MATHEMATICAL MODEL OF THE INFLUENCE OF LASER PARAMETERS ON THE ABLATION RATE OF DENTAL HARD TISSUES

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REZUMAT

Sistemele laser în regim pulsat Er:YAG și CO_2 sunt considerate a fi instrumente adecvate pentru ablația smalțului și dentinei deoarece ambele țesuturi au un nivel ridicat al aborbției pentru radiația cu lungimea de undă cuprinsă între 2,9 și 9,6 μm. Scopul acestui studiu este de a evidenția modul în care sistemele laser Er:YAG și CO_2 influențează din punct de vedere cantitativ și calitativ diametrul și adâncimea craterului în urma ablației țesuturilor dure dentare: smalț și dentină. În acest experiment s-au utilizat molari 3 umani proaspăt extrași. Sursele laser au fost reprezentate de Er:YAG Kavo Key dental model 1240 și CO_2 Laser Sonics LS 860. Dimensiunile craterelor obținute au fost măsurate prin microscopie optică. Rezultatele obținute au fost modelate experimental cu programele: GRAPHER și STATGRAPHICS. După procesarea matematică a rezultatelor, am obținut informații pertinente în ceea ce privește influența parametrilor cheie în eficiența ablației conform tipului de laser utilizat. În concluzie, rezultatele cercetării noastre demonstrează faptul că ambele tipuri de laser execută o ablație eficientă a dentinei atunci când energia laser variază între 200 și 300 mJ.

Cuvinte cheie: CO_2, Er:YAG, țesut dur, eficiența ablației.

ABSTRACT

Pulsed Er:YAG and CO_2 lasers should be suitable instruments for dentin and enamel ablation because both tissues have absorption peaks for radiation situated at 2.9 and 9.6 μm wavelengths. This is the context of our research that emphasizes the way in which the diameter and the depth of the crater made in enamel and dentin with the laser Er:YAG and CO_2 is influenced in quantity and quality. Freshly extracted human 3rd molar were used for this experiment. The laser sources were Er:YAG Kavo Key dental model 1240 and CO_2 Laser Sonics LS 860. The dimensions of the obtained craters were measured using the optical microscopy method. The obtained results were modeled experimentally with the programs: GRAPHER and STATGRAPHICS. After the mathematical processing of the results, we obtained relevant information regarding the influence of key parameters in the efficiency of the ablation according to the type of laser. Finally, our research results shows that both lasers ablate dentin efficiently when the laser energy ranges between 200 and 300 mJ.

Key Words: CO_2, Er:YAG, hard tissue, ablation efficiency

INTRODUCTION

Research on processing of hard dental substance is of great interest at the moment. This fact is due to the appearance of a large number of laser types and the tendency to improve dentistry maneuvers through a fast, painless and without side effects treatment. Taking into account these three points of view, none of the lasers merchandised for dentistry purposes have been considered adequate until now. Practically, researches have been focused on the use of laser in dentistry on dental hard tissue for both processing the enamel surface (increase of microhardness, sealing of pits and fissures, conditioning), dentin surface (conditioning, closing of dentin tubules, sterilization), and also for the removal of decayed and healthy dental hard tissue. The drawback of this last procedure is the secondary thermal effect that could lead to irreversible lesions, intolerable for the hard tissue and within the pulp. This fact induced researchers[1,2] to affirm that laser could limit its use in dentistry if new lasers with appropriate wavelength and an optimal use of the laser's parameters would not appear. Meanwhile, the utilization of Er:YAG laser on the dental hard tissue with no thermal effects has already been proved by some researchers.[3] The possible application of Excimer l = 193 nm[4] and 308 nm[5] Nd:YAG[6] and

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CO_2[7] ultrapulse with no adjacent thermal effects has also been proved. The use of these lasers on the dental hard tissue is also connected to the efficiency of the ablation and the degree of erosion. Several studies on this problem have been made, using lasers with excimer,[8] Nd:YAG,[9] Er: YAG.[10,11,12]

Lately, research has been focused on the utilization of CO_2,[13,14] Er: YAG,[15,16,17,18] excimer lasers as a possible processing technology of the dental hard substance in modern dentistry.[19] This is also the context of our research that emphasizes the way in which the diameter and the depth of the crater made in enamel and dentin with the laser Er:YAG and CO_2 is influenced in quantity and quality. This influence depends on the laser power, the pulse duration, and the number of pulses.

MATERIAL AND METHOD

The model of the experiment is presented in Figure 1.

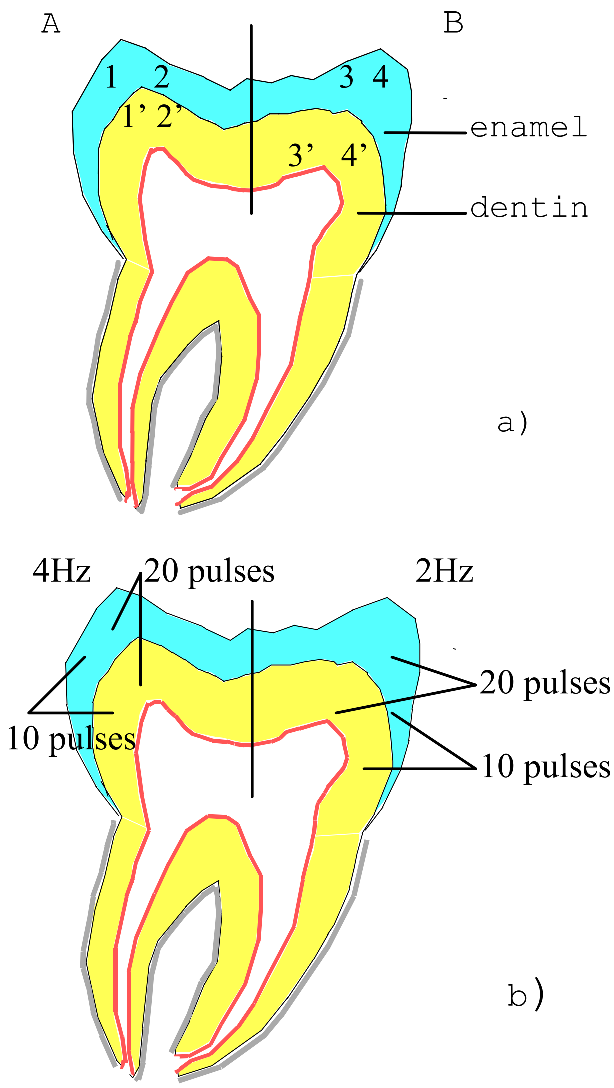

Fig. 1. The sample exhibit with crater made by: a). CO_2 laser; b). Er:YAG laser.

The 3rd molars were sectioned longitudinally from the occlusal to the apical area in two halves. The resulting enamel and dentin flat surfaces were exposed to laser radiation. The dimensions of the obtained craters were measured using the optical microscopy method. The samples were placed on a device that presents the capacity of x-y-z translation for positioning the enamel and dentin surfaces in the focal plane of the laser radiation. The results obtained were modeled experimentally with the following programs: GRAPHER and STATGRAPHICS. These two programs assisted us to find the regressive equation through a quadratic polynomial, the representation of the influential factors' histogram, the estimation of the model's confidence. From the above mathematical data, it was also possible to plot the curvilinear response surfaces and subsequently the response curves.

Preparation of Teeth

In this study, healthy human 3rd molars were used within 48 hours after extraction. They were sectioned longitudinally as described above, and fixed in 3.8% formaldehyde. In order to get a flat surface, the cutting surfaces were polished 9 µm to 43 µm with a diamond paste. These teeth were then placed in holders so that the surface to be irradiated was situated in the laser beam's focal plane.

Laser Sources

Pulsed Er:YAG and CO_2 lasers were used. The Er:YAG was a KAVO KEY dental model 1240, operating at a wavelength of 2.94 µm and delivering pulses of 60 - 500 mJ, with a pulse duration of 250 ms each. This means that every pulse represents a peak power of 0.24-2 KW. Since the laser beam was focused on the tooth surface with a spot of 500 mm, the energy density (ED) was 30 - 250 J/cm^2, with a peak power density (PPD) of 0.12-1MW/cm^2 per pulse. Pulse frequency could be set from 1 to 4 Hz.

The CO_2 (LaserSonics LS 860) delivered 1-60 W power in CW mode, at 10.6 mm wavelength. The laser was operated in the pulsed mode and provided 6.25 - 350 mJ in a burst of 25 pulses, each with a time duration of 250 ms, with a 2 ms time interval between successive pulses. The laser beam was focused to a 500 mm spot diameter to produce up to 180 J/cm^2 ED in every burst. Each pulse within the burst contained up to 14 mJ energy to produce an ED of 7.2 J/cm^2 and a PPD of 28 KW/cm^2.

Experimental Procedure

During the experiment, the samples were treated with the two types of laser (CO_2 and Er:YAG) in the following manner: 8 samples were irradiated with CO_2 laser and 16 samples were irradiated with Er:YAG laser. For each sample, 4 craters (holes) were made on the enamel, respectively 4 craters (holes) on the dentin with each laser type. According to Figure 1a, the tooth was separated in two laser attack areas (using laser CO_2): A and B. Given the established objective functions: the crater's diameter and the crater's depth, we used the arithmetical mean of the two craters for each of them, with the same value of the laser parameters.

The influential factors were: the laser power P[W] and the laser radiation's energy E[mJ]. The following parameters of the CO_2 laser were constant: pulse length = 6.25 ms, the length of the exposure = 50 ms. Because the energy was directly proportional with the power and the duration of the impulses, only the modifications made by the laser power on the rate of ablation in the dental hard tissues were taken into consideration. Figure 1b depicts the way the teeth were treated with the Er:YAG laser: 4 craters on the enamel and 4 on the dentin for different pulses, respectively frequencies. Apart from these parameters, the laser's energy has also changed within the 140 to 500 mJ interval. The modeling of the experiment has been done with the programs GRAPHER and STATGRAPHICS. The following modeling methods were used: the least squares method, for both the simple and the multiple regression method. The purpose of the data processing using the mathematical model method with the two programs was to establish the model $y = f(x_1, x_2, \dots x_n)$, where x_n are the significant influential factors. The decisions that need to be made before the experiment on factors are as follows:

• Setting the initial domain of the experiment that represents the area where the significant influential factors are defined and can be controlled.

• Establishing the central point of the experiment (zero level). This is the point where the experiment is made in the most general case with n influential factors. This point is situated in a n+1 dimensional plane.

• Establishing the variation intervals. The variation interval represents the quantity added or subtracted from the central point, which is the superior or inferior level of the influential factors.

The effective experiment performance refers to these levels.

RESULTS

The ablation volume calculation was obtained measuring the depth and geometry of the craters produced by the CO_2 and Er:YAG lasers on enamel and dentin. Before the measurements, the laser holes were observed by light microscopy. Thermal damage adjacent to the edge of the holes after the CO_2 laser drilling in the enamel shows opacity in the lased area and changes of the normal enamel color, from chalky white to yellow. The laser hole borders are clear, round or ovular. The dentine carbonization is accompanied by cracks. These can be seen when the focus of the microscope was adjacent to the studied surfaces, and also on the bottom of the holes. On the dentin wall, melting occurs together with carbonization. The dentin edges are clear and round, with various numbers of fissures (small cracks).

When drilling with Er: YAG laser on the enamel, the defective ablation is visible, but the edge of the crater is irregular and most of the time ovular. Comparing with the CO_2 laser effects, carbonization and cracks were not found in many craters. However, these thermal effects are likely to occur at the side of the laser rim, when the energy is between 350 to 450 mJ. In dentin, the edge of the holes presents a round, ovular, or irregular aspect. Focusing inside the holes, the bottom becomes asymmetrical from the center toward the periphery.

The values of CO_2 laser's parameters and the values measured for the crater's depth and diameter are presented in the Tables 1 and 2.

Table 1. The measured values of the diameter and depth of craters in the enamel after CO_2 laser exposure.

AREA A								
No. crt	P[W]	E[mJ]	Diameter d[mm]			Depth a[mm]		
			d_1	d_2	d_{12}	a_1	a_2	a_{12}
01	16	100	0,36	0,39	0,38	0,47	0,23	0,35
02	32	200	0,56	0,52	0,54	0,270	0,191	0,230
03	48	300	0,57	0,60	0,59	0,95	0,205	0,150
04	62	400	0,65	0,66	0,66	0,136	0,155	0,145
AREA B								
No. crt	P[W]	E[mJ]	Diameter d[mm]			Depth a[mm]		
			d_3	d_4	d_{34}	a_3	a_4	a_{34}
01	8	50	0,28	0,33	0,31	0,40	0,42	0,41
02	24	150	0,44	0,48	0,46	0,183	0,151	0,167
03	40	250	0,57	0,62	0,59	0,194	0,134	0,164
04	56	350	0,61	0,59	0,60	0,158	0,102	0,130

For the samples treated with CO_2 laser, GRAPHER was used to model the experiment. The diameters of the craters in dentin and enamel extend with the increase in the pulse number (Table 1 and 2). The crater's depth extends together with the increase of the energy in the case of enamel (Table 1 and 2).

Table 2. The measured values of the diameter and depth of craters in the dentin, after co_2 laser exposure

AREA A								
No. crt	P[W]	E[mJ]	Diameter d[mm]			Depth a[mm]		
			d'_1	d'_2	d'_{12}	a'_1	a'_2	a'_{12}
01	16	100	0,59	0,57	0,58	0,236	0,258	0,247
02	32	200	0,61	0,60	0,61	0,280	0,230	0,255
03	48	300	0,64	0,62	0,63	0,276	0,256	0,266
04	62	400	0,66	0,64	0,65	0,299	0,311	0,305
AREA B								
No. crt	P[W]	E[mJ]	Diameter d[mm]			Depth a[mm]		
			d'_3	d'_4	d'_{34}	a'_3	a'_4	a'_{34}
01	8	50	0,51	0,51	0,51	0,208	0,126	0,167
02	24	150	0,59	0,56	0,57	0,279	0,250	0,264
03	40	250	0,61	0,57	0,59	0,250	0,446	0,348
04	56	350	0,59	0,67	0,63	0,367	0,393	0,380

For the samples treated with CO_2 laser, GRAPHER was used to model the experiment. The diameters of craters in dentin and enamel extend with the increase in the pulse number (Table 1 and 2). The crater's depth extends together with the increase of the energy in the case of enamel (Table 1 and 2). The functional dependence- model is most convenient through power functions and the equations are as it follows:

DENTIN; AREA A
ENAMEL; AREA A
- diameter: $Y= 0,340159 \times X^{0,102858}$
- diameter: $Y= 0,076746 \times X^{0,358725}$
- depth: $Y= 0,031876 \times X^{0,425929}$
- depth: $Y= 3,733092 \times X^{-0,581483}$

DENTIN; AREA B
ENAMEL; AREA B
- diameter: $Y= 0.399093 \times X^{0,080671}$
- diameter: $Y= 0.065474 \times X^{0,387079}$
- depth: $Y= 0.106933 \times X^{0,168913}$
- depth: $Y= 8.812173 \times X^{-0,698526}$

Y= diameter: d[mm]
X= energy: E[mJ]

Tables 3 and 4 present the measured values for each crater obtained in the enamel (Table 3) and dentin (Table 4), which correspond with the variations in the Er:YAG laser parameters.

In the case of samples that were treated with Er:YAG, it can be noticed that the experimental data show an optimum point for both the diameter and depth, situated around the value of the energy of 250mJ. This dependence is valid for the enamel and the dentin as well, at 2 - 4 Hz frequency. In addition, the curvilinear response surfaces have the largest curvature. In the case of the enamel, the influence of the number of pulses on the crater's parameters is insignificant.

Table 3. The measured values of the diameter and depth of the crater in the enamel after the Er: YAG laser exposure.

No. Crt.	E[mJ]	No. Pulses [-]	Diameter d[mm]		Depth a[mm]	
			f=4[Hz]	f=2[Hz]	f=4[Hz]	f=2[Hz]
H1	140	10	0,58	0,29	0,161	0,106
H2	200	10	0,61	0,50	0,193	0,124
H3	250	10	0,65	0,56	0,260	0,145
H4	300	10	0,68	0,58	0,323	0,174
H5	350	10	0,71	0,62	0,394	0,248
H6	400	10	0,78	0,64	0,310	0,282
H7	450	10	0,75	0,69	0,254	0,216
H8	500	10	0,50	0,66	0,214	0,206
H1	140	20	0,43	0,32	0,162	0,161
H2	200	20	0,52	0,53	0,211	0,168
H3	250	20	0,56	0,60	0,243	0,182
H4	300	20	0,64	0,62	0,249	0,321
H5	350	20	0,75	0,71	0,324	0,272
H6	400	20	0,86	0,75	0,315	0,222
H7	450	20	0,69	0,79	0,299	0,166
H8	500	20	0,57	0,53	0,290	0,140

The appropriateness of the model was determined based on the coefficient of the simple/multiple determination (R -squared). These equations are as follows:

ENAMEL
f=2[Hz]; i= no.of. pulses[-]; i=10
$Y= 0.02043 \times X^{0,57789}$
Y=diameter: d[mm]
X= energy: E[mJ]
R-squared- the appropriateness of the model
R-squared= 83.81 %

Table 4. The measured values of the diameter and depth of the crater in the dentin after the Er: YAG laser exposure.

No. crt.	E[mJ]	No. pulses[-]	Diameter d[mm]		Depth a[mm]	
			f=4[Hz]	f=2[Hz]	f=4[Hz]	f=2[Hz]
H1	140	10	0,62	0,42	0,538	0,592
H2	200	10	0,52	0,58	0,860	0,761
H3	250	10	0,56	0,63	0,785	0,850
H4	300	10	0,71	0,62	0,803	0,721
H5	350	10	0,84	0,74	0,744	0,885
H6	400	10	0,80	0,60	0,729	0,746
H7	450	10	0,83	0,66	0,605	0,833
H8	500	10	0,71	0,67	0,784	0,914
H1	140	20	0,64	0,59	0,616	0,736
H2	200	20	0,63	0,59	1,196	0,913
H3	250	20	0,57	0,68	1,063	1,045
H4	300	20	0,69	0,64	0,841	0,852
H5	350	20	0,82	0,65	0,873	0,771
H6	400	20	0,78	0,61	1,038	1,140
H7	450	20	0,81	0,73	1,021	0,929
H8	500	20	0,71	0,67	0,888	0.952

f=2[Hz]; i=10

$Y= 0.003315 \times X^{0,698712}$

Y= depth: a[mm]

X= energy: E[mJ]

R-squared= 77.79 %

DENTIN

f=2[Hz]; i=10

$Y= 0.18234 \times X^{0,218299}$

Y=diameter: d[mm]

X=energy: E[mJ]

R-squared=68.05 %

f=2[Hz]; i=10

$Y= 0.29668 \times X^{0,195154}$

Y=depth: a[mm]

X=energy: E[mJ]

R-squared=43.22 %

Using a multiple regression, we can include both the influence of the energy and of the number of pulses, and we get an adequate function of the crater's parameters, given the variables of the process.

These equations are as follows:

Y= diameter: d[mm]

X_1= energy: E[mJ]

X_2= no. of pulses [-]

R-squared= the appropriateness of the model

ENAMEL

Crater diameter for f=4[Hz]

$Y=0.040463 + 0.004106 \times X_1 - 0.003 \times X_2 +$

$+ (-5.764276\ E\text{-}6) \times X_1^2$

R-squared= 50%

Crater diameter for f=2[Hz]

$Y= -0.139972 +0.004512 \times X_1 + 0.003812\times X_2+$

$(-5.712508\ E\text{-}6) \times X_1^2$

R-squared= 82%

Crater depth for f=4[Hz]

$Y= -0.132773 + (-3.364577\ E\text{-}6) \times X_1 -$

$- 0.0002\times X_2+ 0.002461\times X_1^2$

R-squared= 67%

Crater depth for f=2[Hz]

$Y= -0.070345 + 0.001646\times X_1 - 0.000387\times X_2+$

$(-2.258036\ E\text{-}6) \times X_1^2$

R-squared = 39%

DENTIN

Crater diameter for f=4[Hz]

$Y= 0.30173 + 0.001866\times X_1+0.001778\times X_2 +$

$(-1.948793\ E\text{-}6) \times X_1^2$

R-squared=60%

Crater diameter for f =2[Hz]

$Y= 0.233809 + 0.001983\times X_1 + 0.002778\times X_2+$

$(-2.442176\ E\text{-}6) \times X_1^2$

R-squared=70%

Crater depth for f=4[Hz]

$Y= - 0.09607 + 0.003704\times X_1 + 0.025511\times X_2+$

$(-5.383761\ E\text{-}6) \times X_1^2$

R-squared=52%

Crater depth for f=2[Hz]

$Y= 0.288145 + 0.00198\times X_1 + 0.0123633\times X_2+$

$(- 2.25989\ E\text{-}6) \times X_1^2$

R-squared=53%

DISCUSSIONS

Apart from the interaction of laser radiation with dental hard tissues (enamel, dentin), there are craters with variable depth and diameters depending on the laser type used, the number, length, and energy of laser pulses.[20,21] After the mathematical processing of the results (measurement of the diameter and the depth of penetration), what we obtain is relevant regarding the influence of the key parameters in the efficiency of the ablation and also for indicating the quality of the ablation according to the laser chosen.

Our research confirmed the results from literature[22,23,24] regarding the capacity of the CO_2 and Er:YAG lasers[25,26] to ablate dental hard tissues. The experiment project allowed us to get the models of response functions concerning the diameter and depth of each crater. Thus, the regressive functions resulted. Using these regressions, the two parameters were obtained with a confidence interval of 70%. Therefore, with the obtained models we can explain the tendencies that the influential factors should have in order to achieve the optimal values. Moreover, they allow ranking the influential factors in the order of their importance over the objective functions.

During processing with Er:YAG, given the direction of the laser beam, there is a deviation of 90° of the crater's axis after a certain crater.

The geometry of the crater's surface is influenced by the laser parameters and the structure of the treated tissue. Hence, during the irradiation with either CO_2 or Er:YAG lasers we get elliptic surfaces that extend as the quantity of the used laser increases. On the other hand, the crater in dentine is circular, which indicates the appropriateness of the laser in the ablation of this tissue.

Presently, from our studies results that both lasers ablate efficiently the dentine when the laser energy varies between 250 and 350 mJ. From these two lasers, Er:YAG is the one that is more efficient for ablating enamel and the dentine. The margin of the enamel crater showed sharp edges and projections. Explosive forces fracturing the enamel would create this effect. Because the water content of the dentin is greater than that of the enamel, dentin can be ablated more easily. The secondary thermal effects, like carbonized areas are more frequent when using CO_2 laser; however, they cannot be ignored in the case of Er:YAG either. These results strongly suggest that both lasers should be used with a water coolling system if vital teeth are subjected to testing. This suggestion corresponds with the speculations of Keller and Hibst that the Er: YAG would produce little thermal damages to the dental hard tissues.[3,15] Knowing the values of the crater diameter and depth and the crater form being approximated with the geometrical shape of a cone, we can easily determine the volume of the expelled material after the irradiation with laser.

CONCLUSIONS

Both lasers can ablate dental hard tissues. Controlling the power density, it is possible to establish a level of energy where the efficiency of ablation has a maximum point. It is necessary to use a very high energy density and very short pulse durations in order to limit thermal damages that may occur and, furthermore, to remove dental hard tissues quickly. Unfortunately, both lasers appear to drill tissue rather slowly. Overall, the complex mathematical processing of experimental results data have led to the conclusion that the optimum ablation point is situated somewhere between 250 and 350 mJ energy.

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REFERENCES

1. Melcer J, Chaumette MT, Melcer F, Dejardin J, Hassan R, Merard R, Pinandeau Y, Weill R. Treatment of dental decay by CO_2 laser beam. Preliminary results. Las Surg Med 1984;4:311-321.
2. Frentzen M, Koort HJ. Lasers in dentistry new possibilities with advancing laser technology. Dent Jorn 1990; 40: 323-332.
3. Hibst R, Keller U. Experimental studies of the Er:YAG laser on dental hard substances. Measurements of the ablation rate. Laser Surg Med 1989;9:338-344.
4. Neev J, Liaw Lih-Huel L, Raney DV, Fujishige JT, Ho PD, Berns M. Selectivity, efficiency, and surface characteristics of hard dental tissues ablated with ArF pulsed excimer lasers. Las Surg Med 1991; 11:499-510.
5. Frentzen M, Koort HJ. Excimer Laser- Grundlagen und mögliche Arwendungen in der Zahnheilkunde. Laser in der zahnmedizin, Berlin: Quintessenz Verlags GmbH 1992, p. 115-40.
6. White JM, Neev J, Goodis HE, Berns MW. Surface temperature and thermal penetration depth of Nd:YAG laser applied to enamel and dentin. SPIE 1992; 1643: 423-435.
7. Walsh LJ. Clinical evaluation of dental hard tissue. Applications of carbon dioxide lasers. Journal of Clinical Laser Medicine & Surgery 1994;12(1):11-15.
8. Arima M, Matsumata K. Effects of ArF: Excimer laser irradiation on human enamel and dentin. Las Surg Med 1995;13:97-105.
9. Herring T, Rechmann P, Pilgrin HC, Schwarzmaier J, Koufmann R. Caries selective ablation by pulsed lasers. SPIE 1991; 1424:99-105.
10. Altshuler GB, Eroffev AV, Egorov V, Semenova TL. Model of laser destruction of hard tooth tissue. SPIE 1995;2323:203-210.
11. Kim KS. Advances of laser dentistry in Korea and various factors of Er:YAG laser affecting the ablation rate of dental hard tissue. Proceedings of the 8th International Congress on Lasers in Dentistry, Elsevier Science,2003;1248:45-50.
12. Altshuler GB, Belikov AV, Skrypnik AV, Parakhuda SE, Cernavin I. An improved method of Er:YAG laser treatment of hard dental tissue. Proceedings of the 8th International Congress on Lasers in Dentistry, Elsevier Science 2003; 1248:127-129.

13. Melcer J, Melcer F. CO_2-laser anwendung in der Konservierenden Zahnheilkunde. Laser in der zahnmedizin, Berlin: Quintessenz Verlags-GmbH, 1992, p. 91 - 104.
14. Duncan YU, Powell GL, Higuchi WI, Fox JL. Comparison of three lasers on dental pulp chamber temperature change. J Clin Las Med Surg 1994;11(3):119-122.
15. Keller U, Hibst R. Laser in Dentisty. Clinical application today and tomorrow. SPIE 1993; 2080:2-9.
16. Wigdor H, Ellit ABT, Ashrafe S, Walsh JT. The effect of lasers on dental hard tissues. JADA 1993; 24:65-70.
17. Reckmann P, Henning T. Influence of different laser wavelength on the ablation characteristics of healthy dentin. SPIE 1994; 2327.
18. Colojoară C, Miron M, Leretter M. Laseri în Stomatologie. Actualități și perspective, Timișoara: DA&F Spirit, 1998.
19. Moss JP, Patel BCM, Pearson GJ, Arthur G, Lawes RA. Krypton fluoride excimer laser ablation of tooth tissues precision tissue machining. Biomaterials 1994;15(12):1013-1018.
20. Kim ME, Jeoung DJ, Kim KS. Effects of water flow on dental hard tissue ablation using Er:YAG laser. J Clin Laser Med Surg 2003; 21(3):139-44.
21. Mercer CE, Anderson P, Davis G. Sequential measurement of enamel and dentine ablation by an Er:YAG laser using 3D X-ray microtomography. Proceedings of the 8th International Congress on Lasers in Dentistry, Elsevier Science2003; 1248: 131-134.
22. Wigdor HA, Walsh JT, Featherstone JDB, Visure SR, Fried D, Waldvogel JL. Laser in dentistry. Las Surg Med 1995;16:101-133.
23. Burkes Jr E J, J Hoke, Gomes E, M Wolbarsht. Wet versus dry enamel ablation by Er:YAG laser. The Journal of Prosthetic Dentistry 1992; 67(6):847-851.
24. Pearson GJ, Mc Donald AV. Use of infra-red and ultra-violet lasers in the removal of dental hard tissue. Laser in Medical Science1994;9:227-237
25. Hirai Y. Pulp response to the Er:YAG laser in the cavity preparation. Proceedings of the 8th International Congress on Lasers in Dentistry, Elsevier Science 2003;1248:37-43.
26. Awazu K. Novel aspects of dental laser and tissue interaction. Proceedings of the 8th International Congress on Lasers in Dentistry, Elsevier Science 2003;1248:29-36.