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Influence of the Pulse Duration of an Er:YAG Laser System on the Ablation Threshold of Dental Enamel

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Abstract. The present study examines the dependence of the ablation threshold on the duration of the applied laser pulses in the dental enamel of human wisdom teeth. To this end, 600 treatments with the Er:YAG laser (λ=2940 nm) were carried out on a total of 50 extracted teeth. The laser light was coupled into a fluoride glass light guide for this purpose, in order to ensure almost gaussian distribution of the light in a radially symmetrical beam. The beam diameter on the specimen was 610 µm. The radiant exposure on the tooth surface was varied between 2 and 20 J/cm^2, while the duration of the pulses applied was changed in four steps from 100 µs to 700 µs. The irradiated tooth surfaces were examined for visible signs of ablation under a reflected-light microscope. The experiments revealed that, when pulses of shorter duration are used, the limit at which ablation sets in is reduced by up to approx. 3 J/cm^2. This expands the ablation threshold range of Er:YAG laser radiation to between 6 and 10 J/cm^2. In this context, both the pulse duration and the radiant exposure have a statistically significant influence on the ablation threshold (logistic regression, $p<0.0001$). Although the ablation threshold of the dental enamel can be changed by varying the pulse duration of the Er:YAG laser, no clinical consequences can be expected, as the shift is only slight.

Keywords: Ablation; Ablation threshold; Dental enamel; Er:YAG laser; Pulse duration

INTRODUCTION

The scientific investigation of fundamental problems plays a decisive role in understanding the mechanisms of action and their consequences when exposing biological material to laser radiation. One of these fundamental questions is the investigation of the ablation threshold of dental enamel at different laser wavelengths and pulse durations. Knowledge of the relationships and factors influencing the laser ablation of dental hard tissue constitutes the basis for use in patients and the introduction of new indications.

Based on the principles of physics, it is obvious that, at constant radiant exposures (corresponds to the energy density), changes in the light/material interaction will occur if the duration of exposure to the laser is reduced. Thus, the interactions occurring at a constant radiant exposure can range from biostimulation to photodisruption [1–3]. Against this backdrop, the present paper discusses whether a change in the pulse duration in the time window from 100 to 700 µs at FWHM (full width at half maximum) has an effect on the ablation properties of an Er:YAG laser, thus resulting in a shift in the ablation threshold of dental enamel. So far the ablation threshold of dental enamel was only investigated with fixed pulse durations in the range between 150 and 250 µs [4–9]. The present study is the first attempt to describe the influences of the pulse duration on the ablation threshold.

The erbium:YAG laser, which emits light with a wavelength of λ=2940 nm, was introduced into dental medicine specifically for the preparation of dental hard tissue. The good absorption of the radiation in water is exploited. Despite the low water content of 2–4% by weight in dental enamel, the sudden evaporation of the water bound in the tissue causes micro-explosions that blast away tiny particles of hard tissue [4].

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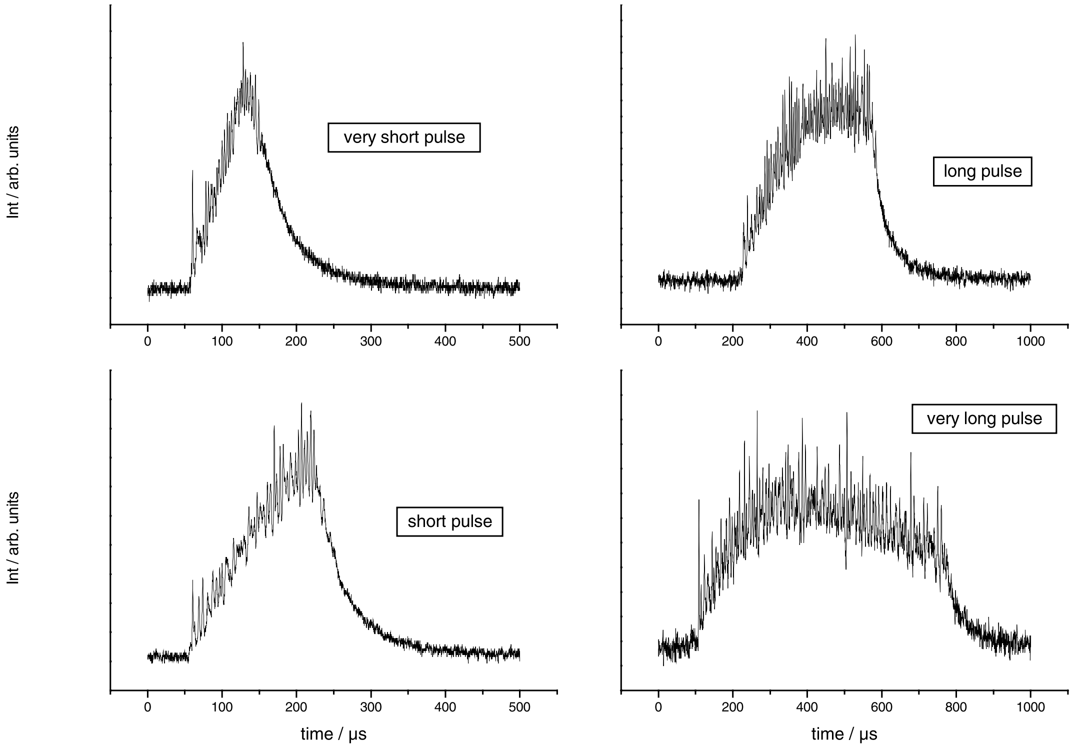

Fig. 1. Time-based pulse profiles of the four laser settings: very short (VSP), short (SP), long (LP), and very long (VLP) pulse.

Table 1. Overview of the pulse durations used

Type of pulse	Pulse duration acc. to manufacturer (µs)	Measured pulse duration (µs)
Very long pulse	750–950	700
Long pulse	450–550	350
Short pulse	250–300	150
Very short pulse	75–100	100

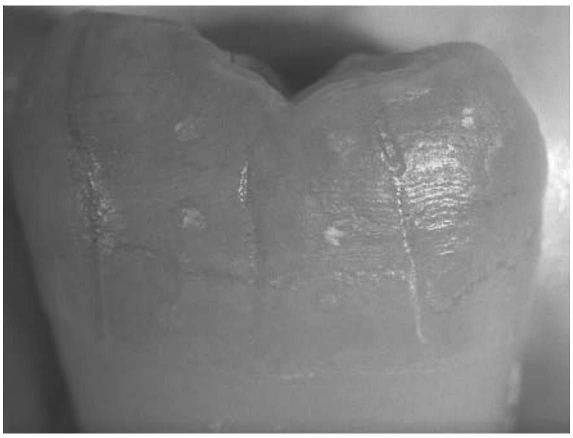

Fig. 2. Overview of the positioning pattern on the tooth surface. The 3×4 area and several applied laser pulses can be seen. The energy density used was 12 J/cm^2 at all four pulse durations.

MATERIAL AND METHOD

The commercially available 'Fidelis' Er:YAG laser (Messrs. Fotona, λ=2940 nm) was used to carry out the experiments. This laser system permits variation of the pulse duration in four defined steps from 100 µs to 1000 µs. Before the start of the experiments, the FWHM pulse durations were measured with the help of an atom layer thermopile detector (Fortech HTS) (Fig. 1). The results were in the same magnitude, but slightly shorter then the manufacturer's data, except the very short pulse (Table 1). The test material used consisted of 50 tooth crowns of wisdom teeth that had to be removed by extraction or osteotomy for medical reasons. After extraction, the teeth were cleaned and stored in physiological saline solution for no more than one week. A rotary, diamond-tipped drill was used to mark a 3 × 4 grid on the natural tooth surface for positioning the laser pulses and identifying the laser-treated area after completion of the experiments (Fig. 2). In this way, all four pulse durations used could be applied to each tooth in a defined fashion, and in a total of three times.

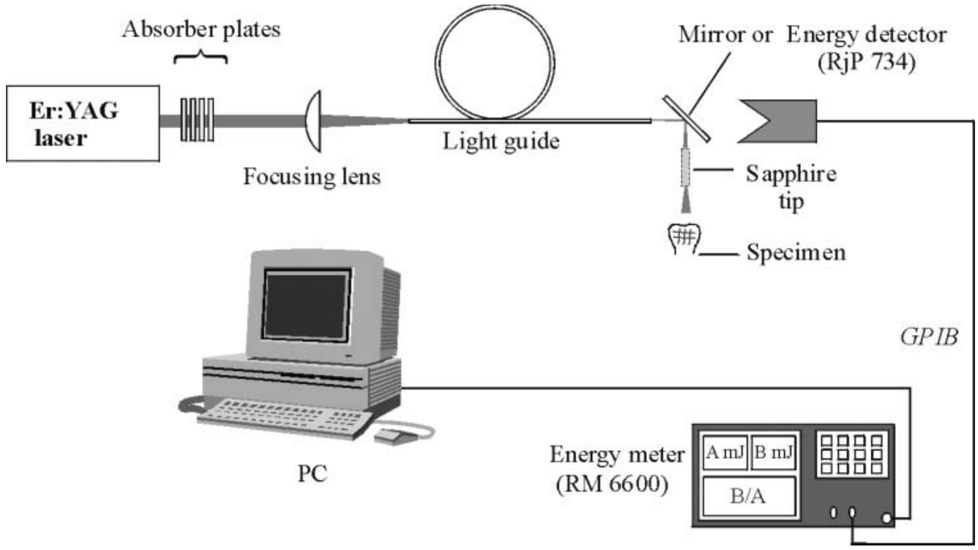

Fig. 3. Test set-up.

In order to rule out effects of the mode profile of the erbium solid-state laser, the laser radiation was coupled into a fluoride glass fibre of 1 m length. This ensured that, as a result of multiple reflection, the emerging light showed a virtually gaussian distribution over the beam diameter. Downstream of the light guide, the laser light was further coupled into a sapphire tip via a parabolic mirror arrangement, the sapphire tip assuming the role of the applicator system (Fig. 3). In order to determine the beam diameter at the end of the tip, and the divergence angle of the light, the beam diameter was measured at several distances downstream of the tip using the knife-edge method. These measurements yielded a beam diameter of 610 µm at the tip surface. The divergence angle was 15.2° (complete angle of beam spread).

All tooth crowns were irradiated in direct contact with the sapphire tip at 2 Hz and an irradiation duration of 4 s, meaning that eight laser pulses were applied to each irradiated point. In order to establish the threshold radiant exposure for ablation of the hard tissue, the radiant exposure on the tooth specimens was increased from 2 to 20 J/cm^2 in steps of 2 J/cm^2. Increments of 1 J/cm^2 were used in the region of the anticipated threshold between 6 and 10 J/cm^2. The exact radiant exposure was determined by recording the laser pulse energy with a pyroelectric detector and relating it to the beam area.

Groups of five teeth were irradiated three times with all four available pulse durations. This was followed by visual inspection of the irradiated areas under a reflected-light microscope (Leitz) in order to detect any visible signs of ablation. Crazing and cracking of the enamel surface (Fig. 4) were rated as incipient ablation, whereas discoloration of the dental enamel (Fig. 5) was not counted as ablation.

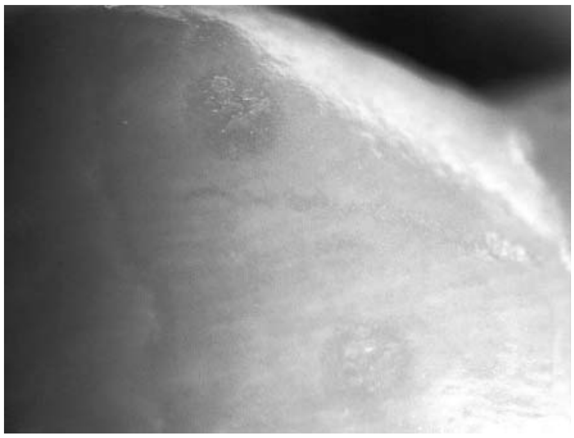

Fig. 4. Incipient ablation at 9 J/cm^2 and a pulse duration of 100 µs (VSP pulse).

RESULTS

Table 2 shows an overview of the percentage of ablations on the tooth surface as a function of the pulse duration and radiant exposure used.

Radiant exposures below 7 J/cm^2 generally showed no ablation, whereas radiant exposures of more than 10 J/cm^2 resulted in tissue ablation in all specimens (Fig. 6). This result is independent of the laser pulse duration used.

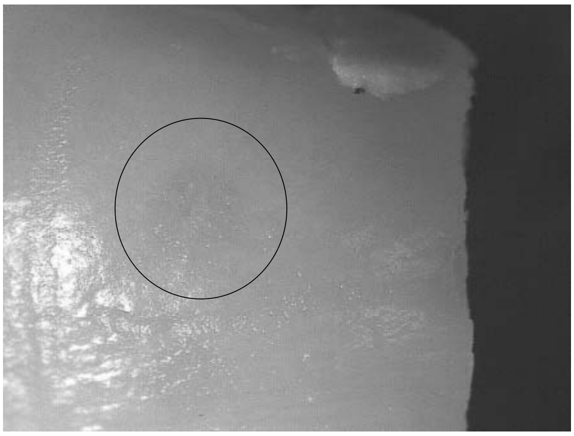

Fig. 5. Discoloration (circle) of the tooth specimen at 9 J/cm^2 and a pulse duration of 350 μs (LP pulse). This tissue alteration in the region of the threshold energy density was not rated as ablation.

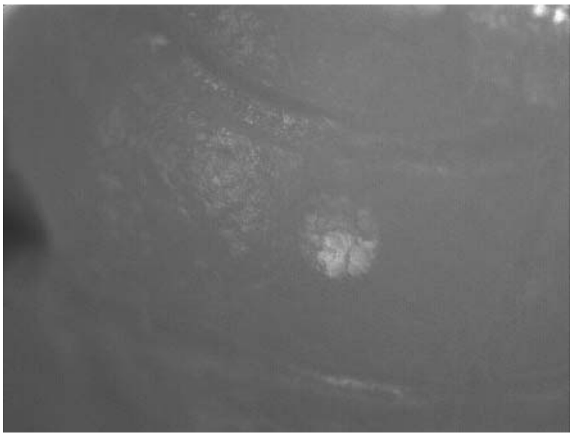

Fig. 6. Marked ablation on a tooth specimen at an energy density of 16 J/cm^2 and a pulse duration of 100 μs (VSP pulse).

Table 2. Number of ablations observed on the tooth surface as a function of the radiant exposure and pulse duration. n=15 per test group

Radiant exposure (J/cm^2)	Number of specimens with ablation (%)			
	Pulse durations			
	100 μs	150 μs	350 μs	700 μs
2	—	—	—	—
4	—	—	—	—
6	—	—	—	—
7	13	7	—	—
8	73	40	20	7
9	67	47	20	—
10	87	100	100	100
12	100	100	100	100
14	100	100	100	100
16	100	100	100	100
18	100	100	100	100
20	100	100	100	100

Major differences in the ablation properties can be observed in the transitional range between 6 and 10 J/cm^2 when the pulse duration is varied. Laser pulses with a duration of 700 μs displayed a clearly defined limit for the ablation threshold in the region of 9–10 J/cm^2. Even with shorter pulses, a radiant exposure of 10 J/cm^2 is sufficient to achieve ablation in every case. The sole exception in this context is the 100 μs pulse duration, which led to ablation in only 87% of the irradiated specimens. There is a shift in the lower limit for the onset of ablation when the pulse duration becomes shorter. At pulse durations of 350 μs and less, radiant exposures of 8 J/cm^2 already suffice to bring about ablation in some of the specimens (350 μs: 20%; 150 μs: 40%; 100 μs: 73%). At pulse durations of 150 and 100 μs, ablation already begins at radiant exposures of just 7 J/cm^2 (150 μs: 7%; 100 μs: 13%).

Statistical analysis of the results indicated a significant dependence of the ablation threshold (ablation yes/no) on both the radiant exposure and the pulse duration (logistic regression, both p<0.0001).

DISCUSSION

In order to determine the dependence of the ablation threshold of dental enamel on the pulse duration used with an Er:YAG laser, a total of 600 areas of enamel on 50 teeth were irradiated with four different pulse durations and various radiant exposures. So far the ablation threshold of dental enamel has only been investigated with fixed pulse durations [4–9]. Starting points can be found only in the study by Majaron et al. [5], who examined the ablation threshold in dentine. The authors concluded that a change in the pulse duration in the range of 50 μs to 1 ms has no effect on the ablation threshold of dentine.

The results of the present experiments reveal that the ablation process does not set in at a clearly defined threshold, but that there is a transitional range. The size of this transitional range increases when shorter pulse durations are applied. The upper limit of the transitional range is invariably 10 J/cm^2. The size of the range for the onset of ablation increased solely as a result of the shift in the lower radiant exposure limit (Table 2). The ablation threshold of 6–10 J/cm^2 determined for the Er:YAG laser in dental enamel in the present paper essentially agrees with the values stated in the literature [6–9]. Fried et al. [7] define the ablation threshold as being 7–9 J/cm^2. Hibst and Keller [4] state approx. 10 J/cm^2 as the ablation threshold for the Er:YAG laser. Belikov et al. [9] found the ablation threshold at 8 J/cm^2 in their study. Apel et al. [6] found the transition in a radiant exposure range of 9–11 J/cm^2. All studies were performed with pulse durations between 150 and 250 μs.

The dependence of the ablation threshold on the laser pulse duration is statistically significant. However, it was found that only a maximum difference of 3 J/cm^2 can be achieved in the available time window of 100–700 μs. This slight shift is thus of the order of magnitude of the usual fluctuation of the ablation threshold in human dental enamel that results from natural and local differences in the composition of this biological composite [6]. In terms of clinical application, the ablation threshold thus cannot be influenced by varying the pulse duration in the range from 100 μs to 700 μs.

A potential explanation for the observed dependence of the ablation threshold on the pulse duration is that the thermal loss mechanism is a function of the time. That means with longer exposure times a larger amount of energy will be dispensed in the surrounding tissue. The energy gets lost and is not available for the ablation process. Reciprocally, with the use of shorter pulse durations the ablation threshold will be reached with less energy.

REFERENCES

1. Niemz MH. Laser-Tissue Interactions – fundamentals and Applications. Berlin, Heidelberg, New York: Springer Verlag, 1996.
2. Kar H, Ringelhan H. Grundlagen der Technik der Photoablation. In Müller GJ, Berlien H-P (eds) Advances in Laser Medicine, Vol. 6. Landsberg/Lech: Ecomed, 1992.
3. Katzir A. Lasers and Optical Fibers in Medicine. San Diego, New York, Boston: Academic Press, 1993;59–106.
4. Hibst R, Keller U. Experimental studies of the application of the Er:YAG laser on dental hard substances: I. Measurement of the ablation rate. Lasers Surg Med 1989;9:338–44.
5. Majaron B, Luka M, Sustercic D, Funduk N, Skaleric UM. Threshold and efficiency analysis in Er:YAG laser ablation of dental hard tissue. Proc. SPIE 1996;2922: 233–42.
6. Apel C, Meister J, Ioana RS, Franzen R, Hering P, Gutknecht N. The ablation threshold of Er:YAG and Er:YSGG laser radiation in dental enamel. Lasers Med Sci 2002; complete on proofs.
7. Fried D, Featherstone JDB, Visuri SR, Seka W, Walsh JT. The caries inhibition potential of Er:YAG and Er:YSGG laser radiation. Proc SPIE 1997;2672:73–8.
8. Majaron B, Lukač M. Thermo-mechanical laser ablation of hard dental tissues: an overview of effects, regimes and models. Proc SPIE 1999;3593:184–95.
9. Belikov AV, Erofeev AV, Shumilin VV, Tkachuk AM. Comparative study of the 3 μm laser action on different tooth tissue samples using free-running Er-doped YAG, YSGG, YAP and YLF lasers. Proc SPIE 1993;2080:60–7.

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