Comparative Study of the Ablation Rates of Single-pulsed Er:YAG Laser Irradiation on Dentin and Enamel

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Ⅰ. INTRODUCTION

For many centuries, light have been used as a therapeutic agent. In ancient Greece, for instance, the sun was used in heliotherapy[2]. It is the exposure of the body to the sun for restoration of health or treatment of disease. This use of light for treatment of various pathologies referred to as phototherapy. Laser therapy is one of phototherapies and now the most prospective one in medicine and dentistry. The first laser, or "maser" as it was initially called, was developed by Maiman[10] of Huges Aircraft Corporation in 1960. It was a pulsed ruby laser and is an acronym for "Microwave Amplification by Stimulated Emission of Radiation" which describes the basic principle by which all lasers operate.

Almost immediately after the development of the ruby laser by Maiman, researchers and dentists thought that it could be applied to dental treatment, especially for mineralized tooth tissues. Stern and Sognnaes[23] in 1964 began looking at the possible use of the ruby laser in dentistry. They were the first in a long list of researchers looking for a better way to treat dental patients with lasers.

During the past decades, several in vitro studies with different laser devices were performed on dental hard tissue applications. However, results were not encouraging[3,15,21,22,24]. Their major problem have been thermal side effect, restricting the indications for lasers such as continuous-waved CO_2 and continuous-waved and pulsed Nd:YAG laser to the vitrification of the residual dentinal caries[11,13,22]. Considering the ablation rate, the short pulsed CO_2 laser seems to be suitable for hard tissue ablation. However, problems such as heat generation and plasma formation persist[12,26].

Erbium:yttrium-aluminum-garnet or Er:YAG laser that was cleared by Food and Drug Administration for marketing in the United States is the first laser for use in cutting human teeth in vivo. It offers a new perspective for the effective removal of mineralized tooth tissues. Based on a thermally induced, mechanical ablation process, dental cavity preparations can be created by microexplosions without thermal damages to the adjacent hard and soft tissues[4,5,7]. Initial studies of Er:YAG laser ablation of dental hard tissues were performed by Hibst and Keller[5,6], who measured the depth of ablation in dentin and enamel after delivering 10 pulses of laser radiation at various energy levels. Li et al.[9] determined the ablation rates of these materials as well but expanded the fluence range up to approximately $140 J/cm^2$ and also explored two different repetition rates, 2 and 5 Hz. These investigators and others have shown that erbium lasers readily ablate hard biological tissues such as dentin, enamel, and bone with thermal damage zones no greater than approximately 50 ㎛[1,6,8,20,25].

As dentin and enamel have absorption peaks for radiation of 2.9 and 9.6 ㎛ wavelengths[14], the pulsed Er:YAG(λ =2.94㎛) or CO_2(λ =10.6㎛) laser should be suitable for ablation of dental hard substances. The purpose of this study was to investigate the ablation rate of single-pulsed radiation of Er:YAG laser at 2.94 ㎛ with various energy levels on dentin and enamel, using a new apparatus developed in Korea recently.

II. MATERIALS AND METHODS

Laser Apparatus

The laser device used in this study was the SDL-3000EN (Samsung Advanced Institute of Technology, Suwon, Korea). It has two different lasing medium, Erbium:YAG and Neodymium:YAG. Er:YAG laser device used in this study emits approximately 250 ㎲ pulsed laser and the wave length is 2.94 ㎛ . The focal length was 9 mm and focal spot diameter was 300 ㎛. The energy of laser apparatus used in this study is varied from 20 mJ up to 350 mJ per pulse and its peak output power was 3.5 W.

Samples

The tissue samples were derived from extracted adult molars. Immediately following extraction, the teeth were placed in ordinary tap water to which a small amount of bleach was added to disinfect the samples. The time from extraction to experimentation varied considerably with the maximum being several weeks. Ten teeth were selected, and each of them was embedded in epoxy resin, and hardened.

Five teeth samples were cut flat to exposure dentin surface by occlusal reduction with a slowly rotating diamond blade(Model 650, South Bay Technology Inc., USA) under running water(Fig.2, 3). Enamel surfaces of 5 teeth were

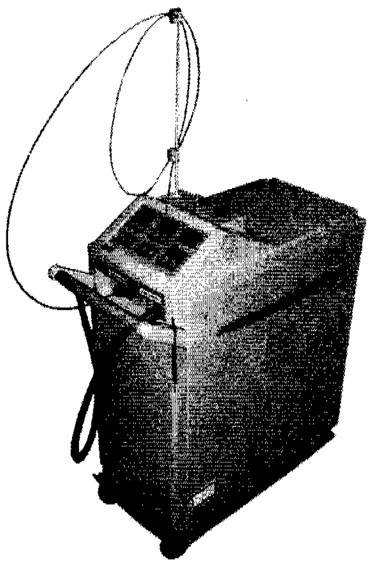

Fig. 1. The laser device used in this study(SDL-3000EN, Samsung Advanced Institute of Technology, Suwon, Korea).

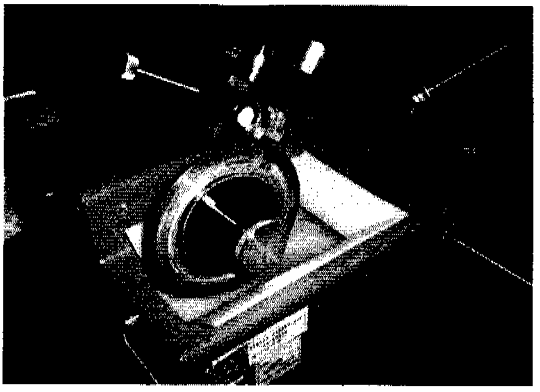

Fig. 2. Teeth samples were cut flat by occlusal or buccal or lingual reduction with a slowly rotating diamond blade under running water.

Fig. 3. Prepared dentin sample.

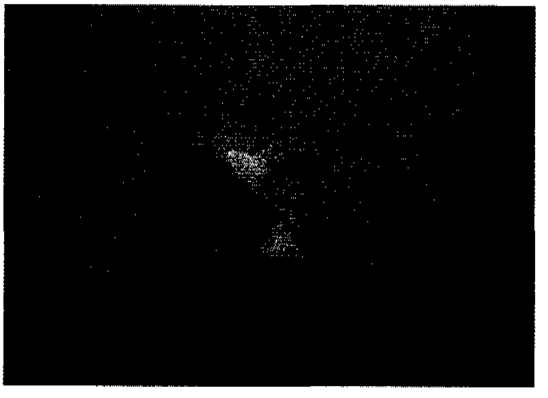

Fig. 4. Prepared enamel sample.

also cut flat by buccal or lingual reduction with the same blade(Fig.4). Each dentin or enamel surface of prepared teeth was divided into 6 partitions, to which Er:YAG laser would be applied. Therefore, 30 dentin and 30 enamel samples were used in this study. Both dentin and enamel samples were divided into 5 experimental groups(40 mJ, 80 mJ, 120 mJ, 160 mJ, 200 mJ) to determine ablation rate.

Lasing

The laser was focused perpendicularly onto the surface of each dentin or enamel partitions using spherical lens with 9 mm focal length. Focal length was precisely reproduced using the guide pin attached on the side of handpiece. All teeth samples were clamped to a movable stage and were adjusted vertically and tilted so as to be in the focal point of the laser beam perpendicularly(Fig.5,6). And then, single-pulsed Er:YAG laser applied to each dentin and enamel partition of 5 energy level groups(40 mJ, 80 mJ, 120 mJ, 160 mJ, 200 mJ).

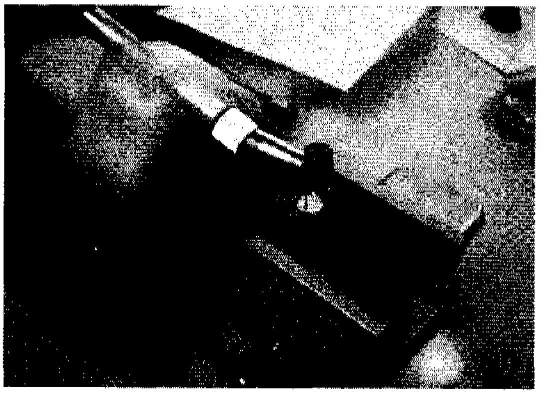

Fig. 5. Teeth samples were clamped to a movable stage and were adjusted vertically and tilted so as to be in the focal point of the laser beam perpendicularly.

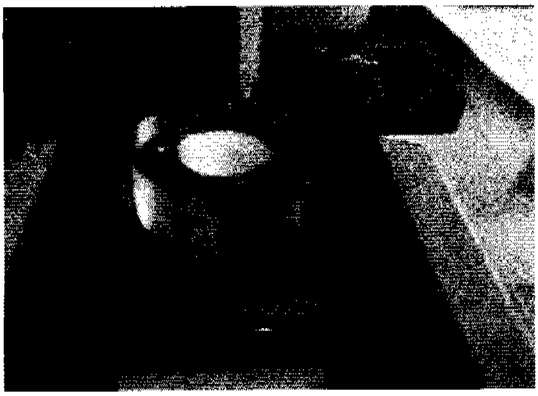

Fig. 6. Focal length(9 mm) was precisely reproduced using the guide pin attached on the side of handpiece.

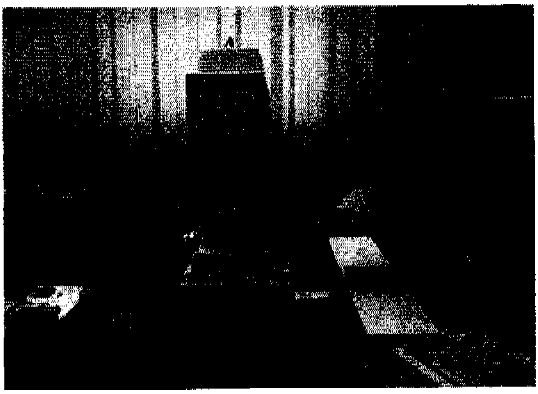

Fig. 7. Three dimensional imaging surface structure analyzing system (NT-2000).

Measuring

The equipment used for measuring the volume of ablation in dentin and enamel in this study was the NT-2000 (3-D Imaging Surface Structure Analyzer, WYKO Corp., USA). It can measure volume of ablation utilizing vertical-scanning interferometry, and its resolution was 1~3 nm.

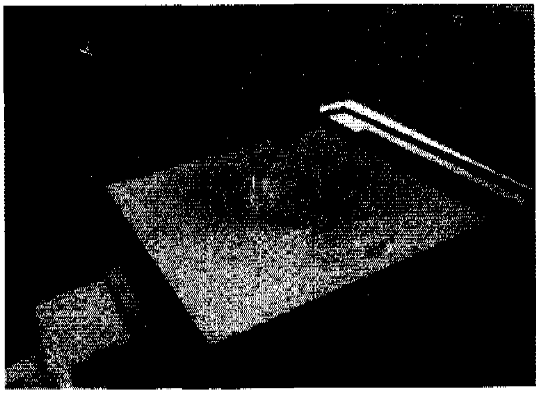

Fig. 8. Tooth sample being measured volume of ablation by NT-2000.

Statistical Analysis

To determine the statistical significance for the difference of ablation rates between dentin and enamel, ANOVA test and paired t-test were used with StatView® 4.0(for Macintosh) program, and for the difference of ablation rates between energy levels, multiple comparison t-test was used.

Ⅲ. RESULTS

Figure 13 shows mean volume of ablation of dentin and enamel according to the energy levels. Ablation rates increased according to energy levels, and dentin shows higher volume than enamel. Table 1 presents the means and standard deviation of volume of ablations of all groups. In ANOVA test, there were statistically significant differences between dentin and enamel groups($p<0.0001$) and significant differences between energy levels($p<0.0001$). And comparing dentin and enamel groups in each energy level using paired t-test, there were significant differences between both groups except 40 mJ and 80 mJ groups.

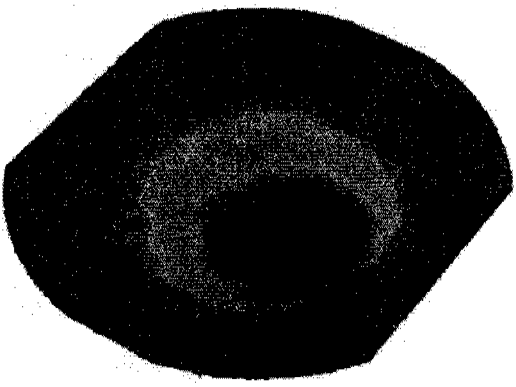

Fig. 9. Scanned image of dentin sample irradiated by Er:YAG laser(120 mJ).

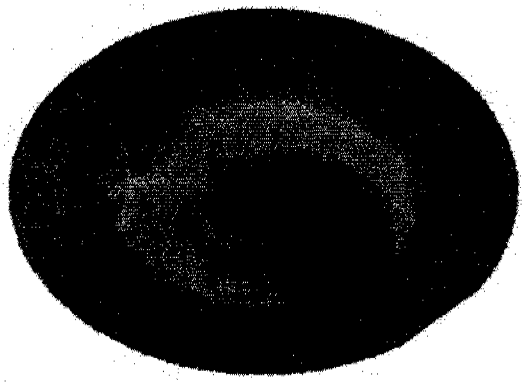

Fig. 10. Scanned image of enamel sample irradiated by Er:YAG laser(120 mJ).

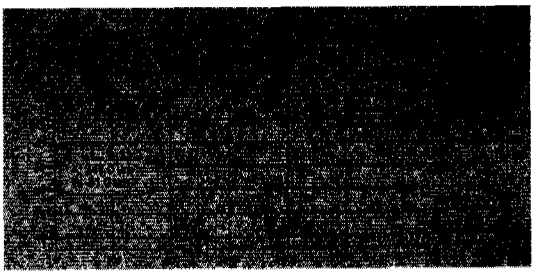

Fig. 11. Cross-sectioned appearance of lased hole in dentin in teeth of Figure 9.

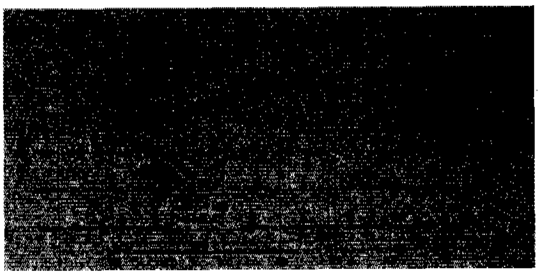

Fig. 12. Cross-sectioned appearance of lased hole in enamel in teeth of Figure 10.

Multiple comparison t-test were also given to identify statistically significant mean volume of ablation between energy levels. Table 2 shows the result of multiple comparison t-test for volume of ablation of dentin groups. There were significant differences between all energy level groups except between 160 mJ and 200mJ group. Table 3 shows the result of multiple comparison t-test for volume of ablation of enamel group. There were significant differences between all energy level groups except between 120 mJ, 160 mJ and 200 mJ group.

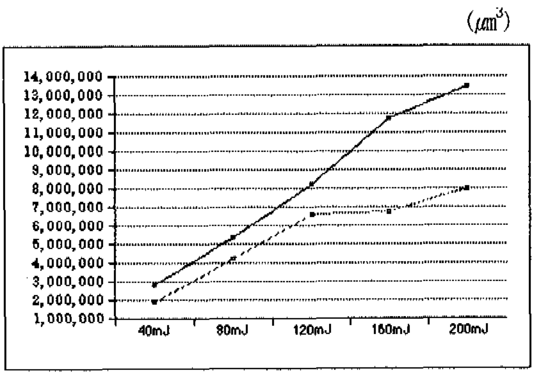

Fig. 13. Volume of ablation of dentin and enamel according to the energy levels.

Table 1. Means and standard deviations of ablationvolume of all groups and results of ANOVA test and paired t-test. (μm^3)

groups	energy levels					p-value (ANOVA)
	40mJ	80mJ	120mJ	160mJ	200mJ	
dentin	2839087.96 ±503608.27*	5396405.75 ±1863486.03	8236398.25 ± 594735.38	11749096.00 ±1140352.68	13431527.00 ±3148623.40	<0.0001
enamel	1916042.94 ± 821411.73	4220525.13 ±1356783.65	6642847.42 ± 651871.74	6744876.83 ± 558003.00	7996732.17 ± 427185.88	
p-value (paired)	0.2483	0.1430	0.0491	<0.0001	<0.0001	
(ANOVA)			<0.0001			

*=mean±standard deviation

Table 2. Result of multiple comparison t-test for ablationvolume of dentin groups.

groups	energy levels				
	40mJ	80mJ	120mJ	160mJ	200mJ
40mJ					
80mJ	**				
120mJ	**	**			
160mJ	**	**	**		
200mJ	**	**	**	-	

**=statistically significant(p<0.01)

Table 3. Result of multiple comparison t-test for ablationvolume of enamel groups.

groups	energy levels				
	40mJ	80mJ	120mJ	160mJ	200mJ
40mJ					
80mJ	**				
120mJ	**	**			
160mJ	**	**	-		
200mJ	**	**	-	-	

**=statistically significant(p<0.01)

IV. DISCUSSION

The Er:YAG (λ = 2.94 ㎛) laser emits in the midinfrared near the IR peak of the water absorption curve and the OH- absorption of hydroxyapatite. These lasers represent the best near-term hope for a laser that can effectively remove dental hard tissues. In brief, the radiation that these laser emits is strongly absorbed by water. The absorbed energy induces a rapid rise in temperature and pressure, and the heated material is explosively removed. Although the amount of water in dentin or enamel (20% and 10%, respectively) is relatively low, there appears to be enough absorption to initiate the ablation process. Further, there are some evidence that carbonated hydroxyapatite, the mineral of dentin and enamel, also absorbs strongly in the midinfrared[16-19] because of the OH- ions present in the structure.

The reults of this study indicate that a 2.94 ㎛ Er: YAG laser can effectively remove enamel and dentin surfaces. Ablation efficiency of enamel and dentin plotted vs. laser energy reflects a linear relationship contrary to a logarithmic relationship as demonstrated by Hibst and keller[5]. The differences between this and their study were as follow: (1) The spot diameter sizes were 300 ㎛ in this study and 580 ㎛ in their study. (2) The focal length were 9 mm and 63 mm respectively. (3) The laser was irradiated to a dried sample and to a wet sample respectively.(4) The ablation volume and the depth were measured respectively. (5) Single pulse and multiple pulses(6-15 pulses) were used respectively. Further studies should be performed to confirm which factor caused an effect on this difference.

Figures 11 and 12 show the cross-sectioned appearance of lased hole in enamel and dentin in teeth of Figures 9 and 10. The holes are conical in shape. These are similar appearances as shown in Keller and Hibst's study[5,9].

Li et al.[9] reported the depth of ablation in dentin and enamel using their Er:YAG laser device with 580 ㎛ focal spot size, and the ablation depth per pulse for dentin at a pulse repetition rates of 2 Hz after 9-20 pulses was 36 to 78 ㎛ per pulse using their laser fluences ranging from 10 to 140 J/cm^2. The ablation depth per pulse for enamel at the same repetition rate was 37 to 75 ㎛ per pulse using their laser fluences in the same range. Li et al[9]. calculated ablation thresholds for enamel and dentin. For enamel, the ablation thresholds were 7.2 J/cm^2 at 5 Hz and 18.6 J/cm^2 at 2 Hz. The ablation threshold for dentin was 0.7 J/cm^2 at 5 Hz and 1.2 J/cm^2 at 2 Hz. Dentin ablation is better both at 2 Hz and 5 Hz than enamel ablation at the same pulse repetition rate. This study shows similar findings regardless pulse repetition rate and Hisbst and Keller[5] reported similar results in their study.

The net result of this relatively high absorption is that the tissue is removed and little of the incident laser energy remains in the tissue to cause thermal damage. Hibst and Keller[5] measured the cutting rate for an Er:YAG laser. Using their 1.1-mm-diameter spot, a 50 J/cm^2 radiant exposure, and a 10 Hz pulse repetition rate, one would expect to be able to remove a 2.7 mm x 1 mm x 4 mm volume of enamel in 30 seconds. The ablation volume of enamel surface was 0.002 to 0.008 mm^3 being irradiated with 56 J/cm^2(40 mJ of output power) to 280 J/cm^2(200 mJ of output power) in this study. When irradiating at 10 Hz for 30 seconds with 200 mJ of output power, the Er:YAG laser used in this study would be expected to take 135 seconds to remove a 2.7 mm x 1 mm x 4 mm volume of enamel. Nontherless, it should not be thought the ablation rate of laser apparatus used in Hibst and Keller's study be higher than that of laser apparatus in this study, because the experimental conditions and parameters were not the same as each other.

And, the ablation depth, although not stated above, for dentin in this study was 35 to 149 ㎛ per pulse and for enamel was 25 to 79 ㎛. Comparing with the study of Li et al.[9], one would think there is lower efficacy of ablation in this study. But, their samples were irradiated multiple pulses and diameter of the focal spot was greater than the spot used in this study, therefore the ablation rates are to be compared with theirs.

From the results of this study, it can be shown that there were no significant differences between dentin and enamel groups at 40 mJ and 80 mJ, however there were significantly higher differences as energy level increased. And there were decreased elevation of ablation rates ,as energy level increased, from 160 mJ in dentin and from 120 mJ in enamel. Therefore we can consider "adequate energy level". The energy irradiated to the dental hard tissue may be changed into heat, destructive power, light, noise, etc. And we can consider all of irradiated energy did not change into destructive power, but some of it could change into heat generation. Therefore decreased elevation of ablation rates can be explained for this reason. But, why was the point of energy level that decreased elevation of ablation rates started in enamel(120 mJ) lower than that of dentin(160 mJ)? This answer is simple. As stated above, enamel is more highly cacificated than dentin and dentin contains more water than enamel, therefore heat generation of enamel started at lower energy level. Minimal heat generation is very important because of thermal damage, and we can consider adequate energy level is about 160 mJ in dentin and 120 mJ in enamel in this study.

V. CONCLUSION

Many investigators have reported ablation rates of Er:YAG laser, but they only measured ablation depth or mass or diameter. Measuring of volume of ablation have not been reported yet, especially with three-dimensional measuring devices. In this study, we could measure volume of ablation at single-pulsed irradiation in dried dentin and enamel with various energy levels using three-dimensional surface analyzer.

Results from this study were as follows:

1. There were statistically significant differences between dentin and enamel groups($p<0.0001$).
2. There were statistically significant differences between energy levels($p<0.0001$).
3. Comparing dentin and enamel groups in each energy levels, there were significant differences between both groups($p<0.05$) except 40 mJ and 80 mJ groups.
4. There were significant differences between all energy level groups($p<0.01$) except between 160 mJ and 200mJ group in dentin. And there were significant differences between all energy level groups($p<0.01$) except between 120 mJ, 160 mJ and 200 mJ group in enamel.

Results show there were useful effectiveness for ablating dental hard tissues with Er:YAG laser. More extensive researches are needed before the use of Er:YAG laser for dental hard tissue is accepted clincally.

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국문초록

상아질과 법랑질에 대한 Er:YAG 레이저의 일회 조사시 다양한 에너지 수준에 따른 삭제율에 관한 연구

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과거 수십년간 여러 가지 다른 레이저를 이용한 치아경조직에 대한 몇 가지의 생체외적 실험이 이루어졌다. 그러나 그 결과는 좋지 못하였다. 그러한 주 문제는 열작용이었다. 미국 식품의약국(FDA)에서 사용하도록 허가된 Er:YAG 레이저는 인간의 생체 치아를 삭제할 수 있는 최초의 레이저이다. 치아 삭제가 열작용의 원리에 의해 이루어지기는 하지만, 경조직의 미세폭발에 의하기 때문에 주변의 경조직과 연조직에 미치는 열작용은 거의 없다.

본 연구에서는 최근 국내에서 최초로 개발된 Er:YAG 레이저를 사용하여, 상아질과 법랑질에 일회 조사시 다양한 에너지 수준에 따른 삭제율을 연구하였다. 건조된 10개의 치아가 선택되었으며, 각각은 에폭시 레진에 포매되어 경화되었다. 그 후 다섯개의 치아는 저속회전 다이아몬드 휠로써 교합면 삭제를 통해 상아질이 노출되었으며, 나머지 다섯개의 치아는 협측 혹은 설측을 삭제하여 평평한 표면의 법랑질을 만들도록 하였다. 준비된 상아질과 법랑질 치아의 표면은 각각의 에너지 수준의 레이저를 조사할 6개의 구획으로 나누어 표본으로 삼았다. 상아질과 법랑질 표본은 에너지 수준에 따른 5개의 실험군(40 mJ, 80 mJ, 120 mJ, 160 mJ, 200 mJ)으로 나누어 그 삭제율을 분석하였다. 삭제된 부피는 삼차원 영상 표면분석기로 측정하였으며, 통계적으로 분석하였으며, 그 결과는 다음과 같다.

1. 상아질과 법랑질간의 삭제율의 차이는 통계적으로 유의한 차이가 있었다($p<0.0001$).
2. 에너지 수준에 따른 삭제율의 차이는 통계적으로 유의한 차이가 있었다($p<0.0001$).
3. 각각의 에너지 수준에서 상아질과 법랑질간의 삭제율의 차이는 통계적으로 유의한 차이가 있었으나($p<0.05$), 40 mJ과 80 mJ에서는 유의한 차이를 보이지 않았다.
4. 상아질에서 각각의 에너지 수준 간의 삭제율이 유의한 차이를 보였으나($p<0.01$), 160 mJ과 200 mJ 간에는 삭제율의 유의한 차이가 없었으며, 법랑질에서도 각각의 에너지 수준 간의 삭제율이 유의한 차이를 보였으나($p<0.01$), 120 mJ, 160 mJ, 200 mJ 간에 유의한 차이를 보이지 않았다.

본 연구에서는 건조된 치아에 다양한 에너지 수준의 Er:YAG 레이저를 적용했을 경우 상아질과 법랑질의 삭제 부피를 연구하여 정량화 및 통계적 분석을 하였다. 그 결과, Er:YAG 레이저는 치아경조직의 삭제에 매우 유용하였으며, 앞으로도 이를 임상적으로 널리 이용하기까지 좀더 다양하고 심화된 연구가 필요할 것으로 사료된다.