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FEMTOSECOND LASER ABLATION OF HUMAN ENAMEL AND CEMENTUM – A PILOT STUDY

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Abstract

Femtosecond lasers emit optical pulses with a pulse duration in the domain of femtoseconds typically ranging between a few femtoseconds to hundreds of femtoseconds. They focus the energy on a very short time scale within a single laser pulse. That leads to high peak powers that cannot be achieved by continuous wave lasers. The aim of this study is to investigate the effects produced by femtosecond laser light irradiation with different parameters on hard dental tissues.

A Pharos model Ph2-10-1000-02-H0-B femtosecond laser (LightConversion UAB, Lithuania), with bi/burst mode and automated harmonic generator, operating at three wavelengths – 1030 nm, 515 nm and 343 nm, with maximum average output powers of 10 W, 5.9 W and 2.8 W, respectively, was used for the irradiation of two freshly extracted healthy human teeth. All the studies presented in this paper were performed at average power of 2.8 W and pulse repetition rate of 100 kHz for all three wavelengths with pulse widths of 170 fs at 1030 nm, 130 fs at 515 nm, and 130 fs for 343 nm, respectively. A total of 24 experimental subgroups were formed so that each group corresponds to a unique combination of: wavelength, exposure duration, tissue type and age (group of the patient). The output powers of the laser radiation at all wavelengths with which the samples were treated was finally attenuated by internal power control, giving possibility to set the appropriate value in order to have

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equal power densities on the objects. The effects of the treatment were studied for 1 s and 10 s irradiation duration for young and old tooth enamel and cementum with the help of microscope ZEISS LSM 900 with Airyscan 2, resolution – lateral (XY) down to 120 nm, axial (Z) 350 nm. Digital scans in magnification were obtained. Profilometric images were used to obtain, access, and compare topographical data from the irradiated surfaces.

The observed changes of the irradiated enamel and cementum were described and compared. The amount of removed tissue for both is small. The results demonstrate that shorter wavelengths cause a more aggressive material ejection, whereas longer wavelengths contribute to increased thermal effects. Shorter wavelengths, particularly 343 nm, promote high ablation efficiency and controlled enamel removal, which is advantageous in minimally invasive procedures. However, excessive material ejection at this wavelength may lead to compromised structural integrity. Conversely, the 1030 nm wavelength results in increased thermal effects, including charring and cracking, highlighting the necessity of precise control over irradiation parameters. Carbonization is evident for cementum. The profilometric analysis shows roughness of the treated surfaces and demonstrates that femtosecond laser irradiation induces distinct modifications in enamel and cementum based on different laser parameters.

These findings provide critical insights into laser-tissue interaction mechanisms, with potential applications in precision dental treatments and conservative dentistry. Further investigations are needed to explore femtosecond laser treatments of healthy tooth structure, dental caries, and different dental materials.

Key words: femtosecond laser, cementum ablation, enamel ablation, laser-hard dental tissue interaction, microscopy

Introduction. Laser technology has transformed numerous fields of medicine and dentistry, offering precision in surgical and non-invasive applications. In dentistry, laser systems have been widely employed for soft tissue modifications, caries removal, cavity preparation, and hard tissue ablation. Among the various laser systems available, femtosecond lasers have garnered significant attention due to their ultrashort pulse duration and minimal thermal diffusion in most materials. Unlike conventional continuous-wave lasers, femtosecond lasers operate within the optical breakdown threshold, allowing for precise ablation without excessive heat accumulation [1, 2].

The interaction between femtosecond laser pulses and dental hard tissues is complex, primarily influenced by factors such as wavelength, pulse duration, and fluence. Enamel and cementum have distinct optical absorption properties, which dictate their response to different laser wavelengths. Dental tissues tend to exhibit higher absorption when irradiated with shorter wavelengths, such as 343 nm, leading to increased material removal and surface modifications. Conversely, longer wavelengths, such as 1030 nm, result in enhanced thermal effects due to their lower absorption efficiency and increased interaction with water content in biological tissues [3–6].

Numerous studies have explored the application of femtosecond lasers in conservative dentistry, particularly in cavity preparation, enamel etching, and dentin modification. Previous research has shown that femtosecond laser irradiation can create micro-retentive structures on enamel, improving adhesive bonding to restorative materials [7]. Moreover, laser ablation has been proposed as an alternative to mechanical drilling, reducing patient discomfort and preserving healthy tooth structure [8,9]. However, despite these advancements, the precise impact of different wavelengths and exposure times on enamel and dentin remains insufficiently characterized.

This study aims to systematically evaluate the effects of femtosecond laser irradiation on dental hard tissues, focusing on ablation depth, surface morphology, and structural integrity. By investigating the response of enamel and cementum to different laser wavelengths and exposure conditions, this research seeks to provide fundamental insights into optimizing laser-based dental procedures. The findings of this study will contribute to the development of safer and more efficient laser applications in dentistry, ultimately enhancing clinical outcomes and patient experience.

Materials and methods. A Pharos model Ph2-10-1000-02-H0-B femtosecond laser (LightConversion UAB, Lithuania) was employed for controlled irradiation of extracted healthy human teeth. The laser operates at 1030 nm, 515 nm, and 343 nm wavelengths, with maximum average output powers of 10 W, 5.9 W, and 2.8 W, respectively. Pulse durations were 170 fs at 1030 nm, 130 fs at 515 nm, and 130 fs at 343 nm. To ensure uniform power density, the output power was attenuated to 2.8 W. The laser experimental setup included:

- Optical elements: Directing components for precise beam control;
- Scanner: Enabling high-precision treatment of the ablated regions;
- Precision positioning table: Motorized system for accurate sample targeting.

Two freshly extracted third molars were used for this experiment, one young and one old. Enamel and cementum were irradiated and four main experimental groups were formed:

- OTC – Old Tooth Cement
- OTE – Old Tooth Enamel
- YTC – Young Tooth Cement
- YTE – Young Tooth Enamel

Three laser wavelengths were used for this experiment: 1030 nm; 515 nm and 343 nm, for the four main experimental groups. The irradiation times applied for

each specimen were 1 s and 10 s at average power 2.8 W and pulse repetition rate 100 kHz for all laser wavelengths.

The factorial design is calculated by this formula: 3 (wavelengths) × 2 (times) × 2 (tissue types) × 2 (age groups) = **24 experimental subgroups**. Each group corresponds to a unique combination of: wavelength, exposure duration, tissue type and age. As a control of the study non irradiated intact parts (enamel and cementum) of the same teeth were used.

The effects of laser irradiation were examined using a ZEISS LSM 900 laser scanning microscope with Airyscan 2 technology, providing lateral (XY) resolution of 120 nm and axial (Z) resolution of 350 nm. Digital images were acquired at varying magnifications for detailed structural analysis and measurements.

Results. The observed changes of the irradiated cementum and enamel were described and compared in Fig. 1 and 2. The amount of removed tissue for both is

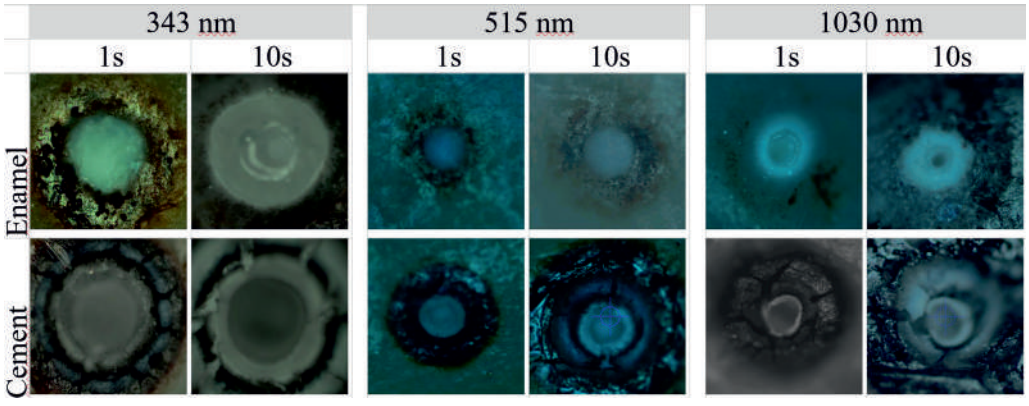

Fig. 1. Irradiated enamel and cementum of an old tooth for 1 s and 10 s at different laser wavelengths – 343 nm, 515 nm, and 1030 nm

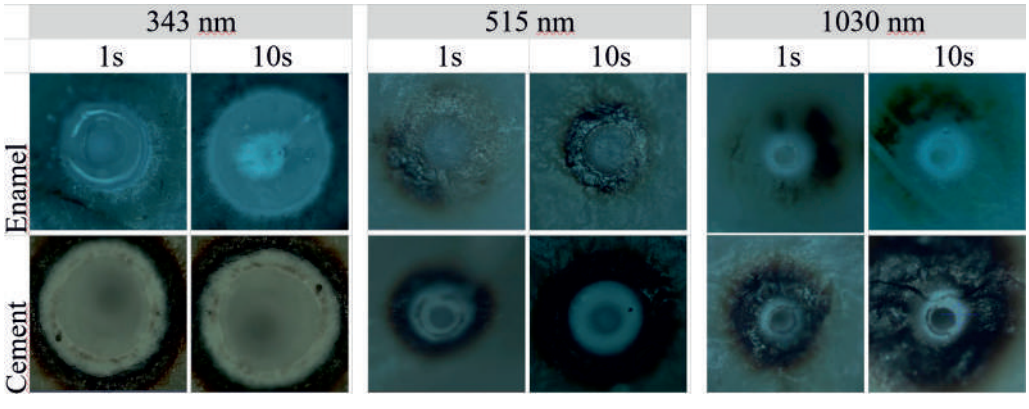

Fig. 2. Irradiated enamel and cementum of a young tooth for 1 s and 10 s at different laser wavelengths – 343 nm, 515 nm, and 1030 nm

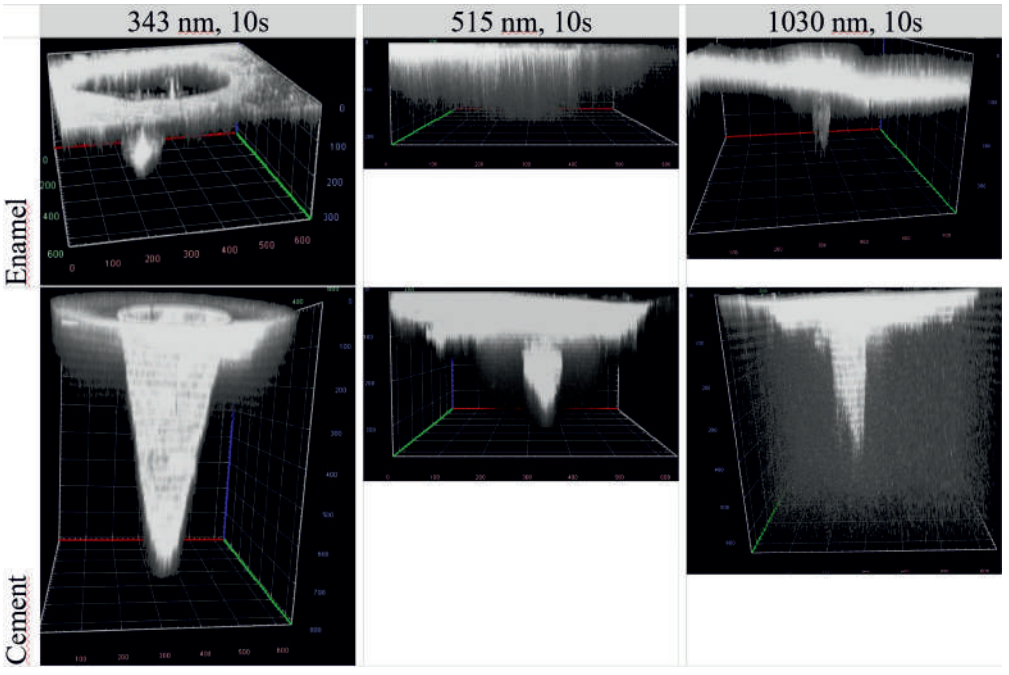

Fig. 3. 3D profilometric photos of irradiated enamel and cementum of a young tooth for time exposition of 10 s, at different laser wavelengths – 343 nm, 515 nm and 1030 nm

small. Carbonization is evident for cementum. The profilometric analysis showed roughness of the treated teeth with femtosecond laser enamel and cementum as evident on the images for each wavelength.

The 3D profilometric analyses of irradiated enamel and cementum show surface roughness. The amount of removed tissue by the femtosecond laser irradiation varies significantly under the different conditions of irradiation – laser wavelength and time of exposition (Fig. 3). Carbonization on enamel is not as evident as in the case of cementum. These observations are valid for both young and old teeth.

The obtained quantitative data is presented in Table 1. In some of the cases it is difficult to determine the exact values of width and depth of the treated material – these are given with "x".

From the experiments and subsequent analysis by wavelength, we collected and established the following results:

- Irradiation at 343 nm. Ablation depth in Old Tooth Cement (OTC) increased twofold when exposure duration increased from 1 to 10 s. Old Tooth Enamel (OTE) displayed insufficient radiation intensity effect at 1-second exposure. Young Tooth Enamel (YTE) exhibited a 1.4-fold depth increase. When irradiation time shifts from 1 to 10 s, the depth doubled for Young Tooth Cement (YTC). At short wavelength (343 nm) aggressive material ejection on YTE was demonstrated, suggesting high interaction efficiency.

Table 1

Detailed measurements of irradiated regions

Wavelength	Type	Width (µm)	Depth (µm)
343 nm	OTE 1s	409.23	x
	OTE 10s	209.9	72.63
	OTC 1s	478.12	413.76
	OTC 10s	463.61	824.71
	YTE 1s	164.35	245.91
	YTE 10s	232.2	345.89
	YTC 1s	349.07	310.12
	YTC 10s	320.77	715.2
515 nm	OTC 1s	146.61	133.14
	OTC 10s	172.76	192.12
	OTE 1s	220.05	x
	OTE 10s	256.33	x
	YTC 1s	142.09	302.98
	YTC 10s	157.66	267.78
	YTE 1s	264.79	x
	YTE 10s	204.27	x
1030 nm	OTC 1s	196	934.24
	OTC 10s	163.08	1063.32
	OTE 1s	120.23	189
	OTE 10s	73.94	343
	YTE 1s	x	x
	YTE 10s	105.79	272.08
	YTC 1s	x	x
	YTC 10s	x	x

- Irradiation at 515 nm. Ablation depth increased by 1.4 times in OTC and 1.8 times in OTE for extended irradiation. Minimal surface modifications were observed in OTE and YTE, with no evidence of structural penetration. Material ejection was recorded in OTC at both exposure durations.

- Irradiation at 1030 nm. OTC depth increased by 1.15-fold, while OTE exhibited a 1.8-fold increase with prolonged exposure. No conclusive data were available for YTE and YTC. Thermal effects such as charring and cracking were evident in OTC for both exposure times. Material ejection in OTE was less pronounced compared to 343 nm irradiation (Table 1).

Discussion. The results indicate that laser-induced modifications in tooth enamel and tooth cement are wavelength-dependent, with shorter wavelengths promoting higher ablation rates and increased material ejection. Conversely, longer wavelengths exhibit pronounced thermal effects, which may compromise structural integrity. These findings align with prior studies on laser-tissue interactions [10,11]. Future research should focus on optimizing irradiation parameters to balance precision ablation with minimal thermal impact [5,12].

Short laser pulses are widely used nowadays in various material processing applications due to the advantage of delivering high peak powers to the investigated object, that cannot be achieved by other types of lasers [13, 14].

The results indicate that laser-induced modifications are wavelength-dependent, with shorter wavelengths promoting higher ablation rates and increased material ejection. Conversely, longer wavelengths exhibit pronounced thermal effects, which may compromise structural integrity. These findings align with prior studies on laser-tissue interactions [15–17].

Shorter wavelengths, particularly 343 nm, demonstrate higher energy absorption and interaction efficiency due to their higher photon energy. This allows for precise and controlled ablation, which is advantageous in minimally invasive dental procedures. However, excessive material ejection at this wavelength could pose challenges in ensuring smooth surface morphology and maintaining enamel integrity [18].

Conversely, irradiation at 1030 nm leads to increased thermal effects, resulting in charring and surface cracking. Irradiation at this wavelength affects more the water content in biological tissues, leading to localized heating and potential structural compromise. Similar effects have been observed in laser-based modification of biological and polymeric materials, where prolonged exposure at near-infrared wavelengths results in excessive heat accumulation and undesirable morphological changes [13, 14].

Future studies should investigate optimal irradiation parameters to balance efficiency and safety in dental procedures. Real-time imaging techniques, such as optical coherence tomography (OCT) and Raman spectroscopy, could offer insights into subsurface modifications and compositional changes post-irradiation. Additionally, computational models could enhance predictive capabilities in understanding laser-tissue interactions.

Conclusion. This study demonstrates that femtosecond laser irradiation induces distinct modifications in dental hard tissues based on wavelength and exposure time. Shorter wavelengths exhibit enhanced ablation efficiency in these tissues, while longer wavelengths contribute to thermal damage. These findings provide critical insights for optimizing laser-based dental treatments, emphasizing the importance of wavelength selection for controlled tissue ablation. Future research should explore real-time monitoring techniques, advanced imaging, and novel laser modulation strategies to further enhance precision and clinical applicability.

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