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Thermomechanical Effect on the Water Wet Dental Hard Tissue by the Q-switched Er : YAG Laser

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요 약 : Q-switch된 Er:YAG 레이저를 이용해서 치아표면에 뿜어준 외부의 물로 인해 유도된 열 및 역학적인 효과를 이해하는 것은 free-running Er:YAG 레이저에 의한 절삭효과를 이해하는데 대단히 중요하다. 이는 (파장 하나의 길이가 250 μs인) free-running 레이저에 의한 한 거대효과가 본 실험에서 이용한 (파장 하나의 길이가 1 μs인) Q-switch된 레이저에 의한 미소효과들의 축적이기 때문이다. 치아표면에 물이 있을 때 Q-Switch된 레이저에 의한 절삭률은 그렇치 않은 때에 비해 증가되었다. 치아표면에 물을 뿜어주는 횟수는 절삭률에 영향을 미쳐서 저에너지에서는 더디게 물을 뿜어줄때 높은 절삭률을 얻었다. 반동압력의 세기는 치아표면 조건에 의존하는데. 표면이 젖을수록 그리고 뿜어준 물의 양이 증가 할 수록, 반동압력의 세기 또한 증가하였다. 이 연구로부터 우리는 1-μs-길이의 pulsed 레이저에 의해 유도된 열 및 역학적인 효과가 외부에 물이 있을 때 free-running Er:YAG 레이저에 의한 절삭을 이해하는데 중요한 정보를 제공해 준다는 것을 알았다.

Abstract : Understanding the exogenous water induced thermomechanical effect on the dental hard tissue by the Q-switched Er:YAG laser (1-μs-long pulse width) has an important impact on the further understanding of the free-running Er:YAG laser (250-μs-long pulse width) ablation on the dental hard tissue because one macroscopic effect in the free-running laser is an accumulation of microscopic effects we investigated in this study. The Q-switched Er:YAG laser with exogenous water on the tooth enhanced ablation rate compared to the case of no water on the tooth. The frequency of exogenous-water jet on the tooth has affected the ablation rate in such a way that as we dispensed water drops less frequently we could get more enhanced ablation rate. The amplitude of the recoil pressure depends on the tooth surface conditions such that as surfaces wet, and as the volume of the exogenous water drop increased, the amplitude of the recoil pressure increased also. From this study we realized that the 1-μs-long pulsed laser induced thermomechanical effect provides us useful information for the understanding of the free-running Er:YAG laser induced ablation with exogenous water.

Key words : Q-switched Er:YAG laser (Q-스위치 된 Er:YAG 레이저), dental hard tissue (치아경조직), ablation rate (절삭률), recoil pressure (반동압력)

INTRODUCTION

Laser ablation of dental hard tissue has been the subject of researches ever since the ruby laser was studied for its possible dental applications. Stern and Sognnaes[1] showed that the ruby laser has the ability to ablate hard tissue. However, the laser caused severe, irreversible damage to the tooth. Since then, various mode of lasers[2-10] have been tested on dental hard tissue to determine the plausibility of the laser as a controllable dental handpiece.

For the laser to be useful for dental hard tissue removal, it should satisfy two criteria: (1) it should have a precise drilling capacity, and (2) it should cause less mechanical and thermal damage to surrounding tissue of the cavity than a mechanical dental handpiece. For this criteria, most researchers have been focused on exploring the ability of pulsed lasers to remove dental hard tissue in a safe and efficient manner. Currently available medical lasers usually generate optical radiation in the visible and near-IR ranges of the spectrum where hard tissues have very weak light absorption[11,12]. However recent research on the application of dyes in combination with pulsed lasers could solve the problem of poor laser absorption in the hard tissue, and significantly improves ablation in the near-IR region[13,14] because of their similar absorption band peak.

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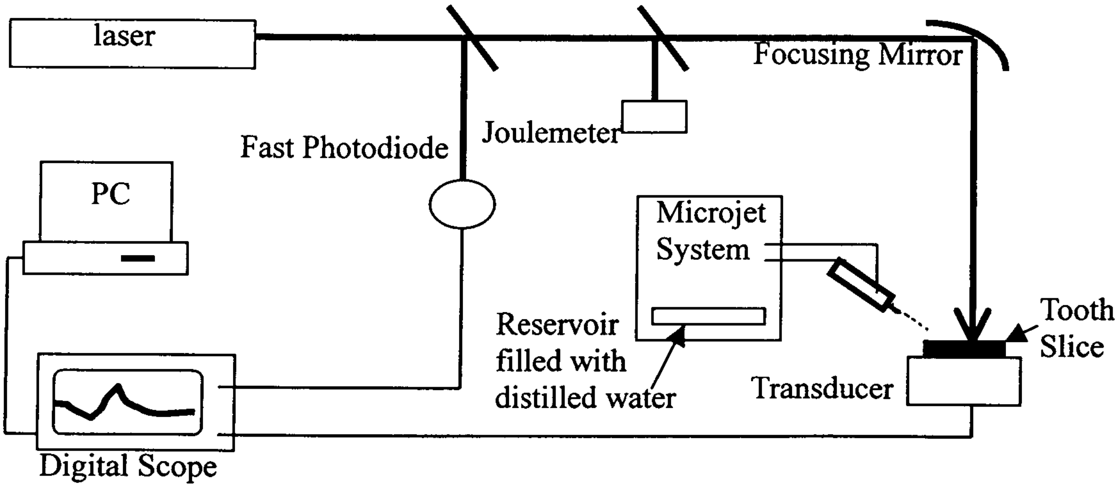

그림 1. 실험장치
Fig. 1. The experimental setup

Based on the researches to date, the Er:YAG laser shows the most promise for dental hard tissue treatment [15]. This is because water, which is a minor constituent of hard tissue, shows the highest absorption peak at the Er:YAG laser wavelength[16]. In the study to circumvent the scarcity of water content in the tooth, an exogenous water drop was put on the surface of the tooth. Actually water is already used in clinical dentistry to cool a tooth during laser treatment[17,18]. Adding an exogenous water drop on the tooth is similar to applying dyes on the tooth in order to promote the laser light absorption[19].

Understanding the Q-switched Er:YAG laser (1-μs-long pulse width) induced dental hard tissue ablation is important for understanding the thermomechanical effect which occurs in the free-running Er:YAG laser mode because one macro pulse (250-μs-long pulse width) of the Er:YAG laser is composed of about 25 1-μs-long micro pulses.

The objective of this work was to investigate the effects of exogenous water on dental hard tissue ablation in the Q-switched laser. Studies focused on (1) determining how much the ablation rate would be enhanced in terms of the frequency of water drop jet by adding a small and precise exogenous water drop on the surface of enamel, (2) measuring, using a calibrated transducer, the absolute amplitude of recoil pressure waves induced during the ablation of enamel.

MATERIALS AND METHODS

Experimental Design

A Q-switched Er:YAG laser (Schwartz Electro-Optics, wavelength = 2.94 μm) was used in the experiments. The pulse width was 1 μs, and it's repetition rate was 2 Hz. Each laser pulse profile was detected and recorded by an indium arsenide photodetector (J12-LD2-R250U) and a digital scope (Tektronix, TDS320), respectively. Incident laser pulse energies were measured with a joulemeter (Molectron, JD2000). Measured energies ranged from 20 mJ to 55 mJ. Focused laser spot diameters were 500 μm for the pressure study and 350 μm for the ablation rate study. Extracted healthy human molars were sectioned along the longitudinal direction approximately 1 mm thick using a slow-speed diamond saw. Small droplets of distilled water were dispensed using a Microjet system on the surface of the tooth to enhance laser light absorption. A Microjet (MicroFab Tech, Plano, TX) system is a piezoelectric ink-jet device which can precisely dispense pre-set amounts of water from 400 pl to 400 nl.

Methods

A calibrated broad-band (0.5-40 MHz, 25 ns temporal resolution) piezoelectric transducer (model PAT-01, Science Brothers Inc, Houston, TX) was employed to measure the transient temporal profile and the absolute values of laser-induced recoil pressure on the irradiated zone. Simultaneously detected transient temporal profiles of the pressure waves and Q-switched Er:YAG laser pulse were displayed and stored on the connected computer. The experimental setup for this study is illustrated in Fig. 1.

In the experiments, three different enamel surface conditions were employed: dry, water drop, and water layer. Volumes of the water drops were 20 nl and 400 nl. The thickness of the water layers were 300-400 μm. Generated pressure waves were propagated through the layers in two ways:

1. water drop or water layer → enamel (1 mm) → thin water layer between the sample and acoustic transducer (several micron) → aluminum conductor (3 mm thickness) → piezoelectric detector,
2. enamel → thin water layer between the sample and acoustic transducer (several micron) → aluminum conductor (3 mm thickness) → piezoelectric detector.

When medium absorbs the laser light, it is converted into the thermal energy. The thermal energy makes the medium boils explosively within a short time if the laser energy is high, and then it accompanies ablation in the direction of the incoming laser light. The ablated particles from the medium fly with a fnite velocity, and then by this way it generates momentum (or force). This force compresses the surface of the ablated area temporally and spatially, and then it spreads its neighbor region like a wave. From the basic physics, pressure can be defined as the division of force by unit affected area. Once pressure waves generate in the irradiated zone, they propagate along the laser beam axis in the sample in two directions (some of them into the sample, and the rest toward the sample surface). Transmittance of pressure waves through a boundary of different acoustic impedances with a condition of perpendicular propagation of waves to the surface of an interface can be expressed as

$$T = \frac{P_t}{P_i} = \frac{2\,Z_A}{Z_A + Z_B} \qquad (1)$$

where impedances ($Z=\rho * c=$ medium density*speed of sound in the medium), Z_A and Z_B are associated with Ahead of and Behind of propagating waves respectively. From the formula (1), we can see the increase of transmittance in accordance with the impedance mismatch at the boundary. If the impedance of Ahead is larger than that of Behind, transmittance of pressure waves will be enhanced; otherwise it will be minimized.

The generated pressure waves attenuate by the absorption and scattering as they propagate deeper into the medium. In the frequency range of interest (f~1 MHz) the acoustic attenuation in water and aluminum is insignificant because of the very low absorption coefficient of water and aluminum [20]. The acoustic attenuation coefficient measured in enamel and dentin are very limited in number and are not consistent with each other[21,22]. Within the limit of published data, ultrasonic attenuation in dentin at 1 MHz can be calculated by extrapolating given data and then by assuming data's linear dependence on the acoustic frequency. The ablation rate was studied for different surface conditions: dry and exogenous water drop jet frequencies. The number of laser pulses required to penetrate the sample was counted. The ablation rate can be calculated by dividing the sample thickness by the number of laser pulses needed to penetrate the sample. The frequency of the water drop jet was changed for different incident laser energies, but the volume of each water drop was maintained at 20 nl.

RESULTS

Ablation Rate Study

In order to study the effect of exogenous water on hard tissue ablation rate, we studied the effect of water drop jet frequency on different incident laser energies. Figures 2 and 3 show the relationship of the ablation rate in enamel to the frequency of the water drop jet. At lower laser energy (22 mJ), frequent release of water drops (one water drop jet per one laser pulse) did not enhance the ablation rate, but rather hindered it. It was because lots of incident laser energy was used to ablate exogenous water on the tooth surface so less remaining energy was available for the ablation of underlying tooth.

The ablation rate in the dry surface case was the worst and we couldn't see the penetration of the tooth at lower laser energies though there were sufficient laser pulses. However, as the laser energy was increased, a frequent jet of water drop enhanced the ablation rate. The ablation rate at the water drop jet frequency of 1/5 (one water drop release per five laser pulses) looked similar for two different laser energies. This similarity was accidental because the ablation rate is a relative value.

Recoil Pressure Waves Study

Transient pressure wave profiles with different surface

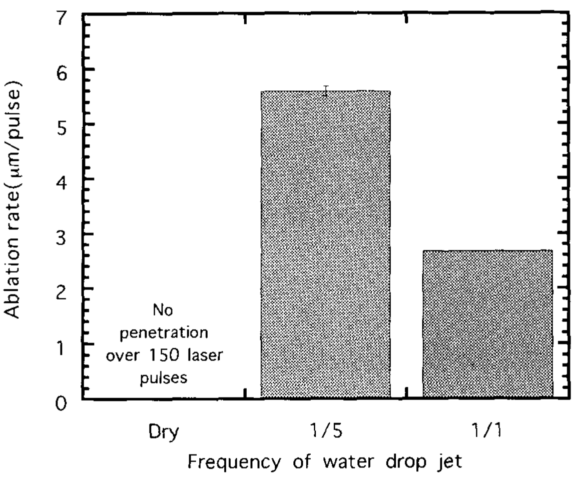

그림 2. 레이저 에너지가 22 mJ 일 때 법랑질에서의 절삭률 비교
Fig. 2. Comparison of ablation rate in enamel at energy, 22 mJ

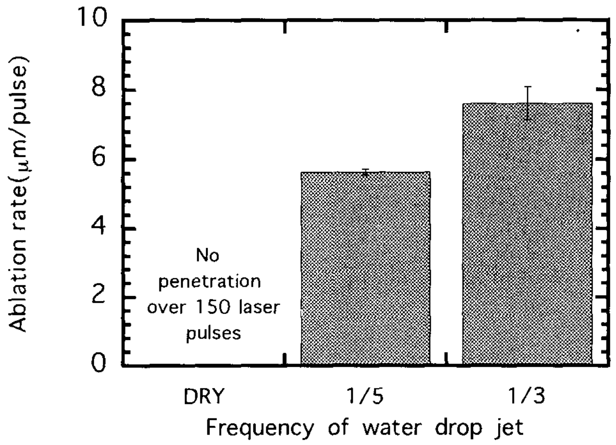

그림 3. 레이저 에너지가 52 mJ 일 때 법랑질에서의 절삭률 비교
Fig. 3. Comparison of ablation rate in enamel at energy, 52 mJ

conditions of dry, water drop, and water layer are presented in figures 4 and 5 for enamel. A monopolar nature of transient stress waves proves that the pressure profile we measured was produced by the ablation process. The first peak pressure waves on enamel with water drop and water layer were due to the ablation of exogenous water. The dip in the middle of the stress profile is due to the reflection of the initial compression wave from the air/water interface for the water-wet surface, or from the air/enamel interface for the dry surface. The time delay between the moment of laser irradiation and the propagated acoustic pulse detection was eliminated in the course of data processing in order to compare the amplitude of recoil pressures.

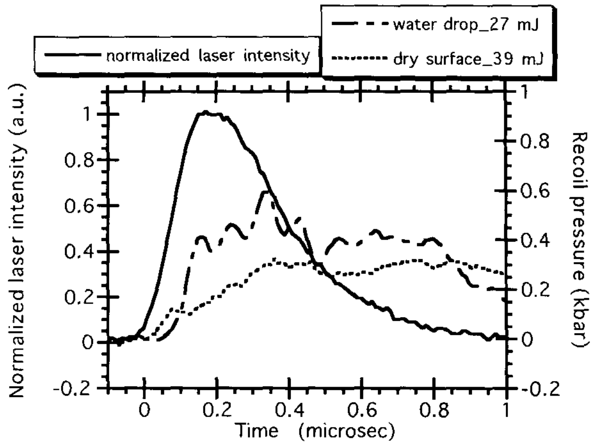

그림 4. 치아표면에 물방울이 있을 때 와 없을 때 법랑질에서 시간에 따라 변하는 압력의 세기
Fig. 4. The profiles of transient pressure generated upon ename ablation with dry and exogenous water drop on the surface

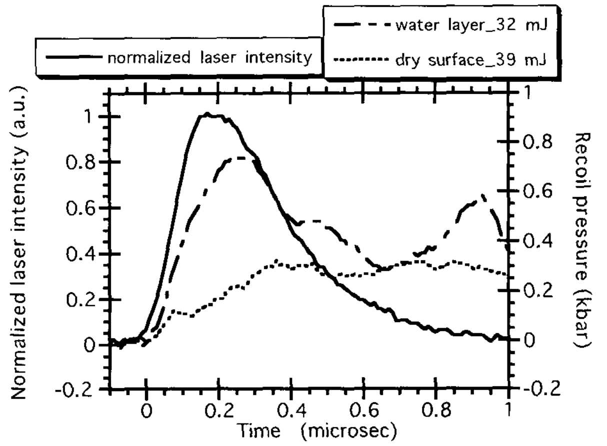

그림 5. 치아표면에 두께가 300-400 μm의 물의 층이 있을 때 와 없을 때 법랑질에서 시간에 따라 변하는 압력의 세기
Fig. 5. The profiles of transient pressure generated upon enamel ablation with dry and water layer on the surface. The thickness of water layer was about 300-400 μm

DISCUSSION

The temporal profiles of transient recoil pressure waves induced by the Q-switched laser ablation of enamel with and without exogenous water on the surface disclose important features of the effect of water on the ablation process. Monopolar nature in figures tells that the recoil pressure is induced by a strong ablation. Once stress waves generate from the laser irradiated zone, some of them transmit into the medium and the rest reflect from the interface. Similar to formula (1), we can define reflectance R as follows:

$$R = \frac{P_r}{P_i} = \frac{Z_A - Z_B}{Z_A + Z_B} \qquad (2)$$

In a rigid boundary, Z_A is the impedance of water (1.5×10^5 $g/cm^2\cdot s$), and in a free boundary, Z_A is the impedance of air ($40 g/cm^2\cdot s$). The estimated compressive pressure in dry surface enamel is in the lower limit of ultimate compressive strength of enamel which ranged between 950 bar to 4 kbar[23]. The estimated tensile strength in dry enamel is, given the same order of initial recoil pressure, higher than the ultimate tensile strength which ranged 300-350 bar[23]. Since the amplitude of stress waves in our experiment is always higher than the threshold for mechanical failure of enamel, ablation occurs every time.

The magnitude of the recoil pressure waves generated by the ablation depends on water for two reasons. The first reason is the form of water itself. Water drop or water layer on the tooth changes the surface condition from a free boundary to a rigid bundary. Transmittance of the generated initial pressure in a rigid boundary (water-enamel interface) is 1.85 times greater than that of a free boundary (air-enamel interface). Enhancement of the generated recoil pressure was accomplished just by changing the surface condition. The second reason involves the ablation of water. Recoil force always accompanies the ablation of material because of the conversion of momentum. The volume of explosively evaporating water is dependent on the volume of exogenous water on the enamel surface. In basic physics, the recoil pressure is defined as (recoil force/enforced area). Recoil force is the temporal integration of recoil momentum. Recoil momentum is the product of total mass lost in the medium and the average velocity of ejecting materials. From these physical relationships, it is clear that the total mass loss of water depends on the total volume of exogenous water such that the greater the volume of ablated water, the stronger the recoil pressure waves on enamel will be. However, increasing the volume of water on the enamel surface requires an increase of laser energy for water ablation, and will result in decreased remaining laser energy for enamel ablation.

The mechanical removal process of dry surface enamel is not different from that of exogenous-water-wet enamel, except for the stage of explosive vaporization of exogenous water on the enamel surface. Since enamel has no chance to be cooled by vaporizing exogenous water, the absorbed laser energy superheats water trapped within the matrix of hydroxyapatite and hydroxyapatite itself. The volume of the evaporating water is so limited due to the scarcity of water in enamel that the amplitude of recoil pressure waves is low compared to the case of exogenous-water-wet enamel, though it is still high enough to initiate ablation. The recoil pressure waves induced by surface ablation exert compressive force along the medium. In this case, the strength of the compressive recoil force is much weaker than it is in exogenous-water-wet enamel, making the depth of the mechanical impact shallow. Since there is apparent temperature gradient between the laser irradiated zone and its surrounding area, it generates a recoil pressure waves gradient between them. Unlike exogenous-water-wet enamel, dry surface enamel has no chance to be affected by pressure waves generated by ablating surface water. Compressive force and stress gradients between the laser irradiated area and surrounding area cause mechanical damage in the radial direction. Radially compressed enamel initiates circumferential stress in order to minimize damage. The combination of radial and circumferential stress generates flakes. Mechanical damages such as cracks and flakes were observed on the surface of dry enamel, though they were absent on the surface of exogenous-water-wet enamel.

CONCLUSION

The study of the exogenous water induced dental hard tissue ablation with the Q-switched Er:YAG laser is important for the further understanding of the one macroscopic effect which occurs in the hard tissue ablation by the free-running Er:YAG laser. The effect of water in the hard tissue ablation was studied for different enamel surface conditions: dry surface and surface with exogenous water. The Q-switched Er:YAG laser enhanced ablation rate as the frequency of exogenous water jet increased (from 1/5 to 1/3) and also as the laser energy increased (from 22 mJ to 52 mJ). The amplitude of the recoil pressure on the enamel was increased as the volume of exogenous water increased. In every case, the amplitude of recoil pressures with exogenous water was higher than the ultimate tensile strength of the enamel (300-350 bar). The observed thermomechanical effect on the free-running Er:YAG laser is an accumulation of the effects induced by many micropulses which have the same pulse width we have employed in this Q-switched Er:YAG laser study. For this reason though the Q-switched Er:YAG laser is not an efficient hard tissue drill, it is useful for the analysis of the free-running laser ablation mechanism. The results we found will be useful for the determination of the optimal and safe ablation conditions with exogenous water in the free-running Er:YAG laser.

REFERENCES

1. R.H. Stern and R.F. Sognnaes, "*Laser beam effect on dental hard tissues*", J. Dent. Res., Vol. 43(suppl), pp. 873, 1964
2. R. Hibst and U. Keller, "*Experimental studies of the application of the Er:YAG laser on dental hard substances: 1. Measurement of the ablation rate*", Lasers Surg. Med., Vol. 9, No. 4, pp.352-357, 1989
3. A.F. Paghdiwala, T.K. Vaidyanathan, and M.F. Paghdiwala, "*Evaluation of erbium:YAG laser radiation of hard dental tissues: Analysis of temperature changes, depth of cuts and structural effects*", Scanning Microscopy Vol. 7, No. 3, pp.989-997, 1993
4. J. Neev, L. Liaw, D.V. Raney, J.T. Fujishige, P.T. Ho, and M.W. Berns, "*Selectivity and efficiency in the ablation of hard dental tissue with ArF pulsed excimer lasers*", Lasers Surg. Med., Vol. 11, No. 6, pp.499-510, 1991
5. A. Stabholz, J. Kettering, J. Neev, and M. Torabinejad, "*Effects of the XeCl excimer laser on streptococus muttons*", Journal of Endodontics Vol. 19, No. 5, pp.232-235, 1993
6. R.M. Pick, "*Using lasers in clinical dental practice*", J.A.D.A., Vol. 124, No. 1, pp.37-47, 1993
7. J.D.B. Featherstone and D.G.A. Nelson, "*Laser effects on dental tissues*", Adv. Dent. Res., Vol. 1, No. 1, pp.21-26, 1987
8. H.J. Koort and M. Frentzen, "*Pulsed laser in dentistry-sense or nonsense?*", SPIE Proc. 1424, pp.87-98, 1991
9. H. Wigdor, E. Abt, S. Ashrafi and J.T. Walsh, "*The effect of lasers on dental hard tissues*", J.A.D.A., Vol. 124, No. 2, pp.65-70, 1993
10. G.C. Willenborg, "*Dental laser applications: Emerging to maturity*", Lasers Surg. Med., Vol. 9, No. 4, pp.309-313, 1989
11. V.A. Vickers, S.L. Jacques, J. Schwartz, M. Motamedi, S. Rastegar and J.W. Martin, "*Ablation of hard dental tissues with the Er:YAG laser*", SPIE Proc. 1646, pp. 46-55, 1992
12. H. Wigdor, "*Light interaction with dental hard tissues spectrophometry*", A.S.N.M.S. (abst), 5, pp.18, 1993
13. S.D. DeCoste, W. Farinelli, T. Flotte and R.R. Anderson, "*Dye-enhanced laser welding for skin closure*", Lasers Surg. Med., Vol. 12, No. 1, pp.25-32, 1992
14. M.C. Oz, J.P. Johnson, S. Parangi, R.S. Chuck, C.C. Marboe, L.S. Bass, R. Nowygrod and M.R. Treat, "*Tissue soldering by use of indocyanine green dye-enhanced fibrinogen wih the near infrared diode laser*", J. Vasc. Surg., Vol. 11, No. 5, pp.718-725, 1990
15. H.A. Wigdor, J.T. Walsh, J.D.B. Featherstone, S.R. Visuri, D. Fried and J.L. Waldvogel, "*Lasers in dentistry*", Lasers Surg. Med., Vol. 16, No. 2, pp.103-133, 1995
16. G.M. Hale and M.R. Querry, "*Optical constants of water in the 200 nm to 200 μm wavelength region*", Applied Optics, 12, pp.555-563, 1973
17. S.R. Visuri, J.T. Walsh and H.A. Wigdor, "*Erbium laser ablation of dental hard tissue: Effect of water cooling*", Lasers Surg. Med., Vol. 18, No. 3, pp.294-300, 1996
18. E.J. Burkes, J. Hoke, E. Gomes and M. Wolbarsht, "*Wet versus dry enamel ablation by Er:YAG laser*", J. Prosthet. Dent., Vol. 67, No. 6, pp.847-851, 1992
19. E. Jennett, M. Motamedi, S. Ragtegar, C. Frederickson, C. Arcoria and J.M. Powers, "*Dye-enhanced ablation of enamel by pulsed lasers*", J. Dent. Res., Vol. 73, No. 12, pp.1841-1847, 1994
20. G.W.C. Kaye, Tables of physical and chemical constants, 15th ed., New York: Longman, 1986
21. G. Kossoff and C.J. Sharpe, "*Examination of the contents of the pulp cavity in teeth*", Ultrasonics, 4, pp.77-83, 1966
22. K.M. Irion, W. Nussle, C. Lost and U. Faust, "*Determination of acoustical properties of enamel, dentin and alveolar bone*", Ultraschall in der Medizin, Vol. 7, No. 2, pp.87-93, 1986
23. M. Barden, "*Biophysics of the tooth*", Front. Oral. Physiol., Vol. 2, No. 1, pp.1-37, 1976