Laser Treatment of Hard Tissue Lesions

Koukichi Matsumoto

Professor and Chair, Department of Cariology and Endodontics, Showa University, School of Dentistry, Tokyo, Japan.

Summary: The present paper describes a number of laser treatments of hard tissue lesions, including caries diagnosis by Nd:YAG and semiconductor lasers; caries treatment, including caries prevention, by argon, Nd:YAG, CO2, Er:YAG, and Er,Cr:YAGG lasers; removal of dentin caries by ruby, CO2, Nd:YAG, Er:YAG, and Er,Cr:YAGG lasers; and cavity preparation by Er:YAG and Er,Cr:YAGG lasers, including dental pulp response to the cavity preparation, treatment time until the end of cavity preparation, morphology of cavity margin and wall after cavity preparation, and microleakage and surface roughness of cavities. In addition, the morphological characteristics of alveolar bone after ablation by CO2, Er:YAG, Er,Cr:YAGG, and ArF excimer lasers are described.

Key words: enamel, dentin, dental caries, alveolar bone, semiconductor laser, Nd:YAG laser, CO2 laser, Er:YAG laser, Er,Cr:YAGG laser, ArF excimer laser.


Einstein first reported his quantum theory of light in 1905. Based on this theory, Maiman developed the ruby laser in 1960. Since then, several types of laser devices have been developed and used in medicine and dentistry, as well as engineering and measurement sciences. The first application of laser in the mouth was the surgical treatment of tumors in the oral cavity, and various lasers – including semiconductor diode, carbon dioxide, helium-neon, neodymium:YAG, argon, erbium:YAG, and erbium, chromium:YSGG – have since been developed and applied in dentistry. In addition, excimer and free-electron lasers are currently being investigated. Dentists throughout the world have raised questions concerning not only the validity of laser therapy in dentistry, but also the methods used to perform laser treatment techniques.

The present paper describes the current and possible future clinical indications, laser devices, assessment methods, and mechanisms in the field of laser treatment of hard tissue lesions.

CARIES DIAGNOSIS

Nd:YAG Laser

A strong reaction to Chinese black ink without a long-term temperature rise on the tooth surface is one of the characteristics of the Nd:YAG laser. The very shallow enamel caries lesion on the fissure of a tooth may be diagnosed by removing debris on the tooth surface using this laser. At the same time, caries prevention can be expected.

Semiconductor Laser

Hibst and Gall have studied the fluorescence occurring in the near-infrared region using a 655-nm laser as the excitation source, with filters at 680 nm, and measured the fluorescent signal at higher wavelengths. In addition, a great deal of research has been conducted regarding fluorescence. This research culminated in the development of a commercial device.
The signal from the device is displayed as a number from 0 to 99 on the instrument. Higher numbers indicate a higher number of caries. Lussi et al.\(^6\) reported that numbers from 0 to 4 indicate either no caries or caries only in the outer half of the enamel, numbers from 5 to 12 indicate caries in the inner half of the enamel, and numbers greater than 12 indicate dentinal caries in the primary teeth. Unlike other visual or tactile examinations, this laser caries diagnosis system can be used to objectively diagnose the degree of dental caries and produces no pain during measurement.

**CARIES TREATMENT**

**Caries Prevention**

In the 1960s, it was reported that the acid resistance of dental enamel could be altered through treatment by argon or Nd:YAG laser irradiation. These studies were carried out using high energy densities.\(^7\)-\(^9\) In 1987, Nelson et al.\(^10\)-\(^14\) proposed that the appropriate lasers for caries prevention would be those that overlap with the major absorption bands of the tissue, and studied fundamental laser-tissue interactions, including transmission, absorption, scattering, reflection measurements, thermal effects, ablation, vaporization, and thermal modeling at certain wavelengths. The results of these studies\(^15\)-\(^21\) have led to progress in establishing laser prevention of caries in enamel and dentin.

Featherstone concluded that irradiation of dental enamel by specific wavelengths and fluences of CO\(_2\) laser light beneficially alters the chemical composition of the crystals, decomposing the carbonate component and markedly reducing the acid reactivity of the mineral.\(^11\) Efficient conversion of light to heat in the outermost few micrometers of enamel increases the resistance of the mineral to acid if a critical threshold temperature is reached. This surface alteration has a marked effect on the inhibition of subsurface caries progression. The initial hypothesis that specific wavelength irradiation is absorbed by the mineral and converted efficiently to heat at the surface, causing thermal alteration of the enamel crystal to a less soluble form, has been proven. However, there have been no reports confirming the clinical effectiveness of these treatments.

**Removal of Dentin Caries**

Caries removal has conventionally been performed using the mechanical cutting and drilling systems. However, these methods have some major disadvantages. First of all, mechanical preparation often induces pain, and thus local anesthesia is needed. Since it was demonstrated that in vitro caries removal was possible using the ruby laser, numerous researchers have investigated the effects of other lasers, including argon, CO\(_2\), and Nd:YAG lasers, on carious dental hard tissues. However, the irradiation produced by these lasers had major thermal side-effects, such as melting, cracking of enamel or dentin, and an increase in the pulpal temperature, because these lasers require a relatively high energy density to vaporize the hard tissues. Recently, effective ablation of dental hard tissues using the Er:YAG laser has been reported, and the application of this laser in caries removal and cavity preparation is expected.

The in vitro effectiveness of caries removal in teeth via Er:YAG laser irradiation was compared with that of the chemomechanical caries removal system and conventional mechanical treatment. Caries removal via Er,Cr:YSGG laser irradiation was found to require significantly more time than removal using the bur, but less time than removal by Carisolv.\(^22\) The average required treatment times for bur, Carisolv, and laser treatment were 18 ± 3 s, 32 ± 5 s, and 26 ± 2 s (mean ± SD), respectively. The laser irradiation time was significantly longer than the bur treatment time but was
shorter than the Carisolv treatment time (p < 0.001). The working time required for the inspection of residual caries, which was not included in this measurement, was also longer after laser irradiation, because evaluation of the completeness of caries removal was more difficult. SEM revealed that, in contrast to mechanical bur or Carisolv treatment, the lased cavity surface displayed various patterns of micro-irregularity, and the smear layer was absent. The orifices of the dentinal tubules were exposed over most of the cavity surface (Figs 2 to 6). In addition, laser removal of carious dentin in primary teeth was investigated; under adequate water spray, cavities having no sign of thermal damage to the surrounding tissues or dental pulp could be produced. Therefore, cavity preparations using this less traumatic removal system may be favorable, especially in pediatric dentistry.23
Cavity Preparation

Cavity preparation by Er:YAG laser was first reported by Keller et al in 1988.24 This laser was later developed further in Japan, the United States, and Germany, and has been used not only on dental hard tissues but also on soft tissues. As a second Er:YAG laser, the Er,Cr:YSGG laser has been approved for similar hard tissue applications. Recently, a high-power Er:YAG laser was developed by DEKA (Italy). Using the Er:YAG laser, even Class I and II cavities can be prepared within minutes. In the near future, cavity preparation for inlays will also be possible using this laser.

Dental pulp response to cavity preparation

No problems have been reported with respect to the pulpal response after cavity preparation with the Er:YAG laser,25 if the cavity preparation is carried out under sufficient water supply. In addition, the pulpal response to the Er:YAG laser after accidental exposure of the pulp during the cavity preparation demonstrated good healing capacity with the formation of a dentin bridge and reparative dentin (Figs 7 and 8).26

Heat shock protein (Hsp) 25, a low-molecular-weight Hsp, is expected to be found in various normal cells and under stressful conditions,27-29 although it was first discovered under stressful conditions. This protein has been reported to possess diverse functions.
In addition to the above-mentioned conditions, the transient expression of Hsp 25 has been reported in various cells during development and cell differentiation. Odontoblasts have also been found to have a stage-specific expression pattern of Hsp 25 immunoreactivity in intact teeth and under experimental conditions, suggesting that this is a useful marker for the differentiation of odontoblasts during the pulpal healing process.

**Pain during cavity preparation**

In clinical studies, an Er:YAG laser emitting at a wavelength of 2.94 µm developed by Luxar was used for the clinical preparation of Class V cavities. Irradiation was performed at 8 Hz and a maximum output of approximately 250 mJ/pulse. Sixty teeth of 40 patients were used in these clinical studies. The Er:YAG laser used in these studies was found to be suitable for clinical application. No adverse reaction was observed in any of the patients. Class V cavity preparation was performed without inducing pain in 48 of 60 (80%) patients. All of the 12 cases that complained of mild or severe intraoperative pain had complained of cervical dentin hypersensitivity during the preoperative examination. Cavity preparation was completed using this laser system in 58 of 60 cases (91.7%). Keller et al reported that the need for local anesthesia was 11% for mechanical preparation compared to 6% during laser application, and that 82% of the patients reported that they would prefer Er:YAG laser preparation for future caries treatment. Cavity preparation using the Er,Cr:YAG laser was performed without inducing pain in 34 (68%) patients, whereas slight pain was reported by 11 (22%) patients, tolerable pain was reported by 2 (4%) patients, and intolerable pain was reported by 3 (6%) patients. Moreover, in their study, 42 out of 50 patients (84%) felt no discomfort, and 8 (16%) patients reported the machine noise to be slightly uncomfortable.

**Treatment time until the end of cavity preparation**

In a clinical study on the preparation of Class V cavities, cavity preparation took between approximately 10 s and 3 min, and was related more or less to cavity size and depth. Keller et al reported that the mean time for preparation by laser was 7.5 ± 4.6 min (15 s to 30 min) compared to 4.3 ± 3.9 min for the mechanical preparation. In the cases of Er,Cr:YAGG laser, the time required for cavity preparation was found to be related to the cavity size, as follows: Class I, 10 to 15 min; Class II, 13 to 20 min; Class III, 1 to 3 min; Class IV, 2 to 5 min; and Class V, 30 s to 3 min. Recently, the high-speed cutting Er:YAG laser was developed by DEKA (Fig 9). According to basic and clinical investigations, it was possible to cut enamel in approximately 3 s and perforation into the dental pulp was performed in approximately 5 s at 7 W and 15 Hz. Class I and II cavities can be prepared within several minutes (Figs 10 to 13), and patients do not feel pain even if the cavity is very deep. In some cases, patients do not feel pain until the dental pulp is exposed. A clinical assessment of this laser technique will be published in the near future.

**Morphology of cavity margin and wall after cavity preparation**

Er:YAG laser irradiation produced different morphological features after cavity preparation. Upon visual inspection, the shade or color on surfaces treated with the Er:YAG laser indicated a white, undulating surface. In some cases, the cavity margin and wall showed a smooth, clear prepared surface, but in some cases, an uneven, rough cavity margin and surface was observed by light microscopy and SEM (Fig 14). Gentle undulation with relatively clean dentinal tubule orifices and some debris were observed by SEM (Figs 15 to 17). TEM observation of the cross section of lased dentin presented three zones. The uppermost surface, characterized as the zone of complete ablation, revealed irregular microparticles of 0.5 µm in diameter. Underneath this structure, an ablation zone of mineral components and an unaffected zone, in which intertubular dentin appeared intact, were observed (Fig 18). Atomic analysis revealed that the quantities of Ca (Ca wt%) and P (P wt%) were significantly greater (p < 0.001) in the irradiated area compared to the nonirradiated area. However, there was no significant difference between the Ca:P ratio of the irradiated area and that of the nonirradiated area. A technique for preparing smooth, even cavity walls and margins must be developed.

The morphological and atomic analytical changes in enamel and dentin after Er,Cr:YSGG laser irradiation were examined by stereoscopy, FE-SEM, and SEM-EDX. Regular holes having sharp edges and smooth walls, but no melting or carbonization, were observed in both samples. Atomic analytical examination showed that the ratio of calcium to phosphorus did not change...
significantly between the lased and unlased areas (p > 0.01).

Although CO₂ laser irradiation at wavelengths of 9.3 µm and 9.6 µm produced no craters or cracks, several small molten and rehardened particles, as well as slight carbonization and discoloration were observed on the samples using LM (Fig 19) and SEM (Figs 20 to 22). The cavity floor and wall showed a relatively even, clear surface (Figs 18 to 21).

In an in vitro study, the ArF excimer laser beam was observed to produce defects with clean-cut margins, floors, and walls in human extracted teeth (Figs 23 to 25). No carbonization or cracks were observed by stereoscope. SEM observation of the cavity ablated using the ArF excimer laser showed very interesting morphological characteristics. In particular, the junction between the enamel and dentin, and detailed examination of the surface of the exposed enamel indicates that this laser can be used to examine the inner structure of materials.
Fig 14  Cavities prepared with Er:YAG laser, showing uneven, rough margins.

Fig 15  Representative scanning electron microscopic image of the surface of human enamel lased by Er:YAG laser at 3 W and 10 Hz for 10 s. This image shows the scale-like surface that is characteristic of enamel ablation by the Er:YAG laser.

Fig 16  Representative scanning electron image of human dentin prepared using a turbine. The dentinal tubules cannot be observed because the dentin surface is covered with smear layer.

Fig 17  Representative scanning electron microscopic image of the surface of human dentin lased using an Er:YAG laser at 3 W and 10 Hz for 20 s. This image shows the open dentinal tubules which were exposed by Er:YAG laser irradiation.

Fig 18  Transmission electron microscopic image of the cross section of dentin after Er:YAG laser irradiation with water mist. On the outermost cutting surface, the collagen matrix, which is a hydroxyapatite component, is exposed.

Fig 19  Light microscopic image of enamel and dentin ablated using a 9.6-µm CO₂ laser at 4 W and 10 pps, with a pulse duration of 100 µs, a focus distance of 70 mm, a spot size of 1.5 mm, a pulse energy of 200 mJ/pulse, and water mist of 10 ml/min for several minutes. Although no carbonization is present on the enamel, slight carbonization can be seen on the dentin.
Microleakage and surface roughness of cavities prepared by lasers

Khan et al.\textsuperscript{39,40} investigated microleakage in cavity margins after filling restorative materials in Class I cavities prepared using an Er:YAG laser or an air turbine. Dye penetration studies and in vitro scanning electron microscopy revealed no significant difference in microleakage for cavities prepared using either method. SEM revealed good adaptation in the laser-prepared cavities restored by composite resin or glass-ionomer cement. In addition, the surface roughness and a microleakage test for cavities prepared by Er:YAG laser irradiation and etched bur cavities have also been conducted. Morphologically, the prepared cavities showed an irregular surface with the absence of a debris-like smear layer; enamel prisms and the openings of dentinal tubules were recognizable. Surface roughness was significantly increased using the laser system. A microleakage test revealed no significant differences between the laser- and bur-prepared cavities. Crosscut sections of the cavities with no microleakage showed no gap at the interface (Fig 26). Laser cavities may facilitate good adaptation of composite resin to enamel and dentin,

*Fig 20* Representative scanning electron microscopic image of the surface of human enamel lased using a 9.6-µm CO\textsubscript{2} laser at 4 W and 10 pps for 3 min. This image shows the relatively smooth up-and-down defects after ablation.

*Fig 21* Higher magnification of Fig 20. The lased surface shows a molten lava-like surface formed by the melting and recrystallization due to 9.6-µm CO\textsubscript{2} laser irradiation.

*Fig 22* Dentin surface irradiated by 9.6-µm CO\textsubscript{2} laser at 4 W and 10 pps for 5 min. The dentin surface appears to have been torn away, exposing the dentinal tubules. However, in some areas, melted and recrystallized dentin can be observed.

*Fig 23* Scanning electron microscopic image of human enamel and dentin surfaces lased using a 193-nm excimer laser at 1.2 J/cm\textsuperscript{2} and 10 Hz for 5 min. This image shows a very smooth and clean margin and cavity floor and wall after ablation.
because an increase in the surface roughness and the openings of dentinal tubules may promote the formation of a hybrid zone. Primer and an adhesive can penetrate the surface better when the smear layer is removed. Shallow cavities prepared by Er:YAG laser have decreased microleakage for composite resin restorations, and the preparation efficiency is similar to that of etched bur cavities. Microleakage of composite resin restorations in cavities prepared by Er,Cr:YSGG laser irradiation and etched bur cavities in primary teeth has been reported in an in vivo study. The surface alterations of enamel and dentin in cavities prepared by Er,Cr:YAGG laser irradiation were investigated by SEM and were compared to the degree of microleakage after composite restoration for etched bur cavities in human primary teeth. The results confirmed that the laser cavity surface facilitated good adhesion with the restorative materials. The acid etch step can be avoided for the laser treatment.

Removal of alveolar bone by laser

Alveolar bone ablation by laser is also important in the field of dentistry. Since the initial application of the ruby laser on dental hard tissue in 1960s, studies have continued to examine bone ablation and cutting using different lasers, including the argon, CO2, Nd:YAG, Er:YAG, Er,Cr:YSGG, and ArF:Excimer lasers.

Lasers of infrared wavelengths have been demonstrated to be strongly absorbed by water and hydroxyapatite so that these lasers are capable of ablating bone tissue efficiently. A number of investigations have

Fig 24 Scanning electron microscopic images show the fine enamel and dentin structure ablated using an ArF excimer laser. No debris, open dentinal tubules or clear enamel rods can be seen.

Fig 25 A magnified scanning electron microscopic image of human enamel rods lased using a 193-nm excimer laser at 1.2 J/cm² and 10 Hz for 5 min. This picture shows very clear enamel rods arranged regularly, and the stripes on the enamel rods can be seen.

Fig 26 Cross sectional image of filled Er:YAG laser cavities after a microleakage test. Top: Stereoscopic observation revealed good adaptation between the enamel (E), dentin (D) and resin cement (R), and no microleakage was detected. Bottom: Scanning electron microscopic observation revealed that the resin-dentin interface was also intact (100X, bar = 20 µm).
demonstrated the use of CO₂ lasers to produce experimental osteotomies in animals. However, these studies have also confirmed a significant delay in the healing of laser osteotomies compared to those performed via conventional mechanical methods. Thermal necrosis, or carbonization, generated by the laser adjacent to the irradiated area is thought to be responsible for the delay, and foreign body reactions to charred material could complicate the healing process. Recently, Er:YAG laser and Er,Cr:YSGG laser devices that emit laser beams at wavelengths of 2940 nm and 2780 nm, respectively, have been made available. These infrared lasers were proven to ablate dental hard tissues effectively. These lasers offer the advantages of straight, clean, and precise cutting by laser energy interaction with water at the tissue interface. Furthermore, damage around the ablation area is minimal in laser stapes surgery. However, there have been few reports investigating the histological and morphological changes of mandibular bone irradiated by either Er:YAG (Figs 27 to 29) or Er,Cr:YSGG lasers (Figs 30 to 35). Excimer lasers have been confirmed to cause less thermal damage than other lasers in cardiac surgery and ophthalmology. This is attributed to the photodecomposition
Fig 31  Hole produced in mandibular bone by an Er,Cr:YSGG laser (4X). No carbonization areas are present around the hole.

Fig 32  Histological microscopy revealed thermal damage of bone tissue after Er,Cr:YAGG laser irradiation. A transparent necrotic layer having an irregular margin was observed (T). A tinted cluster of cells was noticed in the layer (arrow). Neither carbonization nor degeneration zones were observed. Osteocytes in the adjacent thermally damaged zone were less than 10 µm in diameter.

Fig 33  Beneath the carbonization (arrows) and transparent necrotic zone (T), an additional lightly stained necrotic layer was observed (L), which was clearly distinguishable from normal adjacent tissue. The thickness of the thermally damaged zone was >100 µm.

Fig 34  Scanning microscopic image revealing thermal damage to the lased matrix. The carbonization of the bone matrix is visible (arrow). The intact prism structure was broken (500X).

Fig 35  Melting and recrystallized bone matrix (3500X).

Fig 36  Histological results for the mandibular bone irradiated for 90 s by an ArF excimer laser. A defect showed a sawtooth structure without carbonization or necrotic zone. Some vacuolar degeneration of osteocytes adjacent to the defect were observed (arrows). However, other osteocytes in the surrounding bone tissues were morphologically intact (100X).
of the irradiated tissue. Among excimer lasers, the ArF excimer laser allows tissue ablation with the least amount of thermal damage to the bone and dental hard tissue. In a previous in vivo study, we reported the morphological changes of the rat mandible and measured the rise in temperature at the lased area. The results showed that the ArF excimer laser permitted bone tissue ablation with a minimum increase in temperature. The relationship between ablation depth and irradiation time was approximately linear. Macroscopically, the ArF excimer laser beam produces a defect with clean-cut margins and with no carbonization in the mandibular bone. Histologically, minimal evidence of thermal damage to the surrounding tissue was observed. The bottom of the defect revealed a sawtooth appearance (Fig 36). In SEM observation, mosaic structures corresponded to the sawtooth structures observed via light microscopy (Fig 37). These findings suggest that it is possible to remove bone tissue by ArF excimer laser irradiation without thermal damage. The effectiveness of this laser can be attributed to the photoablation of the bone tissue.

REFERENCES

STATE OF THE ART


Contact address: Professor Koukichi Matsumoto, Chairman, Department of Endodontics, Showa University School of Dentistry, 2-1-1 Kitasenzoku, Ohta-ku, Tokyo 145-8515, Japan. Tel/Fax: 81-3-5702-1484. e-mail: koukichi@senzoku.showa-u.ac.jp