properly low pulse durations.[14-17] The recent introduction of quantum square pulse (QSP) technology provides dental practice with a new option. Quantum square pulse utilizes a train of suitably short (50 µs) pulses separated by such a short temporal spacing so as to avoid the prohibiting formation of an ablation cloud from the dental debris. The debris cloud is known to interfere, by both absorbing part of the energy that was originally meant for the tissue and by causing a possible secondary thermal damage when it finally collapses on the tooth.[18] It is obvious that this evolution calls for a proper experimental evaluation of this novel technique and, i.e., exactly what the present study is aiming to achieve.

MATERIALS AND METHODS

In the present study, an Er:YAG 2940 nm laser was used, equipped with the novel QSP technology (Light Walker AT by Fotona).

As it has been previously mentioned, Er:YAG lasers operate in genuine pulse mode. This is an absolute prerequisite for the generation of the necessary heat at the treatment location only for a very short time period and therefore within a locally limited area. For effective and safe ablation of hard tissues, laser parameters ought to be chosen in such a manner that the ablation will take place within the so-called cold ablation regime. This method guarantees minimal thermal influence on the adjacent tissues. The cold ablation regime is achieved by using high pulse power, which in effect implies the use of sufficiently short pulse durations at a certain energy level.[4,5,19]

Therefore, when low energy pulses are in order for high finesse treatments, the pulse duration has to be reduced accordingly in order to keep the laser pulse power (peak power) at a sufficiently high level for effective cold ablation.

Procedures

For this study 20 class I occlusal cavities were prepared in freshly extracted teeth (premolars, third molars) conserved in physiological saline. Dimensions of the prepared cavities were 4 × 3 × 3 mm (length, width, and depth) using laser Er:YAG 2940 nm (Fotona company L/W AT). In the first group (10 samples) cavity surface was prepared using the following settings: Energy 120 mJ, 10 Hz frequency, and QSP mode. Cavity surfaces in the 10 samples of the second group were prepared in medium short pulse (MSP) (125 µs pulse duration) mode with the same energy and frequency settings. Finally, five samples of the 3rd (control) group were prepared by means of a Bien Air (Black Pearl) high-speed handpiece with a diamond bur. Table 1 summarizes the three separate groups used for this study.

Scanning electron microscopy (SEM) microphotographs of the surfaces prepared with QSP modification are carefully compared with those prepared with the conventional bur.

Table 1: Sample groups and parameters

Groups	*n*	*Energy (J)*	*Frequency (Hz)*
1. QSP	10	120	10
2. MSP	10	120	10
3. Bur	5	–	–

n = number of samples

RESULTS

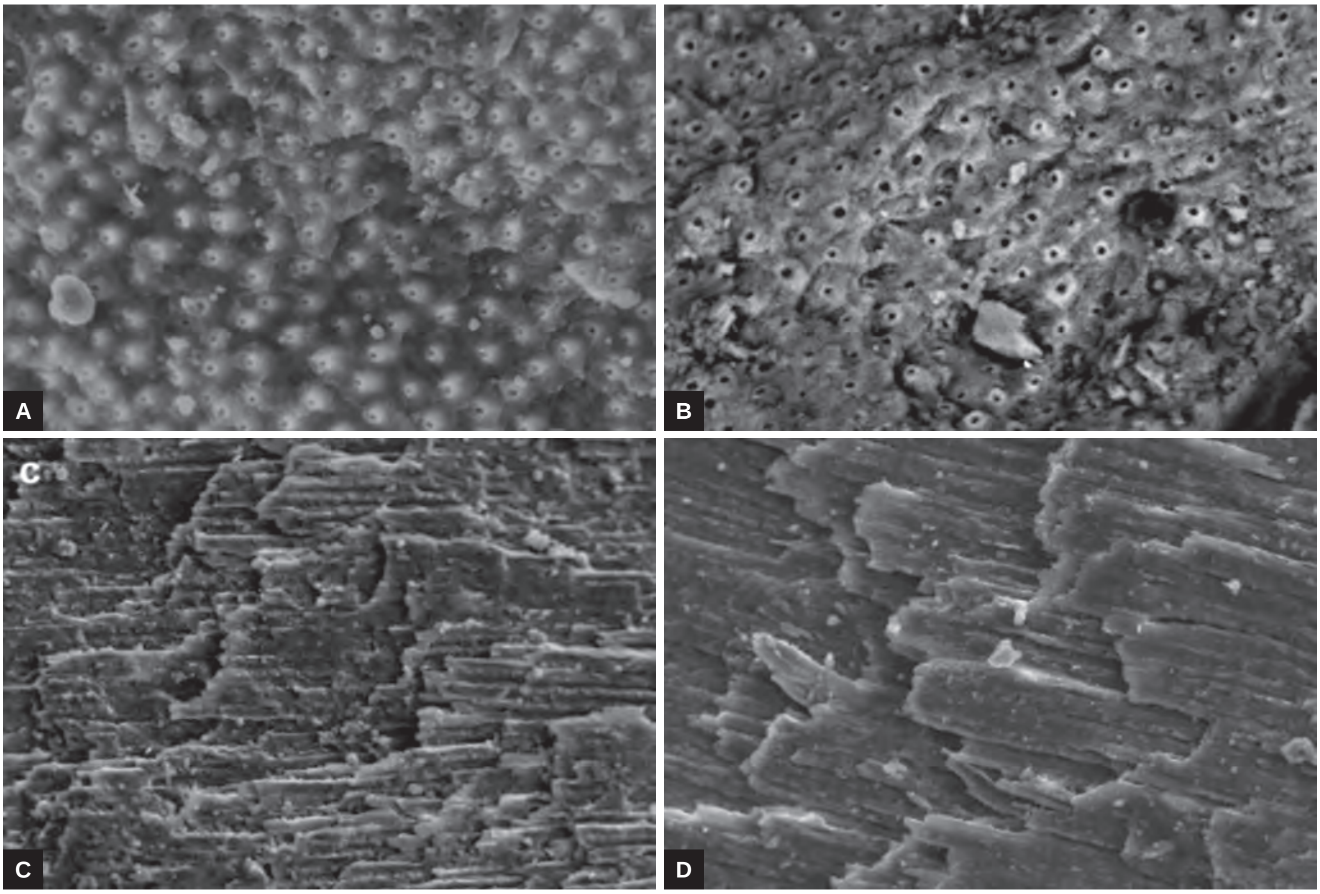
By carefully examining the details of the SEM microphotographs, a repeated pattern of similarities as well as differences was observed.

First Group

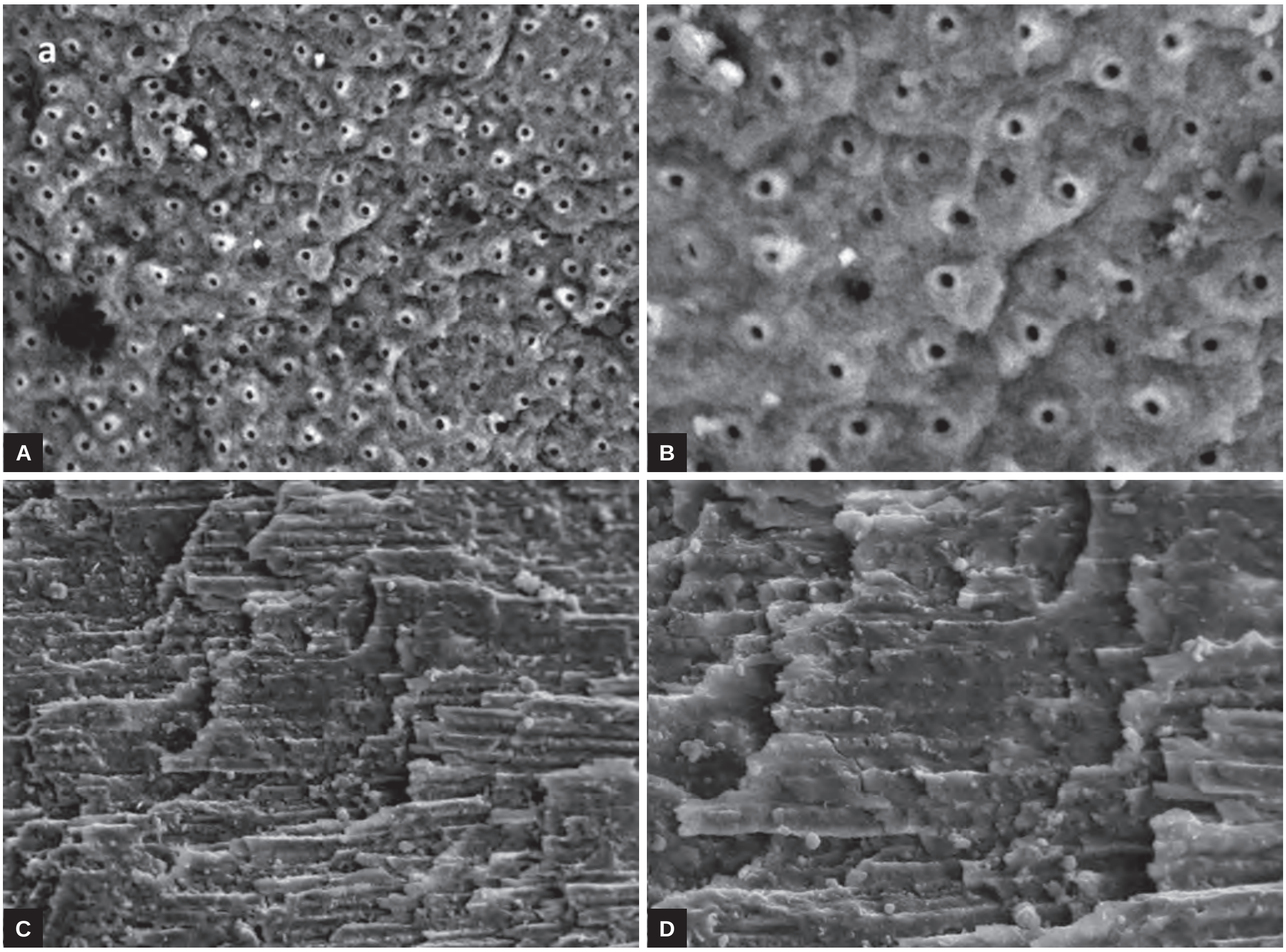
- Dentin surfaces are free of smear layer while at the same time they are comparatively clean, flat, and with minimal roughness and prominent peritubular dentin (Figs 1A and B). The dentinal tubules are open with clear circular mouths of the holes. The structural margins are well defined (sharp), there are no crater-like structures evidencing the lack of "melting zones," or any thermal damage at all.
- Enamel surfaces are also clean and without any smear layer whatsoever. There is as expected a lack of homogeneity due to the existence of the typical relatively rough scaly zones of enamel surfaces (Figs 1C and D).

Second Group

With the appropriate care taken during cavity preparation with the MSP setting (pulse duration 125 µs), the surfaces of both (i) dentin and (ii) enamel in this group



Figs 1A to D: (A and B) Two SEM photographs of QSP laser-treated dentin showing smear layer-free dentin surfaces with wide open dentinal tubules; (C**)** SEM photograph of QSP laser-treated enamel showing smear layer free surfaces and the typical scaly roughness; and (D) the same as in (C) in more detail



Figs 2A to D: The SEM photographs treated with MSP (125 μs pulse duration) laser treated enamel (C and D) and dentin (A and B). Despite the observed microstructural alterations, all major structural and histological elements remain intact more or less the same as in Figure 1

looked almost identical with those of the 1st group. The end result can be described by noting that although few microstructural alterations are evident, both main structural and histological elements remained intact (Figs 2A to D). Nonetheless, the clinical procedure for that group was a bit more time-consuming for interruptions had to be made in order to avoid the buildup of the debris cloud as well as for cleaning the frontal window of the handpiece from time to time.

Third Group

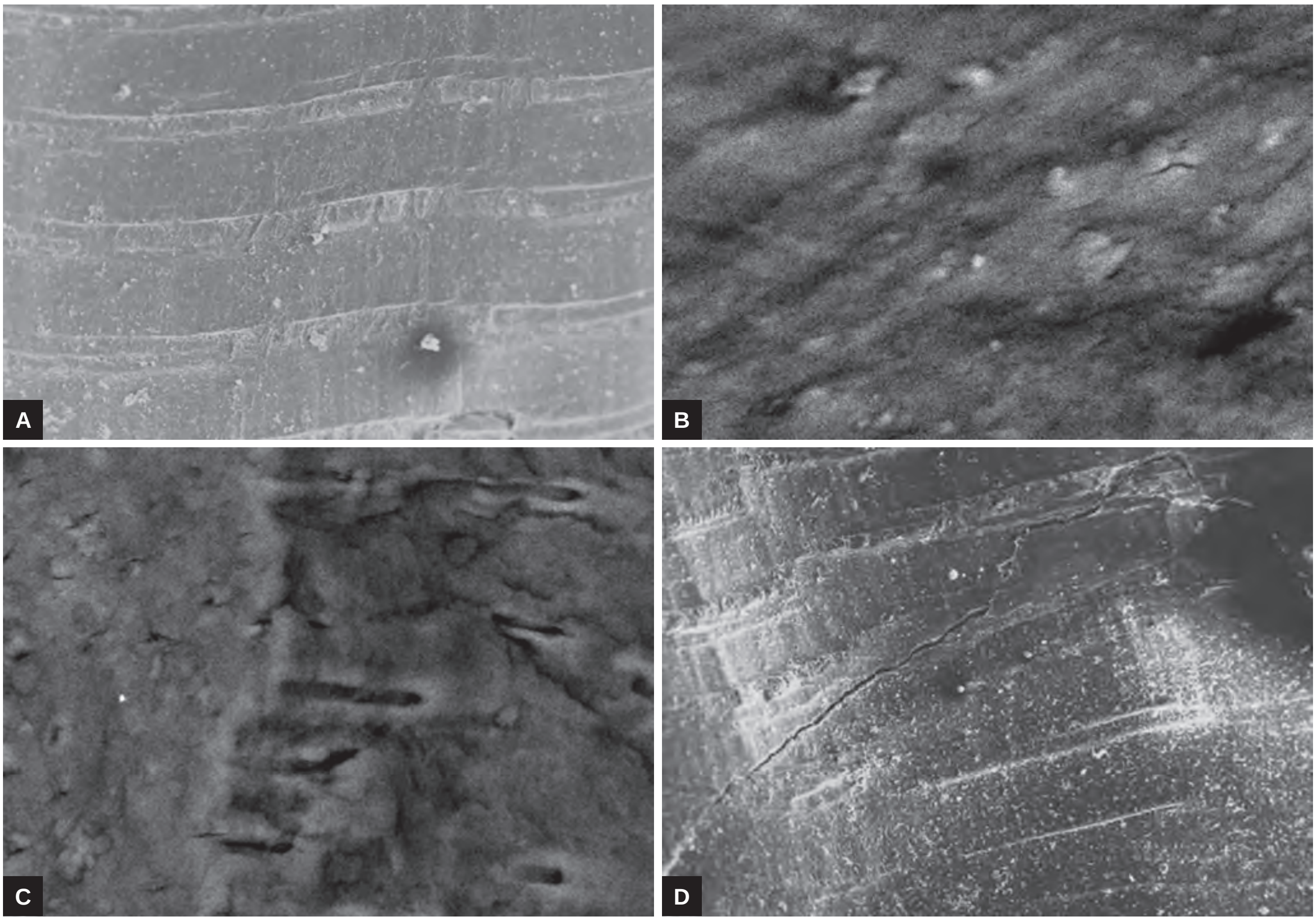
Noticed in Figure 3A are groove marks evident on hard dental tissue that has been prepared with diamond bur. As expected, both dentin and enamel surfaces are dominated by the presence of smear layer caused by the cutting procedure (Figs 3B and C). The roughness and heterogeneity of both surfaces are evident to a great degree. At the same time, a great number of dentin tubules are closed. In addition, microcracks are evident in the samples prepared with the bur (Fig. 3D). These samples would certainly benefit from acid etching.

DISCUSSION

During the past two decades, several studies were carried out on dental tissue applications in order to comprehend laser/tissue interactions and establish the most suitable wavelength for cavity preparation.[7-9,20] The Er:YAG (2940 nm) has been recognized as the most effective laser tool for swiftly, effectively, and safely cutting dental hard tissue due to its outstanding absorption in water. The ability of the user to select the energy, pulse duration, frequency, and air/water spray settings defines the required interaction of the laser beam with various tissues. As it is known from the literature, the measured temperatures are, such as to avoid any serious thermal damage to the tissues.[21,22]

It is known that the water content in enamel is lower than in dentin and even lower than in carious tissue, so in practice we take advantage of higher energy and frequency settings in order to remove carious enamel.

The mechanics of ablation as discussed in the introduction relies on the fact that laser energy is selectively absorbed by water molecules, resulting in very rapid



Figs 3A to D: (A) Grooves on hard dental tissues created by burs; (B and C) dentin surfaces covered by smear layer when cut with the classical bur, noticed are the closed dentin tubules and heterogeneities; and (D) the occasional microcrack

heating of a small volume. The consequent vaporization of the water creates high subsurface pressure and leads to an explosive removal of the surrounding mineral material.[4,12]

By the same token and since the water and organic content in carious tissue is higher than in healthy tissue, with the proper settings we can selectively ablate the carious lesion. In that way we can minimize any waste of healthy tissue.

Moving on to dentin, lower energy and frequency settings are in order since ablation is anticipated faster, again due to the higher water content.

Even lower energy and frequency parameters are required for the final modification, aiming to create a microretentive surface with open dentin tubules capable of high adhesion strength.[23] In practice, tissues should be irradiated while the laser beam is continuously moved across the treatment area.

The purpose of this study is to examine in practice the theoretical advantage of the use of QSP setting. It has recently become evident that both pulse energy and pulse duration of the Er:YAG laser play a significant role in the quality of the resulting surface and the subsequent bond strength of the adhesive to enamel and dentin. The genuine pulses created from a crystal laser-like Er:YAG require the overcome of a certain energy threshold in the laser rod in order to produce a pulse. The above process renders the Er:YAG lasers extremely inefficient in producing very short duration pulses of low energy. Therefore, these pulses are from a technical point of view particularly difficult to produce. The above difficulty has led to a two-step protocol where the cavity is prepared first with high-energy longer pulses (i.e., MSP) and then in the second step the surface is conditioned with even shorter pulses of sufficiently lower energy.[15,24]

Quantum square pulse is a novel technology that improves on the efficiency of short Er:YAG pulses in the following way. A standard laser pulse of a longer duration is divided (quantized) into several individual "pulslets" (quanta) of short duration (50 µs) that are separated by sufficiently short temporal spacing.[18] Quantum square pulse is made possible by a Fotona Co patent that takes advantage of the residual energy after the creation of a pulse in the crystal rod.

It has been shown that at this pulse duration (50 µs) the ablation speed is considerably faster and the screening effect due to the ablation debris is kept at a minimum since debris cloud needs more time to fully form. That way and for the same overall pulse energy setting, the peak power of the originally longer pulse is enhanced, the energy absorption and the optical degradation of the laser beam by the debris cloud are avoided. In addition, the speed of ablation is faster than the diffusion of heat in surrounding tissues. As a result, the cold ablation effect is intensified. Obviously faster ablation, minimum thermal damage of healthy tissue, and less possibility for any patience discomfort are observed.[18]

Several studies have been published on the effect of erbium lasers on the surface morphology of dentin. Several energy settings (200–350 mJ) of an Er:YAG laser in combination with three distinct pulse repetition settings (i.e., frequencies of 2, 3, and 4 Hz) have been tried.[25] As expected, elevated values of energy had an adverse effect on dentin and enamel surfaces. But the increase in pulse repetition had an even more prominent effect, resulting in more evident fissures, cracks, and fused areas.[25] Since the laser device employed for this study has only one choice of pulse duration, variation in this parameter could not possibly be counted. Nevertheless, there are studies[26,27] that have included a variation of the pulse duration parameter from 100 to 1000 μs, reporting irregular enamel margins with rugged cavity walls and with a generally conservative pattern. The roughness has been associated with better retentiveness since it creates an increase of surface area to bonding. The final conclusion from the literature is that there are microstructural alterations rendering the appearance of dentin irregular, without smear layer and demineralization, with open dentinal tubules and prominent peritubular dentin.[15,24]

Keeping in line with previous observations, the meticulous inspection of the SEM microphotographs of this study showed that samples of the 1st and 2nd laser-treated group are more favorably modified for a subsequent successful bonding through the formation of a microretentive surface with open tubules and tags. The reason behind the above picture is that whenever the choice is QSP or the more time-consuming and care seeking MSP (125 μs) modality, the ablation is more precise and effective. Both settings (groups I and II) show minimal thermal damage to the surrounding tissues. However, the easier to use QSP setting due to a more efficient energy management is expected to dissipate less energy to subsurface tissues. Less energy to the subsurface would possibly avoid any thermal damage of the subsurface dentin. If this is the case the observed in some studies fused and partially denatured collagen fibrils[27] might be altogether avoided or kept to a minimum.

On the contrary, SEM microphotographs of the 3rd (control) group exhibit a great deal of smear and grooves from the rotary instrument, all around roughness and heterogeneities that absolutely demand at least a good acid treatment.

CONCLUSION

The use of QSP mode has a definite advantage in cavity preparations and offers an additional fast and effective tool to the dentist. The prepared cavities exhibit flat, homogenous, and retentive surfaces through a quick one-step procedure. More research is required for the possible elimination of subsurface thermal damage and the following microleakage of composite restorations. Nevertheless, the obvious advantage for a modern dentist comes especially when dealing with younger or generally sensitive and anxious patients.

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