ISSN 1855-9913

Journal of the Laser and Health Academy
Vol. 2015, OnlineFirst; www.laserandhealth.com

Investigation of the Existence of an Electromagnetically Induced Mechanical Cutting Mechanism with Er:YAG Lasers

M. Lukac[1], T. Suhovrsnik[2], C. Filipic[1]
[1] *Institut Jozef Stefan, Jamova 39, 1000 Ljubljana, Slovenia*
[2] *University of Ljubljana, Faculty of Physics, Jadranska 19, 1000 Ljubljana, Slovenia*

ABSTRACT

Erbium lasers are well suited for the thermal cutting of hard dental tissues due to the very high absorption of their wavelengths in water, which is an important constituent of hard dental tissue. The thermal cutting mechanism is based on the absorption of laser light within the water contained in the target. There has been an additional cutting mechanism proposed, which is not based on a thermal cutting process but on an external water-spray's "electromagnetically induced mechanical cutting" of the target surface. In order to detect this mechanism, Erbium laser energy in combination with a water spray was directed to various non-porous targets with no internal water content, which were transparent to the Er:YAG laser wavelength. In the absence of thermal cutting, any observed cutting of the tested targets would demonstrate the possible presence of disruptive forces caused by an electromagnetically-induced cutting mechanism. No evidence of the cutting effect was observed on a broad range of non-porous, optically transparent targets under a wide range of laser pulse durations, pulse energies and water spray conditions. Similarly, measurements of the Er:YAG laser cutting efficacy on hard dental tissues, cementum and enamel demonstrated the highest cutting speed in the absence of water spray, i.e., in the absence of any interaction of the water fluid particles with the optical energy. This proves that the Er:YAG cutting of hard dental tissues is based on the heating up of interstitially trapped water within the hard dental tissue, and not on electromagnetically induced mechanical cutting caused by the interaction of optical laser energy with atomized water particles in the volume above the tissue surface.

Key words: Er:YAG laser, ablation, absorption, hardness, water.

Article: J. LA&HA, Vol. 2015, OnlineFirst.
Received: August 21, 2015; Accepted: October 27, 2015

I. INTRODUCTION

It has been well known that Erbium lasers, such as Er:YAG (2.94 µm), are well suited for thermal cutting of hard dental tissues [1-4]. This is due to the very high absorption of their wavelengths in the absorption peak of water at 3 µm, which is an important constituent of hard dental tissue. Dental cementum and dentin consist of 22% water, and enamel consists of 3% water [5].

The thermal cutting mechanism is based on the absorption of laser light within the target. In the case of the "thermal cutting" of hard dental tissues with Erbium lasers, the mechanism is based on the heating of interstitially trapped water within the hard dental tissue up to the evaporation temperature. This leads to explosive subsurface expansion of interstitially trapped water inside the tissue, and subsequently to micro-explosive internal tearing up of the dental tissue.

There has been an additional cutting mechanism proposed [6-8], which is not based on the above thermal cutting process but on "electromagnetically induced mechanical cutting" of the target surface. Instead, the new cutting mechanism directs the laser's output of optical energy into a distribution of atomized fluid particles located in a volume of space not inside the target but just above the target surface. Provided that the temporal distribution of the optical energy is of an appropriate duration and shape, the output optical energy is assumed to interact with the atomized fluid particles, causing them to expand and impart electromagnetically-induced mechanical disruptive forces onto the target surface.

Note that as opposed to the thermal cutting mechanism, the additional cutting mechanism does not require any absorption of laser light within the target. Instead, it relies on the interaction of laser optical energy with the atomized fluid particles located in a volume of space above the target surface.

References [6-8] do not provide specific instructions on how to configure fluid output to direct fluid particles for the reception of energy from at least one laser pulse to impart disruptive forces to the target. In this study we set out to determine whether a particular configuration of the fluid and laser optical energy from commercial Er:YAG laser systems (LightWalker and Fidelis models, manufactured by Fotona, Ljubljana, Slovenia) fulfill the conditions required for impartation of disruptive forces to the target by means of the proposed electromagnetically-induced cutting mechanism. In this order, we carried out two sets of experiments.

In a first set of experiments, the Er:YAG laser energy in combination with a water spray from the tested laser systems' handpieces was directed to various non-porous targets, with no internal water content, which were transparent to the Er:YAG laser wavelength. Since in these targets there was no absorption of the Er:YAG laser light, neither from the material itself nor from any trapped water, the conditions for a thermal cutting mechanism were not fulfilled. On the other hand, the new cutting mechanism does not require the absorption of any laser light within a target, and should impart disruptive forces also onto non-absorbing targets. Thus, in the absence of thermal cutting, any observed cutting of the tested targets would demonstrate the possible presence of disruptive forces caused by an electromagnetically-induced cutting mechanism.

In a second set of experiments, the Er:YAG laser energy, in combination with a water spray from the tested Fotona laser systems' handpieces, was directed to human enamel and cementum targets. In these experiments, the thermal cutting mechanism was present due to the high absorption of laser light in water contained within the dental tissue. For this reason, a possible presence of the additional electromagnetically-induced cutting mechanism was examined by varying the level of water/air spray delivered to the target. The possible existence of any disruptive forces caused by the electromagnetically-induced cutting mechanism was tested by observing whether the cutting speed increased depending on the amount of water spray which was simultaneously applied to the target with the delivery of optical energy.

II. MATERIALS AND METHODS

The Er:YAG systems were the flashlamp-pumped Fidelis Plus III and LightWalker AT (both manufactured by Fotona). The Fidelis Plus III was fitted with either a non-contact (tipless) handpiece (Fotona R02 handpiece), or a fiber tip handpiece (Fotona R14 handpiece). The LightWalker AT was fitted with either a non-contact (tipless) handpiece (Fotona H02 or Fotona SX02), or a fiber-tip handpiece (Fotona H14). A water/air spray intersecting the laser beam above the treated surface was supplied by the laser systems with all tested handpieces.

Both laser systems were operated in the SSP, MSP and SP pulse duration modes. The LightWalker AT was additionally operated in the QSP pulse duration mode. The laser output pulse durations and shapes have been reported in [9, 10]. At least in the SSP pulse duration mode, the output laser pulses were shorter than 300 μs, with the full width at half maximum being located closer to the beginning of the laser pulse.

a) Experiments on non-absorbing targets

The first set of experiments was performed on non-porous optical materials of various degrees of hardness, which, unlike tooth enamel or cementum, contain no interstitial water and do not absorb Erbium laser light. The materials tested were zinc selenide, calcium fluoride, silicon and sapphire, with respective mechanical hardness of 137 kg/ mm², 160 kg/mm2, 1150 kg/ mm² , and 1370-2200 kg/ mm² [11]. For comparison, the hardness of enamel is 200-350 kg/ mm², while the hardness of cementum is 20-30 kg/ mm² [12]. The materials tested and their corresponding hardness are listed in Table 1.

Table 1: Mechanical hardness of tested optical materials (targets). For comparison, the mechanical hardness of human tooth enamel is also shown. Mohs hardness is also shown. The Mohs scale of mineral hardness characterizes the scratch resistance of various minerals through the ability of a harder material to scratch a softer material.

Material	ZnSe	CaF2	Enamel	Silicon	Sapphire
Mechanical Hardness (kg/mm²)	137	160	200 - 350	1100-1150	1370-2200
Mohs hardness	4	4	5	7	9

Before each experiment, the target was positioned to have its surface perpendicular to the laser beam and to be at the focal distance of the laser beam (in the case of non-contact handpieces; see Fig. 1 right) or at a 0.4 - 1 mm distance from the fiber tip to the target surface (in the case of fiber-tip handpieces; see Fig. 1 left). The water/air spray settings were adjusted on the user console to result in a 0 ml/min, 10 ml/min or 25 ml/min water flow.

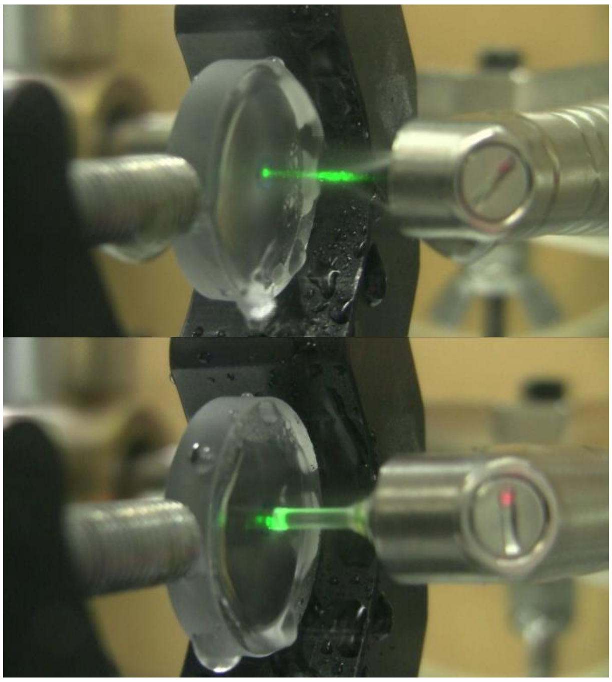

Fig. 1: Optically transparent flat optical elements (targets) were irradiated under the standard Fotona LightWalker Er:YAG laser with water/air spray ablation conditions. A non-contact (tipless) H02 handpiece (left figure above) and a fiber-tip H14 handpiece (right figure above) were used.

b) Experiments on absorbing targets

The experiments were conducted on randomly chosen extracted premolar and molar teeth, which were stored in a physiological saline solution immediately following extraction. For these experiments, only the LightWalker AT laser system was used. The water/air spray was provided by the laser system, and was delivered to the tooth through either the non-contact H02, or a fiber-tip H14 handpiece. Before each ablation experiment, the tooth was positioned to have its surface perpendicular to the laser beam and to be at the focal distance of the laser beam (in the case of the non-contact handpiece) or at the manufacturer-suggested working distance of 0.4 mm between the fiber-tip end and the tooth surface. Measurements were made on enamel, which covers the crown of the tooth, and on cementum, which covers the root of the tooth. The water spray was directed alongside the laser beam and intersected with the beam in the volume above the tooth surface (see Fig. 2). The levels of water and air in the water/air spray were selectable by the user on the laser system console, and were adjusted to result in 0 ml/min, 16 ml/min or 32 ml/min water flow. When experiments with a water flow of 0 ml/min were made, the water spray was turned off during laser radiation. Following each laser pulse, the tooth was sprayed with water for a short re-hydration period of 1 sec, followed by air-blowing of the ablation area with a high pressure external pneumatic air hose for the duration of 4 sec. Re-hydration was applied in order to replace some of the water which had evaporated from the tissue during the hot thermal cutting process and to re-establish the natural conditions which exist in a saliva-moisturized patient's mouth. High pressure air was used in order to ensure that no superficial water remained on the tissue surface, and that before each laser pulse only the water within the internal pores remained within the tissue. It is important to note that re-hydration was partially required to sustain the thermal cutting process only in enamel, which contains just 3% water. In cementum, with 22% water, the slight desiccation of the tissue as a result of tissue heating did not have a significant effect on the thermal cutting process. Just the opposite occurred – the laser cutting speed in cementum was observed to be largest when the cementum was kept dry and was not re-hydrated in-between laser pulses.

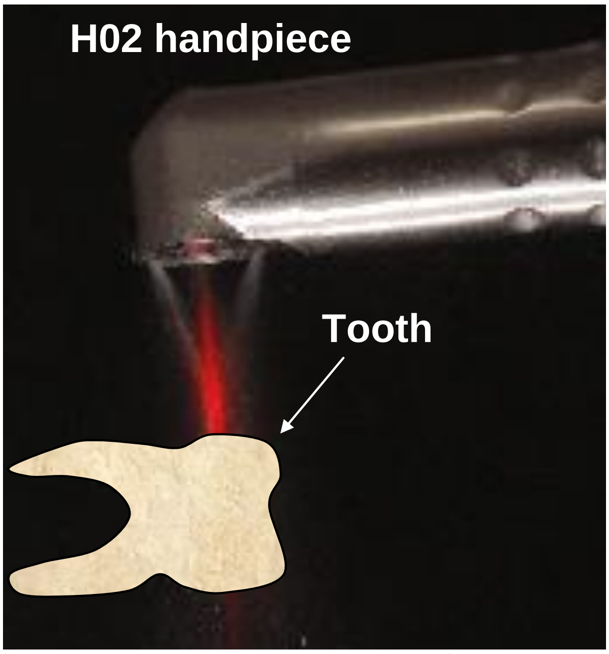

Fig. 2: The coaxially directed, built-in water/air spray of the H02 handpiece. The water/air spray intersecting the laser beam can be clearly seen. A fiber-tip H14 handpiece was also used.

Each ablation cavity was made with N = 10 or N = 30 consecutive pulses of the same laser pulse energy delivered to the same spot. The volume of the cavity (V) was calculated from the depth and external diameter of the ablated cavity, measured using a focusing optical microscope and taking into account also the shape of the cavity as determined by a laser triangulation technique. Each ablation volume data point thus represented an average obtained from ten different cavities, each made with N = 10 or 30 consecutive pulses.

The laser pulse energy, E_{out} as measured by an external energy meter at the exit of the handpiece, was E_{out} = 200 mJ for measurements on cementum, and E_{out} = 300 mJ on enamel. In order to ensure pulse output energy stability of the system, for all experiments the laser system was operated continuously at a constant flashlamp repetition rate of 0.2 Hz, and the delivery of the pulses to the tooth was controlled using an external shutter.

The ablation efficacy (in mm^3/J), i.e. the ablated volume per laser energy, was calculated by dividing the measured ablation volume (V) by the total delivered energy (N x E_{out}).

III. RESULTS

a) Non-absorbing targets

During initial experiments, for each of the experimental settings, a different spot on each of the targets was irradiated with 50 consecutive Er:YAG pulses under different laser and water/air spray conditions. The surfaces of the irradiated spots were examined before and after each experiment under optical magnification using an optical microscope (Leica M205C).

The results obtained with a LightWalker AT laser are shown in Table 3, and the results obtained with the Fidelis Plus III laser are shown in Table 2. No visible change to the irradiated surfaces, and therefore no ablation of the non-absorbing targets, was observed under any test conditions.

Table 2: Test results obtained with the Fidelis Plus III laser system for different experimental test conditions. The result "No ablation" means that no visible change or damage to the irradiated surface was observed.

HP	Mode	En [mJ]	Rep [Hz]	Spray [ml/min]	ZnSe	CaF_2	Si	Sapphire
H02	SSP	450	15	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	SSP	300	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	700	12	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	350	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	SP	1000	20	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	QSP	750	10	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	QSP	120	20	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
H14	SSP	450	15	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	SSP	300	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	600	15	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	350	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	QSP	600	10	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	QSP	120	20	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation

Since no disruptive effect on the surfaces of the tested targets was observed under any of the test conditions, the following final test was made. Each of the targets was irradiated on the same spot consecutively with both laser systems and under all test conditions. This resulted in each of the targets being irradiated on the same spot with 50 x (2x 14 + 12 + 18) = 2900 pulses. Again, as with the individual tests, no visible change or damage to the cumulatively irradiated surfaces was observed. The results are shown in Fig. 3.

Table 3: Test results obtained with the LightWalker AT laser system under different experimental test conditions. The result "No ablation" means that no visible change or damage to the irradiated surface was observed.

HP	Mode	En [mJ]	Rep [Hz]	Spray [ml/min]	ZnSe	CaF2	Si	Sapphire
R02	SSP	450	15	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	SSP	300	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	700	12	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	350	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	SP	1000	20	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
R14	SSP	450	15	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	SSP	300	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	600	15	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation
	MSP	350	30	10	No ablation	No ablation	No ablation	No ablation
				25	No ablation	No ablation	No ablation	No ablation

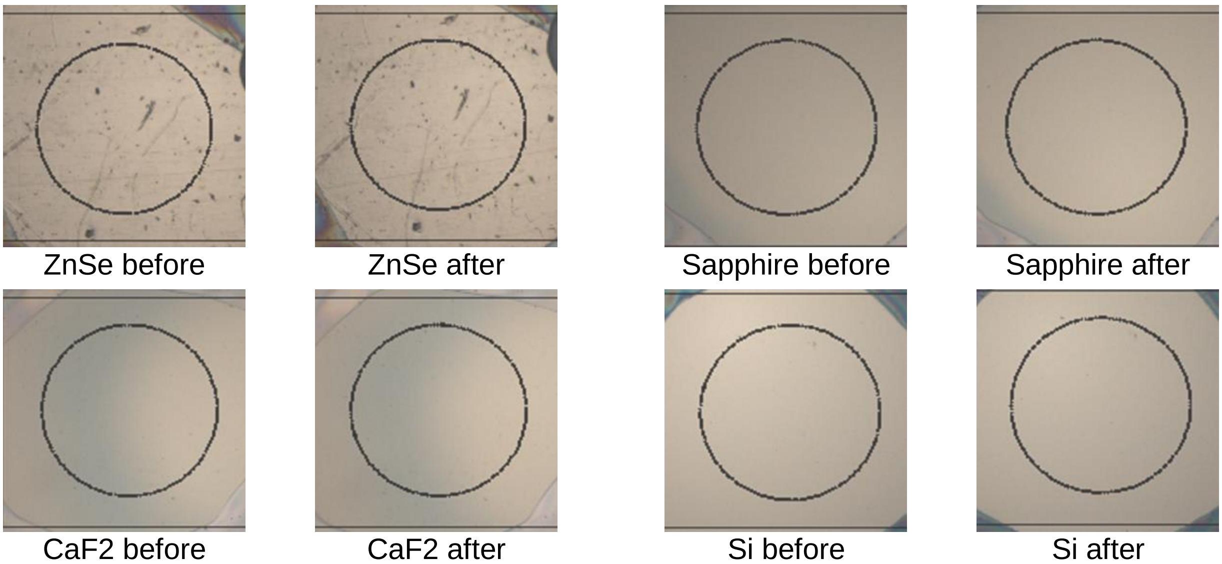

Fig. 3: Microscope pictures of the tested targets following a cumulative consecutive irradiation under all experimental test conditions. The circles with a 1 mm diameter show where the Er:YAG laser beam of approximately the same diameter impacted on the target surface. No visible change or damage to the irradiated surface can be observed.

b) Experiments on enamel and cementum

Figure 4 shows the dependence of the ablation efficacy on the level of water spray delivered to dental tissue, as obtained from cavities made with N = 10 laser pulses. The ablation efficacy is shown relative to the ablation efficacy as measured in the absence of water spray (water flow = 0 ml/min). In addition to the results of our measurements from using the LightWalker laser system equipped with an H02 handpiece, the previously published results as obtained with the Fotona Fidelis Plus III with R02 and R14 handpieces are also shown.

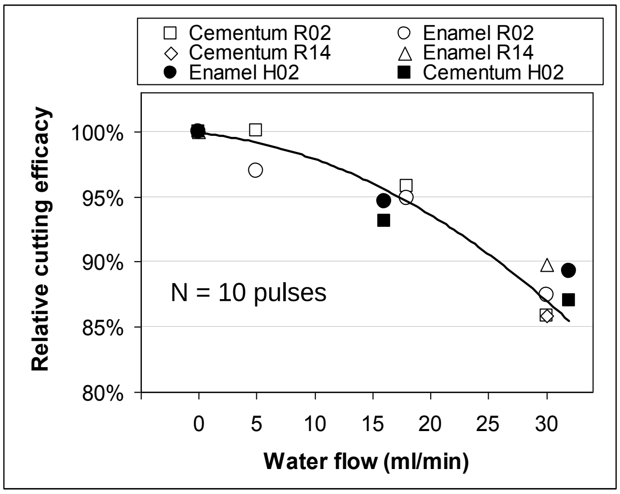

Fig. 4: Dependence of the ablation efficacy on the level of water spray in enamel and cementum as obtained from cavities made with N = 10 Er:YAG (SSP) laser pulses. The results as obtained with a Fotona LightWalker equipped with a non-contact handpiece H02 are shown together with previously published data as obtained with a Fotona Fidelis Plus III equipped with a non-contact R02 and a fiber-tip R14 handpiece, for N = 10 Er:YAG (SSP) laser pulses [7, 8]. The line represents a polynomial fit to all presented data.

Comparison of the results obtained with the LightWalker and Fidelis Plus III laser system shows a good agreement. All of the data points show approximately the same gradual decrease of cutting efficacy as the level of water spray is increased from zero water flow.

Measurements were made also for N = 30 pulses. The results as obtained with a LightWalker AT equipped with a fiber-tip H14 handpiece are shown in Fig. 5.

As can be concluded from Fig. 5, the negative influence of any presence of water spray is even more pronounced when cutting deeper cavities.

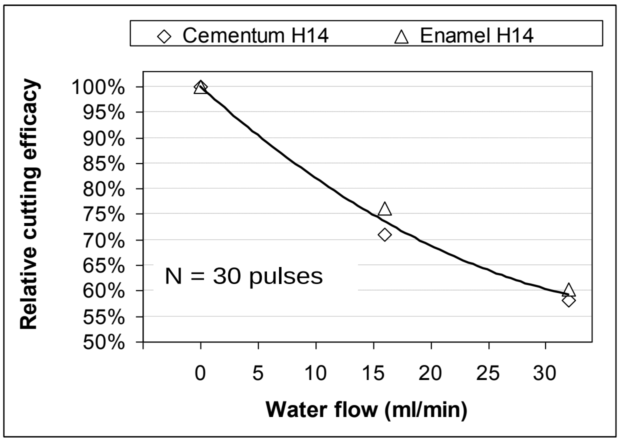

Fig. 5: Dependence of the cutting efficacy on the level of water spray in enamel and cementum as obtained from cavities made with N=30 Er:YAG (SSP) laser pulses. A Fotona LightWalker laser system equipped with a fiber-tip H14 handpiece was used. The line represents a polynomial fit to the data.

IV. CONCLUSIONS

Two Fotona dental laser systems, the Fidelis Plus III and LightWalker AT, were tested for the presence of an electromagnetically induced mechanical cutting mechanism, as proposed in [6]. Tests were made on non-porous, optically transparent materials, and on porous dental tissues containing interstitially trapped water as the absorber of laser light.

No evidence of a cutting effect was observed on a broad range of non-porous, optically transparent targets under a wide range of laser pulse durations, pulse energies and water spray conditions. The targets were chosen to include materials with the mechanical hardness being smaller and also higher than that of human enamel. In particular, no effect of disruptive forces caused by the interaction of the atomized water fluid particles was observed when using SSP pulse duration mode, Er:YAG laser pulses with a pulse duration < 300 μs, and with the full width at half maximum being located closer to the beginning than to the end of the laser pulse.

Similarly, measurements of the Er:YAG laser cutting efficacy on hard dental tissues, cementum and enamel demonstrated the highest cutting speed in the absence of water spray, i.e., in the absence of any interaction of the water fluid particles with the optical energy. For both laser tissues, and for both Fotona laser systems, the cutting efficacy was observed to progressively diminish with an increasing level of applied water spray. This proves that the Er:YAG cutting of hard dental tissues is based on the heating up of interstitially trapped water within the hard dental tissue, and not on electromagnetically induced mechanical cutting caused by an interaction of the optical laser energy with atomized water particles in the volume above the tissue surface.

ACKNOWLEDGMENTS

The authors wish to thank Fotona for providing the laser systems for carrying out the experiments. Two of the authors (Lukac and Suhovrsnik) are currently also employees of Fotona.

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. R. Hibst, Lasers for Caries Removal and Cavity Preparation: State of the Art and Future Directions. J Oral Laser Appl 2002; 2:203-211.
2. R. Hibst, U. Keller, "Experimental studies of the application of the Er:YAG laser on dental hard substances: I. Measurement of the ablation rate", Lasers Surg. Med. 9(4), 338-344 (1989).
3. R. Hibst, U. Keller, "Experimental studies of the application of the Er:YAG laser on dental hard substances: II. Light microscopic and SEM investigations", Lasers Surg. Med. 9(4), 345–351 (1989).
4. E.J. Burkes, J, Hoke, E. Gomes, M. Wolbarsht, Wet versus dry enamel ablation by Er:YAG laser, J Prosthetic Dentistry, 6(67), 847-851, (June 1992).
5. D. Fried et al., "Mechanism of water augmentation during IR laser ablation of dental enamel", Lasers Surg Med 31(3), 186-193 (2002).
6. H.W. Kang, I. Rizoiu, A.J. Welch, Hard tissue ablation with a spray-assisted mid-IR laser, Phys. Med. Biol. 52, 7243-7259, (2007).
7. R. J. Freiberg, C. Cozean, "Pulsed erbium laser ablation of hard dental tissue: the effects of atomized water spray vs water surface film", Proc. SPIE 4610, 74-84 (2002).
8. I. Rizoiu, A. I. Kimmel, "Electromagnetic energy distribution for electromagnetically cutting", patent EP 1560470, July 30, 2008.
9. Kuscer L, Diaci J, Measurements of Erbium Laser Ablation Efficacy in Hard Dental Tissues under Different Water Cooling Conditions, J. Biomed Opt, 18(10), 108002 (October 2013).
10. Lukac M, Suhovrsnik T, Filipic C. Minimally invasive cutting of enamel with QSP mode Er:YAG laser. Journal of laser dentistry, 2014, vol. 22, vol. 1,: 28-34.
11. L. Bachmann et al., "Changes in chemical composition and collagen structure of dentine tissue after erbium laser irradiation", Spectrochim. Acta A 61(11-12), 2634-2639 (2005).
12. P. Klocek, Handbook of optical infrared materials, Marcel Dekker 1991: 172-174.