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Precise femtosecond laser ablation of dental hard tissue: preliminary investigation on adequate laser parameters

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Abstract. This work aims at evaluating the possibility of introducing state-of-the-art commercial femtosecond laser system in restorative dentistry by maintaining well-known benefits of lasers for caries removal, but also in overcoming disadvantages such as thermal damage of irradiated substrate. Femtosecond ablation of dental hard tissue is investigated by changing the irradiation parameters (pulsed laser energy, scanning speed and pulse repetition rate), assessed for enamel and dentin. The femtosecond laser system used in this work may be suitable for cavity preparation in dentin and enamel, due to the expected effective ablation and low temperature increase when using ultra short laser pulses. If adequate laser parameters are selected, this system seems to be promising for promoting a laser-assisted, minimally invasive approach in restorative dentistry.

1. Introduction

Since the first use of lasers in the medical field, the contact-free application of laser light for removal of hard dental tissue has been studied as a means for replacing conventional drilling instruments. For conventional pulsed laser ablation with pulses from 100 ps to μ s, a strong thermal shock wave is accompanied by cracking of the remaining bulk material and inefficient, uncontrolled material removal. Other damages to the tooth surfaces include cracking, melting, charring, fissuring or crazing and inefficient material removal [1]. High laser power causes significant excess heat deposition in the tooth with potential for irreversible intra pulp damage, which may cause pain for the patient [2]. However, in recent years the development of high-average-power, high-repetition-rate subpicosecond lasers is resulting in an increasing interest in laser surgical applications due to their precise and highly effective ablation capabilities and none or minimal thermal and shock wave collateral damage [3]. By decreasing the laser pulse duration to the subpicosecond time regime and increasing the laser peak intensity, it is possible to induce a different mechanism of laser-tissue removal. In this “electrostatic ablation” mechanism, the laser light is absorbed in a small volume of material and electrons and then ions are ejected rapidly, reducing the heat that is conducted to the surrounding tissue [4]. The change in ablation mechanism from thermally induced in the conventional long pulse regime to the electrostatic mechanism, results in distinct changes in tooth morphology, substantially reduced collateral damage to the tissue, and a decrease in the energy fluence required for the fast removal of a significant amount of dental tissue.

In this study, we present the preliminary results of minimally invasive ablation of dentin and enamel using a state-of-the-art commercial femtosecond (fs) laser system (FELS). Different laser



parameters were tested in order to choose optimal parameters for the ablation in which neither collateral damage, nor overheating of the dental tissue was obtained.

2. Materials and Methods

Extracted human molars were sectioned transversely into 2 mm slices, polished with a SiC #1200 grinding paper with water irrigation and subsequently with a 3 μm diamond suspension. Each tooth slice was positioned on an XYZ computer-controlled table (Aerotech, USA) equipped with a precise optical scanning system with a maximum linear scanning velocity of 2000 mm/s.

A pulsed laser (Satsuma Amplitude, France) operating at 1030 nm wavelength and having pulse duration of 350 fs was used. The maximum average power was 5 W, the laser pulse energy was up to 10uJ and the pulse repetition rate was up to 500 kHz. The FELS was equipped with a precise scanning system with a maximum speed of 2000 mm/sec and used to move the laser beam in the XY direction.

Ablated areas in dentin and enamel were thoroughly imaged with an optical microscope (OM; Alicona G4 InfiniteFocus, Austria, Measure Suite software) and coherence scanning interferometry (CSI, Leitz-Linnik microscope, objective x50, NA=0.85, FSA algorithm [5]). Structural characterization was performed with a micro-Raman spectroscope (LabRamAramis, JobinYvon Horiba, λ=532 nm, spectral range 100-3000 cm⁻¹, resolution 1 cm⁻¹).

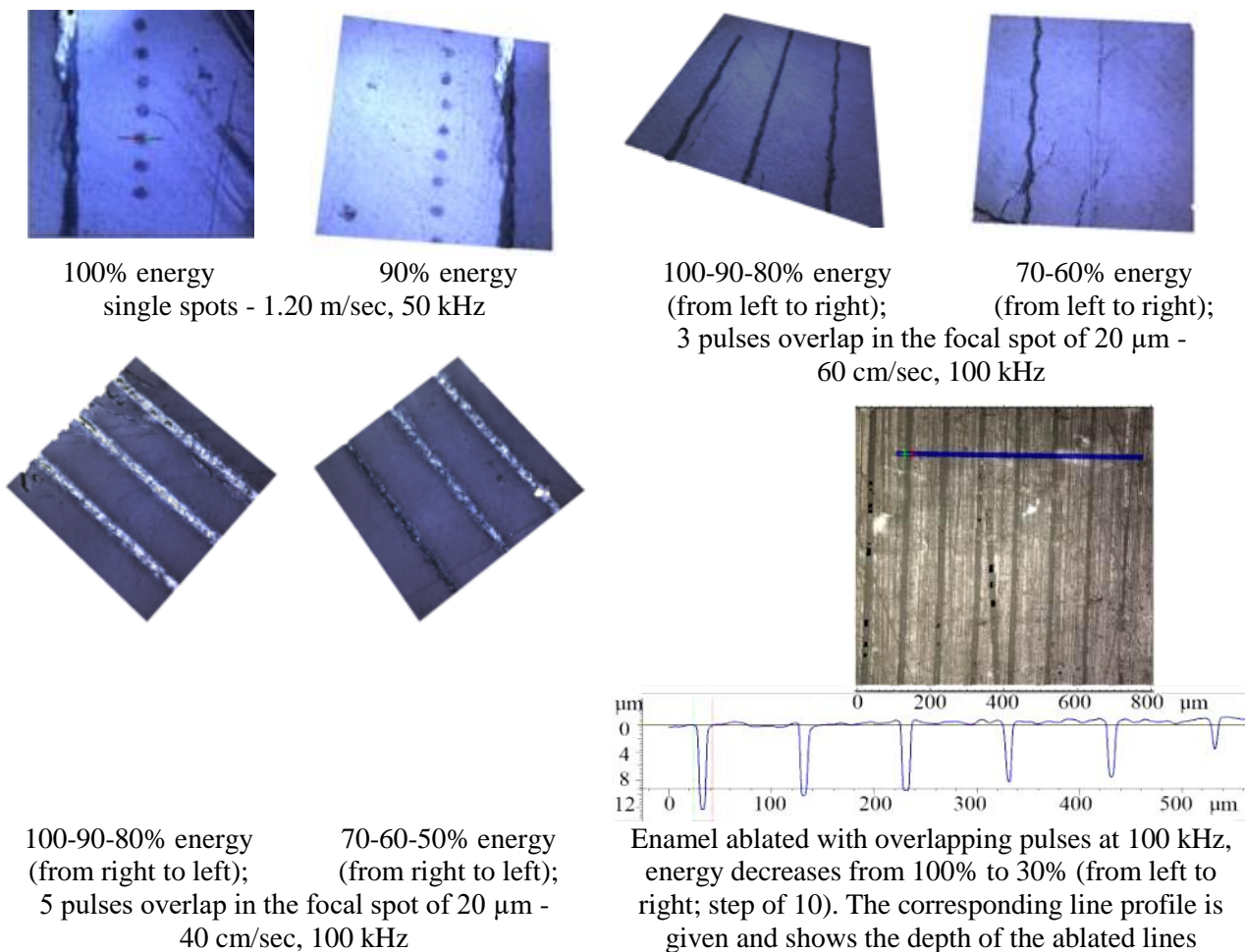
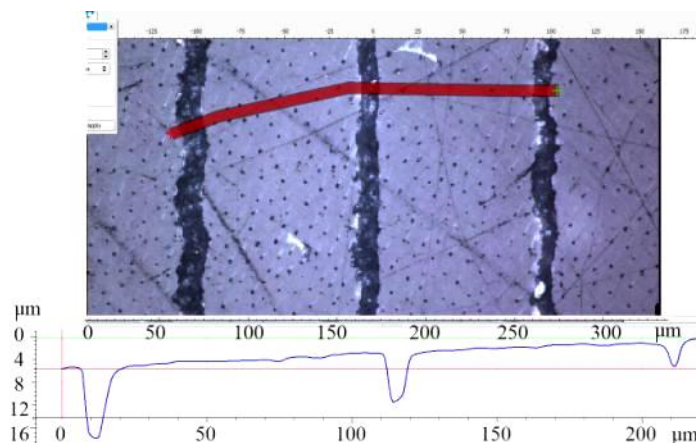
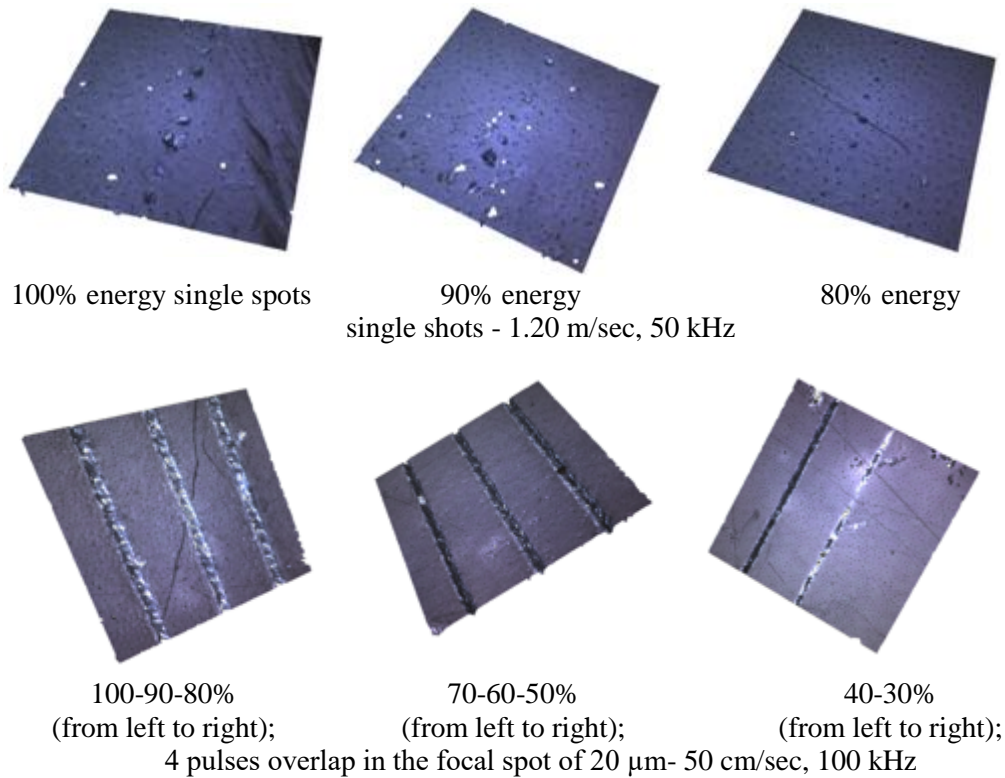


Figure 1. OM images of laser ablated enamel with the corresponding parameters of irradiation given under the images.

3. Results and Discussion

Satisfactory ablation rates, minimal temperature increase and absence of collateral damage were considered as an effective ablation. Thus, the laser pulse energy, pulse repetition rate and scanning speed were varied in order to find optimal parameters for the ablation of dental tissue. The laser beam was focused on the tooth slice using a telecentric lens to produce a focal spot diameter of 20 μm . The maximum laser pulse energy of 10 μJ was taken as 100% and decreased in steps of factors of 10 until no traces were obtained on the tooth surface upon ablating the dentin and enamel with consecutive pulses. The scanning velocity was also varied from one that produced single non-overlapping spots to



Dentin ablated with overlapping pulses at 100 kHz, energy decreases from 100-90-80% (from left to right), 3 pulses overlap in the focal spot of 20 μm - 60 cm/sec, 100 kHz. Line profile shows depth

Figure 2. OM images of laser ablated dentin with the corresponding parameters of irradiation given under the images.

speeds that yielded the formation of lines of overlapping spots. Various OM images of ablated enamel and dentin are shown in figures 1 and 2 with the corresponding laser parameters.

Enamel and dentin consist of the mineral carbonated hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 \cdot \text{CO}_3\text{-HA}$), water and organic materials (collagen proteins and lipids) [6]. Enamel has 85 vol% $\text{CO}_3\text{-HA}$ (of which 2–4 % CO_3), 12 vol% water and 3 vol% organics, which makes it much harder than the dentin. On the contrary, dentin has only 47 vol% $\text{CO}_3\text{-HA}$ and more water (20 vol%) and organic materials (33 vol%) as constituents. After varying the above-specified laser parameters, finally they were set at 100% pulsed energy, 500 mm/sec scanning speed and 100 kHz repetition rate, and these were considered to be the optimal parameters for an efficient and controlled removal of dental tissue with the FELS used in this work. The ablation threshold and ablation rate were measured as a function of the laser fluence.



Figure 3. Ablated craters $1 \times 1 \text{ mm}^2$ in enamel (left) and dentin (right) imaged with OM.

The ablation threshold was 2.0 J/cm^2 for enamel and 1.6 J/cm^2 for dentin. Different ablation thresholds of the two materials come from their different composition. OM images of ablated craters with a size of $1 \times 1 \text{ mm}^2$ in dentin and enamel are shown in figure 3. Laser-tissue interaction depends on the effect of the laser wavelength on the different tissues treated. More energy is needed for the highly mineralized and crystalline enamel and less energy for the dentin, which has a high organic content. After the laser ablation with the optimum parameters, no cracks were present in either the enamel or the dentin and the craters had well-defined precise vertical sides and edges. The craters in both materials were homogeneously machined and collateral damages around them such as discoloration, melting or carbonization as a result of the laser interaction with the dental tissue were not found.

CSI was used for imaging the boundary between the smooth dentin surface and the ablated crater, and to obtain roughness parameters. Figure 4 shows the 3D image of the boundary area. The R_a roughness of the mirror polished dentin surface was 164 nm while the ablation introduced micrometer roughness, and a R_a of $2.31 \text{ }\mu\text{m}$. The increased roughness of the dental tissue may be advantageous since the larger surface area yields improved adhesion strength of dental fillings after the dentist has prepared the cavity for the filling with the fs laser instrument. In addition to the fact that we can obtain fast ablation of dental tissue with the FELS, the resulting dental cavity is clean of contaminants found on the tooth surface and the smear layer usually occurring with the conventional drilling is absent.

Micro-Raman spectra of dentin and enamel (figure 5) were dominated by the characteristic peaks of the P-O vibrational bands of the phosphate (PO_4^{3-}) group. The most intensive and narrow peak at 960 cm^{-1} was due to the ν_1 P-O symmetric stretching which is stronger in the enamel due to the higher content and higher crystallinity of the HA mineral. Peaks centered at 430 and 590 cm^{-1} were due to the ν_2 and ν_4 P-O bending vibrations. A doublet at $1045/1070 \text{ cm}^{-1}$ originated from vibrations of the C-O bond in CO_3 . The latter is characteristic of ν_3 C-O stretching and superimposes on the ν_3 P-O stretching. Peaks due to the amide I, II and III in collagen proteins were found at 1660, 1520 and 1247 cm^{-1} , respectively, with a higher intensity in the spectra of the dentin than those of the enamel which is equivalent to a higher concentration due to the superior organic content in the dentin tissue. Stretching vibration of the C=O bond in carbonyl groups originating from collagen proteins was observed at 1780 cm^{-1} .

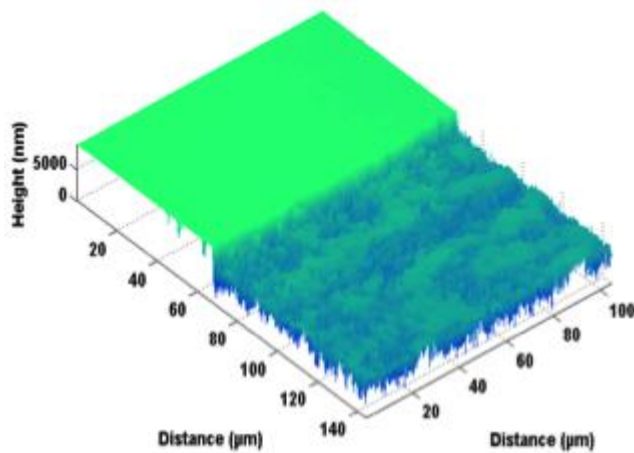


Figure 4. 3D image of the boundary between the smooth dentin surface and the ablated crater.

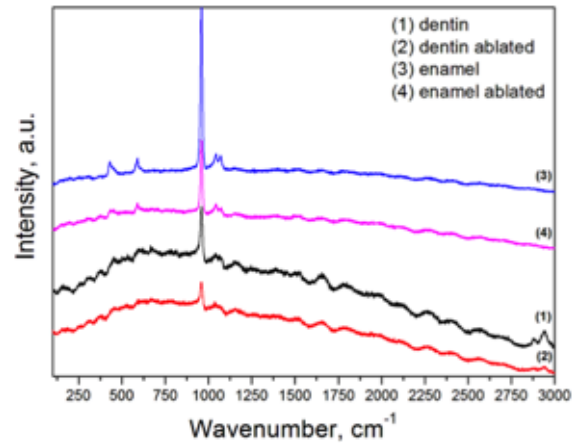


Figure 5. Raman spectra of intact and ablated enamel and dentin.

cm^{-1} in the spectra of intact and ablated dentin. Also in these two spectra, C-H bending at 1450 cm^{-1} and C-H stretching with doublet structure at 2882 and 2942 cm^{-1} due to organic groups were present. The ablation of enamel and dentin did not change their structure (spectra 2 and 4 in figure 5) and the characteristic features of the inorganic HA with weak peaks due to collagen proteins were preserved. This means that no overheating was obtained and the tooth nerves in the pulp cavity of a real tooth would not be damaged which is an additional advantage to the lack of collateral damage. The much lower peak intensity of the ablated materials is due to the fact that the ablated crater is deep enough (1 mm) and the signal coming back to the detector is weaker.

After having found the optimal parameters for the minimally invasive ablation of dentin and enamel, more research work will be performed for increasing the speed of ablation in order to surpass the speed of the conventional drilling instruments while using the benefits of the fs laser energy.

4. Conclusion

Craters with sizes of 1 mm^3 were ablated in enamel and dentin when the adequate parameters of laser ablation with the FELS were set after varying the laser pulse energy, pulse repetition rate and scanning speed. The craters in both materials were homogeneously machined, with well-defined precise vertical sides and edges. No collateral damages around the craters in either materials or overheating effects were observed and the material roughness was increased. Thus, the FELS used in this work is promising for an efficient and controlled cavity preparation in dentin and enamel.

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