Tensile Bond Strength of Er, Cr: YSGG Laser-irradiated Human Dentin to Composite Inlays with Two Resin Cements

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The purpose of this study was to investigate the tensile bond strength of composite inlays to human dentin with two different cavity preparation tools (bur *versus* Er, Cr: YSGG laser) and with two different bonding procedures (total-etch: Variolink II *versus* self-etch: Maxcem). The specimens were divided into four groups: bur-cut/Variolink II, bur-cut/Maxcem, laser-ablated/Variolink II, and laser-ablated/Maxcem. The following characteristics were then investigated: morphological change, dentin-resin cement interface, surface roughness, and tensile bond strength. Results demonstrated that the tensile bond strengths of the four groups were 19.11 ± 5.88 MPa, 8.54 ± 2.38 MPa, 13.72 ± 3.43 MPa, and 12.11 ± 3.71 MPa, respectively. We concluded that Variolink II provided higher tensile bond strength to composite inlays than Maxcem. On the other hand, the bond strength of Variolink II with dentin cavity prepared by Er, Cr: YSGG laser was statistically lower than that prepared by bur.

Keywords: Er, Cr: YSGG laser, Tensile bond strength, Resin cement

INTRODUCTION

For several decades, dentists have been using conventional mechanical cutting and drilling systems to remove diseased dental hard tissues and to prepare cavities for restoration. This process is efficient but uncomfortable as the vibrations and sharp noises make patients anxious. Since lasers were introduced for *in vitro* caries removal^{1,2}, their advantages of decreased discomfort and reduced pain have also led numerous researchers to investigate other potential applications of laser in dentistry.

Unfortunately, ruby, argon, CO₂, and Nd: YAG lasers have been reported by many researchers to produce major thermal effects on dentin, including melting, carbonization, the creation of fissures and cracks in the surrounding tissues, as well as an increase in pulpal temperature. With the discovery of two new laser types, Er: YAG and Er, Cr: YSGG lasers, which were approved by the Food and Drug Administration (FDA), dental hard tissues can now be removed without causing damage.

The Er, Cr: YSGG laser emits a wavelength of 2,780 nm. Using a pulsed-beam system and fiber delivery, it has proved to be a valuable tool for ablating enamel and dentin. It has been studied for Class V cavity preparations and caries removal, and was shown to produce irregular, rugged, and stripped surfaces on dentin, similar to the

morphological changes observed in Er: YAG laser-irradiated dentin^{3,4}.

Compared with conventional mechanical drilling systems, laser preparation produced a cavity floor with Ca/P ratio and Knoop hardness number similar to that produced by bur cutting method⁵. In addition, Er, Cr: YSGG laser preparation was capable of causing significant reductions in *Escherichia coli* and *Enterococcus faecalis*⁶. When Er, Cr: YSGG laser preparation was supplemented with acid etching, there were no significant differences in the microleakage of composite fillings in Class II cavities between laser and classical bur preparations⁷. Moreover, pulpal temperature increased by only 2°C when dentin was irradiated by Er, Cr: YSGG laser⁸, and no pulpal inflammatory responses could be identified either immediately or 30 days after laser preparation⁹. Furthermore, Er, Cr: YSGG laser could be utilized as an etching tool. A study on the microtensile bond strength of porcelain veneers bonded to tooth surface treated with either Er, Cr: YSGG laser or 37% orthophosphoric acid was reported to have similar values¹⁰.

On the other hand, conventional resin cements use etchant, primer or adhesive in the process of bonding tooth-colored inlays to prepared cavities. Bonding effectiveness might thus be compromised due to the multi-step application technique¹¹. Recently, a self-etch resin cement combining all the three

components into a tube has been introduced (Maxcem, Kerr Sybron Dental Specialties, Orange, CA, USA). Without the time-consuming procedure of surface pretreatment, the self-etch resin cement has greatly shortened the clinical chairtime.

Although the bond strength of Er: YAG laser-irradiated dentin has been investigated¹²⁾, little effort has been made on comparing the quality of Er, Cr: YSGG laser-irradiated dentin surface for composite inlays with either etch-and-rinse or self-etch resin cement. Thus, the primary aim of this study was to investigate the tensile bond strengths of bur-cut and Er, Cr: YSGG laser-ablated human dentin to composite inlays with either etch-and-rinse or self-etch resin cement and to analyze the resin cement-dentin interface.

MATERIALS AND METHODS

Materials

Two types of resin cement self-etch, self-adhesive resin cement, Maxcem (Kerr Co., Orange, CA, USA), and dual- and light-curing resin dental luting material, Variolink II (Ivoclar Vivadent, Schaan, Liechtenstein) were used in this study. The composite inlay was made of heat- and pressure-processed polymer-glass dual-cure restorative, belleGlass HP (Kerr/Sybron, Orange, CA, USA). Table 1 lists the compositions of these materials.

Tooth specimens

Extracted human third permanent molars from 16- to 40-year-old individuals were used in this study. They were obtained with informed consent of the

donors. Collection of human teeth was performed under the permission of the Ethical Committee of National Taiwan University Hospital (Case No. 9561702045). Crowns with caries, restorations, or fractures were discarded. Any remaining soft tissue was thoroughly removed from the tooth surface with a dental scaler (Sonicflex 2000, KaVo Co., Biberbach, Germany) under running water. All teeth were then stored in 4 distilled water containing 0.2% thymol to inhibit microbial growth until use. To minimize deterioration, the storage medium was changed every week and all preserved specimens were used for tensile bond test within one month.

While fully hydrated, each molar was first cut just below the occlusal pit and fissure, perpendicular to the long axis of the tooth by means of a low-speed diamond wafering blade (Isomet, Buehler Ltd., Lake Bluff, IL, USA). Next, the crown dentin disk with a thickness of 2.5 mm was obtained by a second cut parallel to the first one. The enamel of each specimen was removed with a plain-cut tungsten carbide fissure bur at high speed under continuous water spray. Then, the dentin specimens were wet-polished with 600-grit silicon carbide abrasive paper followed by sonic vibration in distilled water for 30 seconds to create uniform flat surfaces, as well as to remove any superficial debris created during cutting and polishing procedures. These dentin disks were fabricated for analysis of surface morphological changes and for resin cement-dentin interface observation after being bur-cut or Er, Cr: YSGG laser-ablated.

As for the tensile bond test, specimen preparation procedure was the same except that the second

Table 1 Materials used in this study

Scientific name/Product name (manufacturer)/Lot number	General composition
Self-etch, self-adhesive resin cement/Maxcem (Kerr Co., Orange, CA, USA)/444924	66% filler by weight, with an average filler particle size of 3.6 microns; 20 - 35% uncured methacrylate ester monomers
Dual- and light-curing resin cement/Variolink II (Ivoclar Vivadent, Schaan, Liechtenstein)/H06641	<i>Excite DSC</i> : HEMA, dimethacrylates, phosphoric acid acrylate, silicon dioxide, initiators and stabilizers in an alcohol solution <i>Monobond-S</i> : 3-methacryloxypropyl-trimethoxysilane, water-ethanol solution <i>Paste A</i> : Bis-GMA, urethane dimethacrylate, TEGDMA, inorganic filler, ytterbium trifluoride, initiator, stabilizer <i>Paste B</i> : Bis-GMA, urethane dimethacrylate, TEGDMA, inorganic filler, ytterbium trifluoride, benzoyl peroxide, stabilizer
Heat- and pressure-processed polymer-glass dual-cure restorative/belleGlass HP (Kerr Sybron, Orange, CA, USA)/409999	Methacrylate ester monomer/BisGMA/TEGDMA, particulate composite (78% filler: Ba-Silicate, SiO ₂)

cut was not performed.

Er, Cr: YSGG laser irradiation settings

The laser system used in this study was Er, Cr: YSGG laser (MillenniumTM II, Biolase Technology Inc., San Clemente, CA, USA). It emitted a wavelength of 2,780 nm with a repetition rate of 20 Hz and a beam spot size of 0.442 mm². Output power varied from 0 to 6 W. Laser beam was used in a non-contact mode within 1–2 mm from the target area, and the tip with a fiber of 0.6 mm diameter was held perpendicular to the lased surface during irradiation. Cavities were prepared with a focused mode and water spray cooling. Energy parameters were 3.5 W and 20 Hz with water spray (air pressure level: 80%; water pressure level: maximum level), which were determined in our pilot study to yield better efficiency, minimal thermally induced changes, and favorable surface characteristics.

Specimen preparation for surface morphology observation

Five crown dentin disks were employed to observe the changes in surface morphology. Each disk was equally divided into three areas to receive three different treatments (Groups 1–3). In Group 1, the disks were fixed with utility wax and a cavity was prepared on the allocated surface area in each disk with a high-speed #411 cylinder diamond bur rotating at 350,000 rpm under air-water spray. The cavity was of 2×2 mm² size and 1 mm deep. Then, the cavity was etched with 35% phosphoric acid gel (Ultra-Etch, Ultradent Products, South Jordan, UT, USA) with an applicator sponge for 30 seconds and rinsed with an air-water spray for 20 seconds. In Group 2, cavities of the same dimensions as Group 1 were prepared using the Er, Cr: YSGG laser at an energy setting of 3.5 W and 20 Hz with water spray, but without acid etching. Group 3 received the same treatment as Group 2, but with acid etching.

Specimen preparation for resin cement-dentin interface observation

Another five crown dentin disks were prepared for composite inlay restorations and for resin cement-dentin interface observation. Each dentin disk was equally divided into two areas for receiving bur or laser preparation (Groups 4 and 5). Groups 4 and 5 were equally subdivided into two areas for receiving self-etch adhesive resin cement (Maxcem) or total-etch adhesive resin cement (Variolink II) (Table 1). Dimensions of cavities prepared for Groups 4 and 5 were the same as those of Groups 1–3.

After cavity preparation, silicone impression material (Rapid liner, Coltene/Whaledent Inc., Mahwah, NJ, USA) was mixed according to manufacturer's instructions to make an impression of the

cavity. After 30 minutes, type IV dental stone (Durone, Dentsply-DeTrey, Konstanz, Germany) was poured into each mold and allowed to set in a plastic storage box. The stone casts were then separated from the impressions after one hour.

A disposable swab was used to paint a thin layer of separator on the dies and any part of the model that may come in contact with the belleGlass HP composite material. Subsequently, Opaqueous Dentin was applied onto the preparation floor. Each increment of composite resin was well condensed to fill the cavity and light-cured with a light-emitting diode (LED) light curing unit (LEDemetron II, SDS Kerr, Danbury, CT, USA) for 40 seconds. Energy output was 750 mW/cm² as measured with a power meter (Cure Rite, Dentsply Caulk, Milford, DE, USA). Finally, each die was inserted into the belleGlass HP curing unit chamber for 20 minutes under a specific temperature (135 °C) and pressure (0.41 MPa) within nitrogen environment to reach final cure.

Before cementation with Maxcem or Variolink II, the inner surfaces of manufactured composite inlays were sandblasted with 50- μ m Al₂O₃ particles at an air pressure of 0.25 MPa (PrepStart, PowerPlus Basic Quattro IS, Danville Engineering, San Ramon, CA, USA) for 13 seconds from a distance of 10 mm. Samples were then ultrasonically cleaned in 70% isopropyl alcohol for three minutes.

Maxcem was a self-etch, self-adhesive resin cement that combined the etchant, primer, and adhesive resin into one material. Before placement of Maxcem, the prepared cavity was rinsed thoroughly followed by air-dry if the remaining water on the surface was not dried completely. Subsequently, the cement was dispensed into the cavity using the mixing tip on dual syringe cartridge. The inlay restoration was properly seated, and all excess cement was removed with an explorer. Finally, the surface was light-cured by LEDemetron II unit for 40 seconds.

For cementation with Variolink II, the cavity was etched with 35% phosphoric acid gel. The inner surfaces of the inlay restoration were also silanized with Monobond-S for 60 seconds and then dried with water-free air. The dentin cavity and the inner surfaces of the inlay restoration were then saturated with a generous amount of Excite DSC for 10 seconds. Subsequently, base paste and catalyst paste in a 1:1 ratio were mixed on a mixing pad with a spatula followed by cementation of inlay. All excess cement was removed, and the surface was light-cured by LEDemetron II unit for 40 seconds.

After storing in distilled water for 24 hours¹³⁾, these dentin disks were split perpendicular to the dentin-resin cement-inlay interfaces with a straight unibvel end chisel and a dental hammer. Sectioned specimens were demineralized in 6 N hydrochloric acid (HCl) (Wako Pure Chemical Industries Ltd.,

Osaka, Japan) for one minute, rinsed in distilled water, deproteinized in 1% sodium hypochlorite solution (NaOCl) (Wako Pure Chemical Industries Ltd., Osaka, Japan) for 10 minutes, and finally rinsed with distilled water again.

Specimen preparation for tensile bond test

Extracted human third permanent molars were randomly divided into four groups (Groups 6 - 9: bur-cut/Variolink II, bur-cut/Maxcem, laser-ablated/Variolink II, and laser-ablated/Maxcem) to receive the same surface treatments as Groups 4 and 5. Each group consisted of 10 specimens. The specimens for tensile bond test were prepared according to a previously published method¹⁰. Each trimmed specimen was fixed to a custom-made metal jig using cyanoacrylate and debonded in tension with a universal testing machine (Instron Corp., Canton, MA, USA) at a crosshead speed of 0.5 mm/minute. The forces to dislodge the bonds between dentin and composite inlays were recorded by the load cell and computer software (Merlin Software Suite, Instron Corp., Canton, MA, USA). Dimensions of each side of the debonded specimens were measured using a digital micrometer (Mitutoyo Co., Tokyo, Japan), and tensile bond strength (MPa) was calculated for each specimen.

Fracture types at the dentin-resin cement-inlay interfaces were analyzed using a digital stereoscopic microscope (Leica MZ8, Heerbrugg, Switzerland) at $\times 8 - 25$ magnification. In addition, fractured surfaces of the debonded specimens were examined by SEM. The following classification was employed to determine the fracture mode: Type 1 - Complete adhesive failure between resin cement and dentin; Type 2 - Partial adhesive failure between resin cement and dentin, and partial adhesive failure between resin cement and composite inlay; Type 3 - Complete adhesive failure between resin cement and composite inlay.

Scanning electron microscopy (SEM) evaluation

The morphological changes after treatment with bur cut or laser ablation, as well as the resin cement-dentin interface, were observed under a scanning electron microscope. All specimens were immersed in 2.5% cold glutaraldehyde in 0.1 mol/L cacodylate buffer at pH 7.4 for eight hours. They were then serially dehydrated in graded ethanol solutions (50%, 60%, 70%, 80%, 90%, 95%, and 100% ethanol) at 45-minute intervals, critical point-dried by CO₂, mounted on aluminum stubs, sputter-coated with ~20 nm of gold-palladium alloy, and finally examined by a Hitachi SEM (Model S-800, Tokyo, Japan) at an accelerating voltage of 15 kV.

Atomic force microscopy (AFM) evaluation

To evaluate the surface roughness of specimens after different treatments, three crown dentin disks were prepared *via* the aforementioned methods. Each disk was equally divided into four areas to receive diamond bur preparation plus acid etching, diamond bur preparation only, laser preparation plus acid etching, and laser preparation only. Laser energy settings and acid etching procedure were the same as those for surface morphology analysis. All imaging experiments were carried out with an AFM (NSCRIPTOR™, NanoInk Inc., Chicago, IL, USA) and conventional cantilevers (force constant = 0.10 N/m, Si₃N₄). Five squares of each area of 50 μ m length were randomly selected for scanning with AFM, and the average roughness value was calculated.

Statistical analysis

Surface roughness and bond strength of each group were analyzed with one-way ANOVA and Tukey's test ($\alpha = 0.05$) to determine whether there were any significant differences among the groups.

RESULTS

Morphological analysis of prepared dentin surfaces

The morphology of the cavity floor prepared by a high-speed diamond bur and acid-etched with phosphoric acid is shown in Fig. 1(a). Enlarged dentinal tubule orifices were noted due to loss of mineral phase within peritubular and intertubular dentin. No dentin debris or smear layer was observed and some fibrous structures were noted inside the dentinal tubules. The dentin surface irradiated by Er, Cr: YSGG laser showed a scaly, irregular, and rugged appearance (Fig. 1(b)). There was also no smear layer or debris, and dentinal tubule orifices were open without widening. It also showed peritubular dentin protruding from the surrounding intertubular dentin. Additionally, some cracks could be observed. In the laser-ablated dentin surface etched by 35% phosphoric acid, enlarged dentinal tubule orifices without smear layer were found (Fig. 1(c)). Protrusion of peritubular dentin from intertubular dentin was not noted.

Morphological analysis of dentin-resin cement interface

When the cavity was prepared by a high-speed diamond bur and cemented with Variolink II, numerous resin tags with length of about 50 μ m appeared in an orderly fashion at the dentin-resin cement interface (Fig. 2(a)). They aggregated in a bulb-shaped configuration (arrowhead) and then diverted into dentinal tubules. When the cavity was prepared by a high-speed diamond bur and cemented with Maxcem, no resin tags were found in the

Fig. 1 (a) Microstructure of a cavity floor prepared by a high-speed diamond bur and acid-etched with phosphoric acid showed enlarged dentinal tubule orifices, which were attributed to loss of mineral phase within peritubular and intertubular dentin. (b) Prepared dentin lased by Er, Cr: YSGG laser revealed a scaly, irregular, and rugged appearance. Both dentin surfaces were free of smear layer or debris. (c) When laser-ablated dentin surface was etched by 35% phosphoric acid, enlarged dentinal tubule orifices without smear layer were noted. No protrusion of peritubular dentin from intertubular dentin was found.

Fig. 2 (a) Numerous resin tags with length of about 50 μm (arrow) could be found at the dentin-resin cement interface after receiving bur-cut/Variolink II treatment. Hybrid layer formation (arrowhead) and resin tags diverted into dentinal tubules could be found. (b) No resin tags were found in the microstructure receiving bur-cut/Maxcem treatment. (c) Arrangement of resin tags was irregular and hybrid layer was not well formed (arrowhead) when cavity was prepared by Er, Cr: YSGG laser and cemented with Variolink II. (d) No resin tags existed at the dentin-resin cement interface when cavity was prepared by Er, Cr: YSGG laser and cemented with Maxcem.

Fig. 3 Means and standard deviations of tensile bond strengths of bur-cut/Variolink II, bur-cut/Maxcem, laser-ablated/Variolink II, and laser-ablated/Maxcem were 19.11 ± 5.88 MPa, 8.54 ± 2.38 MPa, 13.72 ± 3.43 MPa, and 12.11 ± 3.71 MPa, respectively. Columns labeled with the same notation (* or †) indicated that they had no statistically significant differences ($n = 10$).

microstructure of dentin-resin cement interface (Fig. 2(b)). Figure 2(c) shows the dentin-resin cement interface of the cavity prepared by Er, Cr: YSGG laser plus cementation with Variolink II. Although some resin tags were observed, their arrangement was irregular and the bulb-shaped configuration was not prominent as in Fig. 2(a). There were also no resin tags at the dentin-resin cement interface when

Table 2 Fracture types by digital stereoscopic microscope and SEM

	Type 1	Type 2	Type 3
Bur-cut/Variolink II	7	1	2
Bur-cut/Maxcem	10	0	0
Laser-ablated/Variolink II	10	0	0
Laser-ablated/Maxcem	3	7	0

Fig. 4 Representative images of dentin disk surfaces after receiving (a) diamond bur preparation plus acid etching, (b) diamond bur preparation only, (c) laser preparation plus acid etching, and (d) laser preparation only. Striations (arrow) could be found in the dentin surface prepared by diamond bur only (b). Laser-irradiated surface (d) exhibited the greatest surface irregularity.

the cavity was prepared by Er, Cr: YSGG laser and cemented with Maxcem (Fig. 2(d)).

Tensile bond strength measurement and failure mode analysis

The means and standard deviations of the tensile bond strengths of bur-cut/Variolink II, bur-cut/Maxcem, laser-ablated/Variolink II, and laser-ablated/Maxcem were 19.11 ± 5.88 MPa, 8.54 ± 2.38 MPa, 13.72 ± 3.43 MPa, and 12.11 ± 3.71 MPa, respectively (Fig. 3). No statistically significant differences were found between laser-ablated/Variolink II and laser-ablated/Maxcem, as well as between bur-cut/Maxcem and laser-ablated/Maxcem.

The predominant fracture modes of bur-cut/Variolink II, bur-cut/Maxcem, laser-ablated/Variolink II, and laser-ablated/Maxcem were Type 1 (70%), Type 1 (100%), Type 1 (100%), and Type 2 (70%), respectively (Table 2).

Surface roughness analysis of dentin disks by AFM

Figure 4 shows the representative images of dentin disk surfaces after receiving different treatments. The surface that received diamond bur preparation plus acid etching (Fig. 4(a)) exhibited 253.28 ± 16.79 nm of surface roughness (Fig. 5). Striations could be found in the dentin surface prepared by diamond bur only (Fig. 4(b)). In addition, this group exhibited the smallest surface roughness value (176.19 ± 47.26 nm). When the surface was treated by laser irradiation and acid etching (Fig. 4(c)), the surface roughness (620.30 ± 80.77 nm) was greater than those of previous two groups. Finally, laser irradiated-only surface (Fig. 4(d)) exhibited the greatest surface irregularity

Fig. 5 Means and standard deviations of surface roughness of dentin specimens after receiving diamond bur preparation plus acid etching, diamond bur preparation only, laser preparation plus acid etching, and laser preparation only were 253.28 ± 16.79 nm, 176.19 ± 47.26 nm, 620.30 ± 80.77 nm, and 975.00 ± 62.90 nm, respectively. There were significant differences between any two groups ($n=15$).

and surface roughness value (975.00 ± 62.90 nm). Further, as shown in Fig. 5, significant differences existed between any two groups.

DISCUSSION

Currently, the most widely accepted concept of dentin bonding is based on the formation of a hybrid layer. The underlying mechanism is that acidic conditioners dissolve the smear layer and demineralize the hydroxyapatite crystals of dentin substrate, followed by infiltration of monomers into the exposed collagen fibers¹⁵. The bonding mechanism of commercial products developed using this concept can be grossly divided into two types: total-etch *versus* self-etch luting materials. Total-etch luting materials are characterized by a complete removal of the smear layer with 37% phosphoric acid, while a self-etch luting material combines the etchant and primer into one application to achieve simultaneous demineralization and resin infiltration¹⁶.

In this study, Variolink II and Maxcem were chosen as representative resin cements of total-etch and self-etch, one-step luting materials, respectively. Both products were designed for cementation of crowns, inlays, and veneers especially those made of composite or porcelain. Due to increasing esthetic demand in the restoration of large-sized posterior cavities, composite inlays (belleGlass HP) were used as the restorative material instead of gold inlays.

The bond strength at dentin-resin cement interface depends on a number of factors: hybrid layer thickness, resin tag length, adhesive lateral branch formation, surface roughness, interface integrity, and void formation¹⁷. When the cavity was prepared by a bur and then etched with phosphoric acid for 30 seconds, no debris or smear layer was left (Fig. 1(a)). Moreover, peritubular and intertubular dentin were excessively demineralized, resulting in enlarged dentinal tubule orifices. The topography under AFM examination (Fig. 4(a)) revealed a relatively flat surface compared with the laser-irradiated surfaces (Figs. 4(c) and (d)). Surface roughness value was 253.28 ± 16.79 nm, which was significantly smaller than those of lased surfaces (Fig. 5).

However, after demineralization in 6 N HCl and deproteinization in 1% NaOCl, dentin-resin cement interface of the bur-cut/Variolink II group revealed many uniformly distributed resin tags of 50 μ m length (Fig. 2(a)). These resin tags aggregated initially and subsequently diverted into dentinal tubules. The aggregation was probably derived from the hybrid layer formation which represented the entanglement of resin monomers with collagen framework. Excite DSC, a dual-polymerized one-bottle dentin adhesive used in this group, has been demonstrated to form a hybrid layer, resin tags, and

adhesive lateral branches¹⁸). Its efficacy was attributed to inclusion of nanoscale inorganic fillers (Table 1), which could carry the primer-adhesive solution into a deeper area that could not be reached by light¹⁹. As hybrid layer principally contributed to dentin-material bond strength, the well-formed hybrid layer, resin tags, and adhesive lateral branches of this group resulted in the greatest bond strength (19.11 ± 5.88 MPa) (Fig. 3). Furthermore, fractured surfaces of two debonded specimens revealed complete adhesive failure between resin cement and composite inlay (Table 2), indicating that the bond strength of dentin-resin cement was occasionally even greater than that of resin cement-composite inlay.

When the cavity was prepared by a high-speed diamond bur without subsequent acid etching, the surface should be covered with an amorphous smear layer. The AFM image showed striations on the smear layer which were left by diamond bur cutting (Fig. 4(b)). Smear layer covering also reduced the surface roughness, consequently causing this group (bur-cut/Maxcem) to exhibit the lowest surface roughness value (176.19 ± 47.26 nm) (Fig. 5). In addition, the dentin-resin cement interface of bur-cut/Maxcem group did not display any resin tags (Fig. 2(b)). The reason suspected was that the weak acidity of one-step, self-etching resin cement could not entirely dissolve the thick smear layer and smear plugs, thereby preventing the acidic monomers from penetrating into the dentin matrix²⁰. Therefore, this group exhibited the smallest tensile bond strength value (8.54 ± 2.38 MPa) (Fig. 3), which was significantly lower than those of bur-cut/Variolink II and laser-ablated/Variolink II groups. Moreover, all debonded specimens demonstrated complete adhesive failure between resin cement and dentin (Table 2).

The Er, Cr: YSGG laser with 2,780 nm of wavelength is highly absorbed by water and hydroxyapatite. After efficient absorption of laser energy, water droplets produce violent microexpansion and simultaneously cut dental hard tissues²¹. In comparison with high-speed bur preparation, cavities prepared with laser are relatively painless and produce less vibration and heat²². Another advantage of laser preparation that has been mentioned is that the irradiated surface is more acid-resistant. This is because laser can reduce the carbonate-to-phosphate ratio, produce less acid-soluble compounds, and consequently enhance the resistance to acid demineralization²³.

Bond strengths of porcelain laminate veneers to tooth surfaces etched with acid or Er, Cr: YSGG laser have been compared¹⁰. Results showed no differences in microtensile bond strength between these two etching methods. The pulpal temperature elevation induced by Er, Cr: YSGG laser has been

reported to be 2°C ⁸), and no pulpal inflammatory responses were triggered⁹. However, temperature increase of 2.8°C at interdontoblastic vacuoles just below the preparation was noted²⁴. In addition, significantly enhanced synthesis of inflammatory mediator, leukotriene B₄, in human pulp cells was observed following thermal stimulation at 38°C ²⁵. At this juncture, it is expedient to highlight and caution about the issue of temperature rise during laser irradiation, even though the usage safety of laser treatment in the clinic is widely accepted.

In this study, the laser-dentin surface displayed a scaly, irregular, and rugged appearance (Fig. 1(b)). No smear layer or debris was noted, and open dentinal tubule orifices were also not enlarged. In addition, the laser ablated more organic portion than the inorganic composition, causing peritubular dentin to protrude from the surrounding intertubular dentin. This effect was contrary to that of acid etchant, which preferentially etched peritubular dentin. The AFM image of laser-irradiated surface (Fig. 4(d)) showed high irregularities and yielded the greatest surface roughness value (975.00 ± 62.90 nm) (Fig. 5).

After acid etching, the protruded peritubular dentin was flattened (Figs. 1(c) and 4(c)), thus reducing the surface roughness value to 620.30 ± 80.77 nm (Fig. 5). However, it was still significantly greater than the surface roughness of bur preparation either with or without acid etching.

With the laser-ablated/Maxcem group, no resin tag formation and observable hybrid layer could be found at the dentin-resin cement interface (Fig. 2(d)). This was due to the weak acidity of Maxcem as described previously. Although laser-ablated/Maxcem group exhibited a greater surface roughness value, and that greater presence of peritubular dentin has been suggested to achieve better bonding to dentin²², this group exhibited a mere tensile bond strength of 12.11 ± 3.71 MPa which was not significantly greater than that of bur-cut/Maxcem group (Fig. 3). One possible explanation was that laser irradiation could cause decomposition of collagen fibers, as characterized by two absorption bands at 2200 and 2015 cm^{-1} in Fourier transform infrared analysis²⁶. Against this background, hybrid layer was not well formed. The predominant fracture mode was partial adhesive failure between resin cement and dentin, and partial adhesive failure between resin cement and composite inlay, indicating that Maxcem bonded roughly equally to both dentin and composite inlay.

The dentin-resin cement interface of laser-ablated/Variolink II group (Fig. 2(c)) revealed some resin tags with length longer than that of bur-cut/Variolink II group (Fig. 2(a)). However, these resin tags did not conglomerate and distributed

relatively scarcely. In addition, possible decomposition of collagen fibers²⁶⁾ after laser irradiation might jeopardize hybrid layer formation. Consequently, the tensile bond strength (13.72 ± 3.43 MPa) of laser-ablated/Variolink II group was significantly lower than that of bur-cut/Variolink II group, but significantly higher than that of bur-cut/Maxcem group (Fig. 3).

Although the surface roughness of dentin is not a critical factor to enamel bonding, the influence of surface roughness of laser-irradiated dentin on bond strength has not been evaluated. From the results of this study, it could be seen that when Variolink II was used, the bond strength of laser-ablated specimens was lower than that of bur-cut specimens even though the former exhibited a greater surface roughness than the latter. Moreover, the tensile bond strength of total-etch resin cement was greater than that of self-etch, one-step resin cement, irrespective of whether the cavity was prepared by bur or Er, Cr: YSGG laser. It should be noted that the adhesive bonding of luting cements is closely related to the fracture resistance of restorations²⁷⁾.

Nevertheless, self-etch resin cements are less technique-sensitive and present less postoperative sensitivity²⁸⁾. Therefore, the use of total-etch or self-etch resin cement depends on the clinical situation and the operator's judgment. It should also be put into perspective that the results of *in vitro* tests cannot be directly applied to clinical conditions. Ultimately, the final performance of a material should be established in a long-term clinical study.

CONCLUSION

Er, Cr: YSGG laser irradiation adversely affected the adhesion of composite inlays to dentin with Variolink II as the resin cement. Compared to Maxcem, Variolink II was found to produce higher tensile bond strengths of composite inlays to dentin.

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