Atomic analysis and knoop hardness measurement of the cavity floor prepared by Er, Cr:YSGG laser irradiation in vitro

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SUMMARY In the present study, the compositional changes and knoop hardness of the cavity floor prepared by Er, Cr:YSGG laser irradiation was compared with that of the conventional bur cavity. Fifteen laser and 15 bur cavities were cross-sectioned, and subjected to atomic analysis by SEM-EDX and knoop hardness test. Statistical analyses were performed using the Mann-Whitney U-test; a value of P < 0.01 was considered significant. Surface characteristics of the prepared cavities were also investigated by light microscopy and scanning electron microscopy (SEM). The results showed that the quantities of Ca (Ca weight %) and P (P weight %) were increased significantly in the laser cavity floor but no significant differences were found between the Ca/P ratio and knoop hardness number of laser and bur cavities. The SEM observation revealed that the lased cavity surface was irregular and there was also the absence of a smear layer; the orifice of dentinal tubules was exposed. Er, Cr:YSGG laser device is considered as one of the most effective and safe devices for cavity preparation because of its many advantages. This includes easy delivery system, minimal thermal damage to the surrounding tissues, minimal thermal-induced changes of dental hard tissue compositions, and favourable surface characteristic.

KEYWORDS: Er,Cr:YSGG laser, cavity preparation, temperature increase, atomic analysis, knoop hardness, smear layer

Introduction

Since the development of the ruby laser by Maiman in 1960, several types of laser such as CO₂ and Nd:YAG lasers have been introduced in the dental clinic to remove carious dental hard tissues or cavity preparations in anticipation of replacing the high speed dental drill. However, these laser irradiations require relatively high-energy densities to vapourize the hard tissues, and they produce major thermal side-effects, such as melting, carbonization, the creation of fissures, cracks in the surrounding tissues and an increase in the pulpal temperature (Frentzen & Koort, 1990; Wigdor et al., 1993; Wigdor et al., 1995; Israel et al., 1997). Therefore, in order to find out a method to remove carious dental hard tissues or cavity preparations without any thermal side-effect, the potential applications of the Er:YAG and Er,Cr:YSGG lasers have been introduced and their application in the dental clinic have been expected. These lasers can ablate enamel and dentine more effectively due to their highly efficient absorption in both water and hydroxyapatite (Wigdor et al., 1995). The ability of Er:YAG laser to remove enamel and dentine was found comparable with that achieved with the conventional dental drill (Hibst & Keller, 1989; Keller & Hibst, 1989a) and produces minimal thermal damage to the pulp or surrounding tissues, especially when irradiated with continuous water spray (Burkes et al., 1992; Visuri, Walsh & Wigdor, 1996a; Hossain et al., 1999a). Animal histological studies showed that pulp response to the Er:YAG laser appears to be similar to...
the response from high-speed hand piece application (Sekine, 1995; Sonntag et al., 1996). On the other hand, the Er, Cr: YSGG laser, which uses a pulsed-beam system, fibre delivery, and a sapphire tip bathed in a mixture of air and water vapour, has been shown to be effective for soft-tissue surgery as well as for cutting enamel, dentine and bone (Eversole & Rizoiu, 1995; Hossain et al., 1999b). When dental hard tissues were irradiated by the Er, Cr: YSGG laser accompanied with a water spray, not only could the temperature be suppressed, but cutting efficiency could also be increased (Eversole & Rizoiu, 1995; Hossain et al., 1999b). Histological studies showed that no pulpal inflammatory responses could be identified in Er, Cr: YSGG laser irradiated with a water spray (Eversole, Rizoiu & Kimmel, 1997; Rizoiu et al., 1998). Surface alterations of the enamel and dentine after Er, Cr: YSGG laser irradiation shows that these surfaces are associated with microirregularities and there was also the absence of a smear layer (Hossain et al., 1999b). From the above results, it can be considered that Er, Cr: YSGG laser irradiation is favourable in the removal of carious dentine or cavity preparation because it does not damage the dental pulp or surrounding tissues. However, before application of this laser in the dental clinic, several other considerations need to be evaluated, especially as there are still no reports on the compositional changes and microhardness of the cavity floor prepared by Er, Cr: YSGG laser irradiation.

Therefore, this present study was performed to compare the compositional changes and knoop hardness of the cavity floor prepared by Er, Cr: YSGG laser irradiation with that of the conventional bur cavity. Surface characteristics of the prepared cavities were also investigated by light microscopy (LM) and scanning electron microscopy (SEM).

Materials and methods

Cavity preparation

A total of 15 extracted human premolar and molar teeth with no carious lesions were used for this study. On the buccal and lingual (palatal) surfaces of each tooth, two shallow cavities (diameter 3 mm, depth 2 mm) were prepared: one with the laser system and one with a high-speed turbine. From these teeth, 15 lasers and 15 bur cavities were produced.

Laser cavities were prepared by using an Er, Cr: YSGG laser system (Millennium™) emitting photons at a wavelength of 2.78 µm, pulsed with a duration between 140 and 200 µm, and a pulse repetition rate of 20 pulses s⁻¹ (20 Hz). The output power could be varied from 0 to 6 W. The beam spot size was 0.442 mm² with the use of a 750-µm diameter fibre at the distance of 2–3 mm. Irradiation was performed according to the manufacturer’s instructions; at the beginning of cavity preparation, we carefully performed laser irradiation in a contact mode to remove enamel with a focused beam of 6 W (67.9 J cm⁻²) at maximum air pressure level and 32% water level. As enamel removal progressed and the treated cavity floor became deeper and closer to the underlying dentine layer, we reduced the power to 3 W (33.9 J cm⁻²) at 70% air level and 20% water level, and cavities were carefully finished by means of the non-contact irradiation mode.

The mechanical cavities were prepared by using a high-speed turbine (Astron Mini®) with a #3411 diamond bur⁴. The following investigations were performed during and after cavity preparation.

Assessment during cavity preparation

The time required for cavity preparation was determined for each treatment and the differences in the times required were statistically analysed by using Mann-Whitney U-test; a value of \( P < 0.01 \) was considered significant. Furthermore, thermal change was measured at the time of each treatment using a thermovision device of 870 system⁵ linked to a personal computer (PC-AT).

Atomic analysis and knoop hardness measurement of the cavity floor

Ten laser and 10 bur cavities were cross-sectioned perpendicularly to the tooth axis through the middle of the treated cavity; one half was used for atomic analysis by SEM-EDX and the other half was used for knoop hardness test.

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⁵U. Morita, Tokyo, Japan.
⁶Shofu, Inc., Kyoto, Japan.
⁷AGEMA Infrared Systems AB, Danderyd, Sweden.

For atomic analysis by SEM-EDX, cut sections were fixed with a 10% formalin solution for 48 h, and then immediately perfused with a phosphate-buffered solution of pH 7.3 at room temperature and rinsed with distilled water. The samples were dehydrated through a graded ethanol series (70, 80, 90, 95 and 100%) for 24 h at each concentration and then embedded in a polyester resin block. After the irradiated areas were flattened as much as possible by polishing, they were sputter-coated using a carbon-coating device (HUS-5GB**) and were examined by SEM-EDX (S-2500Cx** and Model Delta VI ttl at 10 kV accelerating voltage, tilt angle at 35° and 3000 magnification.

For knoop hardness measurement of the cavity floor, cavity sections were embedded in epoxy resin, and the cross-sectional surfaces were polished. As obtaining a knoop hardness measurement of the cavity surface was impossible, recordings were obtained below the cavity floor: the hardness of the subsurface at the point 25 μm below the cavity floor was used as that of the cavity floor. The knoop hardness number (KHN) was measured in each treated cavity by the application of a 50-g load for 15 s by means of a hardness tester. The mean of the measurements was used as the KHN of cavity floor dentine and statistically significant differences between the KHN of laser and bur groups were determined by Mann–Whitney U-test.

Surface analysis of the prepared cavities

Cross sections of the remaining five laser and five bur cavities were examined by LM and then followed by the SEM. None of the laser cavities was acid-etched. One half of the bur cavities were acid-etched with a 30% phosphoric acid gel (Cleaml etching agent**) for 30 s, washed with water spray for another 30 s, and dried with air for 20 s and the other half was not acid-etched. Specimens were dehydrated in a grade series of aqueous ethanol (70, 80, 90 and 100% ethanol) for 24 h in each solution, dried by liquid CO₂ using a critical point dryer device (JCPD-3§§), coated with platinum layer and observed by SEM (JSM-T220A§§) at 20 kV.

Results

Assessment of cavity preparation

The mean required time of laser and bur treatment was 95.5 ± 2.21 and 15.32 ± 2.35 s (mean ± s.d.), respectively (Table I). The laser irradiation time was longer than the bur treatment, which was statistically significant (P < 0.01). Furthermore, the mean temperature rise during cavity preparation with the laser and bur treatment was 2.10 ± 1.20 and 1.90 ± 1.35, respectively (Table I).

Atomic analysis and knoop hardness measurement of the cavity floor

The results of atomic analysis showed that the quantities of Ca (Ca weight %) and P (P weight %) were increased significantly in the laser cavity floor compared with the bur treatment. (Table 1) (P < 0.01). However, no significant differences were found between the Ca/P ratio of laser and bur cavities. Furthermore, there were no significant differences of the KHN of laser cavity floor with that of the bur cavity (Table 1).

Surface analysis of the prepared cavities

Light microscopic observation of cross sections of the laser cavity revealed a rough or irregular surface with the absence of any charring, carbonization, or cracking of the enamel and dentine (Fig. 1A). The SEM observation showed a scaly appearance or irregular surface due to microirregularities after laser irradiation (Fig. 1B). In addition, there was an absence of a smear layer; the orifice of dentinal tubules was exposed. The intertubular dentine had more ablation than the peritubular dentine, showing a protrusion of the tubules.

Table 1. Summary of the results found in this study (mean ± s.d.)

<table>
<thead>
<tr>
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<th>Laser cavity</th>
<th>Bur cavity</th>
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<tr>
<td>Time required (s)</td>
<td>95.5 ± 2.21*</td>
<td>15.32 ± 2.35*</td>
<td></td>
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<tr>
<td>Thermal change (°C)</td>
<td>2.10 ± 1.20</td>
<td>1.90 ± 1.35</td>
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<tr>
<td>Knoop hardness (km cm⁻²)</td>
<td>55.30 ± 3.26</td>
<td>53.50 ± 3.65</td>
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<tr>
<td>Ca (weight %)</td>
<td>36.28 ± 3.35*</td>
<td>29.35 ± 3.25*</td>
<td></td>
</tr>
<tr>
<td>P (weight %)</td>
<td>17.55 ± 3.20*</td>
<td>14.55 ± 2.27*</td>
<td></td>
</tr>
<tr>
<td>Ca/P</td>
<td>0.206</td>
<td>0.202</td>
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* Shows a significant difference (P < 0.01).
Fig. 1. Representative photographs of cross cut section of cavity floors prepared by Er:Cr:YSGG laser irradiation. (A) In light microscopy, laser cavity had an irregular surface with the absence of any charring, carbonization and cracking of the enamel and dentine (original magnification ×8). (B) In SEM observation, there were an absence of a smear layer and the orifice of dentinal tubules was exposed (original magnification ×5000, bar represents 2.2 μm).

Light microscopic observations of the bur cavity showed well-delimited cavity angles, floors and walls, clear margins and relatively smooth cavity floors (Fig. 2A). The SEM observation revealed a relatively flat appearance and the surface was almost covered with a debris-like smear layer; dentinal tubule orifices were plugged (Fig. 2B). After acid etching, the smear layer was completely removed and dentinal tubules were clearly visible (Fig. 2C).

Discussion

Assessment of cavity preparation

Cavity preparation with the laser device showed that it is possible to produce shallow cavities within a few minutes. However, the required time for use of the laser was several times longer than the high-speed bur treatment which corresponded to a previous study using the Er:YAG laser (Aoki et al., 1998). The techniques of laser irradiation used in this study might prolong the required time for cavity preparation. At the
beginning of cavity preparation, irradiation was performed in a contact mode with maximum energy density of 6 W (67.9 J cm⁻²) because the removal of enamel tissues was more difficult with this laser device. Cutting the enamel by laser has a lower efficiency than cutting the dentine because of less water and organic contents of enamel structures (Li, Code & Van de Merwe, 1992; Hossain et al., 1999). When the treated cavity floor became deeper and closer to the underlying dentine layer, we reduced the power to 3 W (33.9 J cm⁻²) and cavities were finished by means of the non-contact irradiation mode. In the clinic, it is possible to reduce the time by increasing the energy densities; in particular, the output power can be increased for cutting the dentine, but it may increase the risk of thermal damage and was therefore avoided for this study.

The results of thermal change revealed that the surface mean temperature did not exceed 4 °C (Table 1), that is believed to be beyond the considered limit for pulp survival (Zach & Cohen, 1965). Furthermore, no pulpal inflammatory responses could be identified in Er:Cr:YSGG laser irradiated with a water spray as reported in previous histological studies (Eversole et al., 1997; Rizoiu et al., 1999). Clinical reports also showed that when compared with the use of the bur, patients felt less pain during cavity preparation with the laser system, and in some cases anaesthesia was not needed (Hadley et al., 2000).

**Atomic analysis by SEM-EDX**

The SEM-EDX examination revealed that quantities of Ca or P in the lased areas were increased significantly compared with bur preparation. It is likely that during the laser irradiation, an increase in Ca or P could be achieved because organic components evaporated; these changes are ascribed to an increase in temperature in the irradiated area (Rohanizadeh et al., 1999). However, no significant difference between Ca/P ratio of lased and bur cavities was found in the present study. Therefore, it can be considered that minimal thermal-induced changes of dentine components after the Er:Cr:YSGG irradiation with a water mist could be achieved. This phenomenon was not seen with Nd:YAG laser of the previous study; due to high temperature or pressure after Nd:YAG laser irradiation, Ca/P ratio was low when compared with the non-irradiated dentine (Rohanizadeh et al., 1999).

**Microhardness measurement of the cavity floor**

Microhardness measurement of the cavity floor confirms that Er:YAG laser produces clean-cut surface of the cavity. No statistically significant differences were found in microhardness of laser and bur cavity floor; these results corresponded to a previous study using the Er:YAG laser (Aoki et al., 1998). An increase of knoop hardness of the cavity floor caused by fusion of the dental hard tissues after CO₂ and Nd:YAG laser irradiation has been reported by previous studies (Marquez et al., 1993; Konishi et al., 1999); the laser cavity surface had a marked resistance to artificial secondary caries when compared with mechanical removal. On the other hand, due to the increase in temperature, higher energy densities of laser irradiation actually decreased the microhardness of dental hard tissues significantly and this condition is said to be unsuitable for improving the properties of dental hard tissues (Kuramoto et al., 2001). It has also been reported that an increase in temperature rise during laser irradiation results in some major thermal side-effects such as melting, cracking of enamel or dentine, and an increase in the pulpal temperature (Frentzen & Koort, 1990; Wgdor et al., 1993; Wgdor et al., 1995; Israel et al., 1997). Such phenomena were not noted in any of the laser cavities of the present study.

**Surface analysis of the prepared cavities**

The results of SEM observation in the laser cavities showed some particular characteristic features. The lased cavity surface was irregular and there was also the absence of a smear layer; the orifice of dentinal tubules was exposed. Typically, these structures were similar to the surfaces after Er,YAG or Er:Cr:YSGG laser irradiation and have previously been described as scaly or flaky, or as an irregular surface (Hibst & Keller, 1989; Keller & Hibst, 1989a; Hossain et al., 1999a,b). It is believed that microirregularity is associated with the microexplosion effects proposed as the mechanism of hard tissue ablation with Er:YAG laser or Er:Cr:YSGG laser (Wgdor et al., 1995). Bur cavities on the other hand showed a relatively flat appearance and exhibited a debris-like smear layer, which may interfere with adhesion, wetting, penetration and hardness of the prepared cavity (Eick et al., 1970; Smith, 1982). After acid etching, the smear layer was completely removed and dentinal tubules were clearly visible; these
structures were almost similar to the unetched laser cavities in the present study. However, in the acid etch technique, chemical changes may produce modification of the fraction of organic matter and decalcification of the inorganic component (Bertolotti, 1992; Pashley, 1992; Pashley, Horner & Brewer, 1992). Therefore, laser technique might have advantage because it produces an etching behaviour and does not damage the underlying tissues and dental pulp. The use of laser therapy also shows promise from the current research; laser therapy induced surface roughness comparable with that of acid etching (Zakkarlasen, MacDonald & Boran, 1991; Arcoria, Lippas & Vitasek, 1993; Walsh, Abood & Brockurst, 1994), and facilitated or even improved bond strength (Cooper et al., 1988; Keller & Hibst, 1988b; Powell, 1992; Miller & Truhe, 1993; Visuri et al., 1996b; Martinez-Insua et al., 2000). Therefore, the acid etch step can be easily avoided with laser treatment.

Conclusions

Based on the present study, Er, Cr:YSGG laser device is considered as one of the most effective and safe devices for cavity preparation because of its many advantages. These includes: (1) Easy delivery system – it uses a pulsed-beam system, fibre delivery and a sapphire tip bathed in a mixture of air and water which increases the cutting efficiency. (2) Minimal thermal damage to the surrounding tissues; under adequate water spray or with a careful irradiation technique, cavities without thermal damage to the dental pulp or surrounding tissues can be produced in the clinical and in addition, patients will experience less pain and anxiety with the laser device. (3) Minimal thermal induced changes of dental hard tissue compositions – Ca/P ratio and knoop hardness of the lased cavity floor was similar to the bur cavities. (4) Favourable surface characteristic – the step of acid etched technique can be easily avoided in the laser cavities.

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References


ATOMIC ANALYSIS AND KNOOP HARDNESS OF LASER CAVITY FLOOR


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