Laser All-ceramic Crown Removal—A Laboratory Proof-of-Principle Study—Phase 1 Material Characteristics

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Background and Objectives: The removal of all-ceramic crowns is a time consuming and destructive procedure in the dental office. The removal of all-ceramic crowns using Er:YAG lasers has not been previously described in the scientific literature. The objective of this laboratory proof-of-principle study was to evaluate whether with regards to absorption and transmission characteristics of bonding cements and ceramics all-ceramic crowns can be removed from natural teeth using an Erbium laser.

Study Design/Materials and Methods: The Fourier Transform Infrared Spectroscopy (FTIR) was used on flat ceramic samples (IPS Empress Esthetic (EE), E.max CAD, and E.max ZirCAD) to assess which infrared laser wavelengths transmit through the ceramics. Additionally, FTIR spectra for four bonding cements (Variolink Veneer, Variolink II, Multilink Automix, and SpeedCEM) were obtained. The Er:YAG laser energy transmission (wavelength 2,940 nm, 10 Hz repetition rate, pulse duration 100 μs at 126 mJ/pulse to 300 μs at 508 mJ/pulse) through different ceramic thicknesses was measured. Ablation thresholds for bonding cements were determined. Cement samples were directly irradiated or laser light was transmitted through ceramic samples.

Results: While the ceramics did not show any characteristic water absorption bands in the FTIR, all bonding cements showed a broad H_2O/OH absorption band. Some cements exhibited a distinct absorption peak at the Er:YAG laser emission wavelength. Depending on the ceramic thickness, EE and E.max CAD ceramics transmitted between 21 and 60% of the incident Er:YAG energy, with E.max CAD transmitting more energy than EE at comparable thicknesses. In contrast, E.max ZirCAD transmitted only 5–10% of the incident energy. Initial signs of cement deterioration occurred at 1.3–2.6 J/cm^2. Multilink Automix, SpeedCEM, and Variolink II started ablation at 4.4–4.7 J/cm^2. Variolink Veneer needed 44% less energy for ablation.

Conclusion: Er:YAG laser energy can be transmitted through all-ceramic materials and those transmitted energies are sufficient for ablation of bonding cements. Lasers Surg. Med. © 2014 Wiley Periodicals, Inc.

Key words: all-ceramic crowns; Er:YAG laser; FTIR; laser energy transmission; laser debonding

INTRODUCTION

When tooth structure has been weakened due to extensive decay, large fillings, fractures or root canal treatments, the placement of a crown to strengthen the remaining tooth against occlusal forces might be indicated. Porcelain fused to metal (PFM) crowns, where porcelain is layered on top of a metallic alloy, still dominate the tooth-colored restoration market. PFM restorations have proved reliable during 40 years of successful use [1]. However, the use of PFMs is declining slightly, as many new all-ceramic and resin-based composite crown products enter the dental market. Several situations may indicate the use of materials other than PFM crowns. They include patients desiring a high level of esthetic compatibility, patients with proven or perceived allergies to the metals used in dentistry, and patients wishing to eliminate metal from their mouths. The constantly rising cost of precious metals is another factor reducing the use of gold alloys for dental restorations. Crowns completely made of ceramics are often less costly.

In the last few decades, there have been tremendous advances in the physical properties and methods of fabrication of ceramic materials [2]. Consequently, there have been trends to replace the metal ceramics systems with all-ceramic systems. Advances in bonding techniques (gluing the all ceramic crown to the tooth) have also increased the utilization of ceramics in dentistry [3,4]. The increasing demand for esthetic, tooth-colored restorations has resulted in an increased use of dental ceramics not only for visible anterior crowns, but also for posterior restorations [5,6]. Moving to all-ceramic crowns for posterior teeth

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results in high mechanical demands to provide predictable long-term success under masticatory function. The use of newer materials, such as Lithium-disilicate (LS_2) and Zirconium-oxide (ZrO_2) which has the highest fracture resistance amongst ceramics have made all-ceramic crowns a viable alternative to PFM crowns [2,3,7]. Using these ceramics to fabricate anatomically shaped CAD/CAM-fabricated monolithic crowns without adding hand-layered porcelain veneering materials is a procedure to fulfill esthetic and functional requirements. By using monolithic crowns, porcelain chipping and other failures such as fatigue failures, can often be prevented [4,6,8–10]. Consequently, these systems are considered to be prospective replacements for metal-ceramic restorations [4].

The most common reason for removal of a dental crown is caries around its margins. The removal of PFM crowns is performed with diamond or tungsten carbide burs. The crown is sliced open, the edges are torqued apart and the halves are removed. Since most metal alloys are relatively soft, a PFM crown can quickly be removed by using diamond burs [11].In contrast, all high-strength ceramic crowns are very difficult to cut and remove. The flexure strength of layered porcelain crowns with a metal substrate is 120 MPa [12]. For bonded leucite-reinforced porcelain it is in the range of 200–220 MPa [13–16]. By comparison, a full contour LS_2 crown offers flexural strength in excess of 360 MPa (CAD/CAM) and 400 MPA (pressed) [17]. A full contour zirconia crown has a strength of more than 1,000 MPa [12]. As a result, the removal process is very time consuming. Diamond burs become dull quickly, and sparks occur typically due to extended contact time between the material and the diamond bur [18]. A re-cementation is not possible after the destructive removal.

Little research has been done in alternative all-ceramic crown removal techniques. With the introduction of pulsed lasers into dentistry, there may be a practical application of such lasers for removing all-ceramic crowns.

Short-pulsed laser ablation may be a promising method for the debonding of veneers, while avoiding overheating of the dental pulp. If the cement is rapidly ablated, then heat conduction by the slow process of thermal softening [19–21] can be avoided [22]. The Er:YAG laser is safe for ablation of dental hard tissues [23–26] as well as composite resin [27–29]. Rising pulse repetition rate during composite removal results in a linear increase in the pulpal temperature, but still does not cause a temperature increase above the limit considered safe for the pulp vitality [28,30].

In a recent study, we have shown that using an Er:YAG laser allows for complete debonding of porcelain veneers from extracted teeth without damage to, or removal of, the underlying healthy tooth structure. The debonding process of veneers is very efficient, with an average removal time of 100 seconds per veneer [31,32]. In the rare occasion that a mishap occurred at the veneer bonding appointment, an inaccurately placed veneer might even be removed without destroying the veneer [31,32].

The objective of the first phase of the proof-of-principle pilot study presented here is to evaluate the optical properties of different Ivoclar Vivadent all-ceramic crown materials and multiple adhesive cements with regards to laser all-ceramic crown debonding. The aim of this study phase is to prove that Erbium laser light can be transmitted through the ceramic materials, but will be absorbed in the adhesive cement. This would allow ablation of the cement and the consequent debonding of an all-ceramic crown. To the best of our knowledge, this is the first scientific publication studying laser debonding of all-ceramic crowns.

MATERIALS AND METHODS

To test the hypothesis that Ivoclar Vivadent Leucite Glass Ceramics, LS_2 and ZrO_2 materials are translucent to specific laser light, and that this laser light is not absorbed/fully absorbed by the ceramics, we performed two different tests.

For the first step, we used Fourier Transform Infrared Spectroscopy (FTIR) to evaluate whether the ceramic materials have specific absorption bands in the infrared wavelength spectrum.

For the second step, we measured laser energy transmission through the ceramic materials by irradiating ceramic sample material on one side with different laser energies and measuring transmitted laser energy on the other side of the ceramic material.

To test whether or not Ivoclar Vivadent adhesive cements absorb infrared laser energy for ablation, we used FTIR to determine absorption bands in the infrared. Finally, we performed basic ablation tests by optically determining at which laser energy settings ablation of the adhesive cement occurred. For verifying ablation thresholds the Erbium laser energy was directed directly onto cement or transmitted through ceramic samples.

All-Ceramic Crown Materials, Standard Flat Samples for FTIR and Energy Transmission Measurements

The porcelain all-ceramic crown materials used in this study were IPS Empress Esthetic (EE) (leucite glass-ceramic), IPS E.max CAD LT A2 (LS_2) (E.max CAD), and IPS E.max ZirCAD MO1 (ZrO_2-oxide) (ZirCAD) (Ivoclar, Vivadent, and Liechtenstein). Ivoclar (Ivoclar, Vivadent, and Lichtenstein) produced the porcelain test samples. The specimens were cut from blocks at the appropriate thicknesses using a diamond saw. Then they were polished with 320 and 600 grit SiC polishing paper on both sides. Next, the specimens were fired according to the manufacturer's instructions for each material. Empress was not fired, E.max CAD was fired using the 19 minutes firing cycle for LT block materials. The zirconia was fired on an S1 firing furnace for 2 hours.

For the FTIR measurements, a set of three ceramic samples with flat surfaces for each material were produced (5 mm × 5 mm, 1 mm thickness) as needed to assess the absorption characteristics of each ceramic material by FTIR in surface reflectance mode (Nicolet, Thermo Fisher Scientific FT-IR Spectrometer, Waltham, MA).

For the energy transmission measurements through the ceramic material from all three materials five samples were requested at 1.0, 1.5, 2.0, and 2.5 mm thicknesses. All of the flat ceramic samples were measured to confirm their thickness (Mitutoyo micrometer, model # IDC-112E, Mitutoyo America, Aurora, IL). These measurements were performed at three areas of the sample and averaged for each sample. The sample thickness for each given thickness was very accurate with only small standard deviations (0.01–0.04 mm) for each group of samples. In addition, these flat all-ceramic samples were used to assess energy transmission characteristics and consequent ablation of cement when applying laser energy through the samples (see below).

All-Ceramic Crown Bonding Cements

To achieve a basic understanding about absorption characteristics as well as ablation thresholds of typical ceramic crown dental bonding cements, a series of cement samples were prepared. The cements tested were Variolink Veneer, Variolink II, Multilink Automix, and SpeedCEM (Ivoclar, Vivadent, and Liechtenstein). To determine the absorption characteristics of these cements FTIR was used. In surface reflectance mode, the FTIR gives information about the chemical composition of a material and reveals absorption bands. While for cementing a crown on a tooth in the mouth the ideal cement thickness should be in the micron range, for the FTIR measurements in surface reflectance mode, the thickness of the tested sample is not relevant. Thus, the cement sample thickness chosen was 1.5–2.5 mm, with a diameter of 3 mm. Light curing of the cement was achieved by an application of light totaling 120 seconds from both sides using the Coltolux LED (Coltene/Whaledent Inc., Cuyahoga Falls, OH) light-curing tool.

To determine the absorption characteristics of the bonding cements in the infrared spectral range, three samples of each cement were used for the FTIR.

Three other cement samples were used to establish the ablation thresholds of the all-ceramic crown bonding cement. The determination of the cement ablation threshold was done by visual inspection using magnifying glasses (2× magnification) and a light microscope (Olympus Microscope BX50; 2, 5, 10, 20, and 50× magnification; imaging micropublisher 3.3, Canada, program image pro). The first visible changes of the cement surface, fume generation, and small ablation crater formation were registered and the corresponding laser energy was noted.

For verification of energy transmission through the ceramic samples and consequent ablation of cement, the standard flat all-ceramic samples were placed on top of cement samples. The distance of the irradiation fiber tip to the ceramic surface at ablation onset was measured.

Laser Settings

The laser utilized in this study was an Er:YAG laser (LiteTouch by Syneron, Yokneam, Israel) with a wavelength of 2,940 nm, 10 Hz repetition rate, and a pulse duration of 100 μs at 126 mJ/pulse up to 300 μs at 508 mJ/pulse. The pulse duration was measured with a thermoelectrically cooled HgCdZnTe (HCZT) detector (BSA Technology Model PCI-L-2TE-12, Torrance, CA) using a straight sapphire tip with 1,100 μm diameter. The laser pulse shape was square with an initial sharp peak. The beam profile at the end of the fiber tip was a tophat. Before and after each step of an experiment, the laser energy output at the end of the fiber tip was verified with an energy meter (Energymax 400, Molectron Detector, Inc., Portland, OR).

For the energy transmission measurements through the all-ceramic crown materials the sapphire tip was used in close proximity of roughly 10 mm from the ceramic. Energy transmission through the material samples was determined using the Er:YAG laser at five different set energies delivered by the laser system (126 mJ, 204 mJ, 304 mJ, 409 mJ, and 508 mJ per pulse) with a pulse repetition rate of 10 Hz. All transmission measurements were repeated for a minimum of three times.

In all cases laser energy was measured the Molectron power meter was used (Energymax 400, Molectron Detector, Inc., Portland, OR).

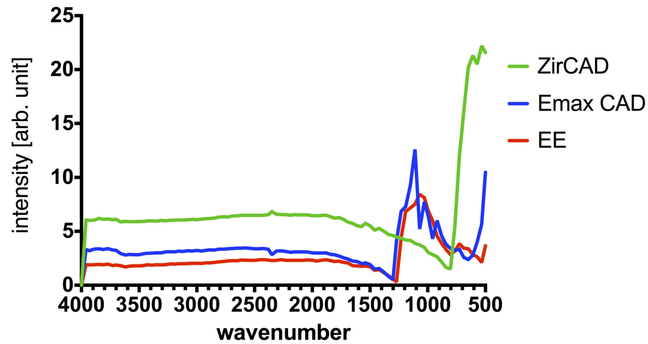

Fig. 1. FTIR spectra from IPS Empress Esthetics (ET) (leucite glass ceramics), IPS E.max CAD LT A2 (LS_2), and IPS E.max ZirCAD MO1 (ZrO_2).

RESULTS

All-Ceramic Crown Materials

Fourier Transform Infrared Spectroscopy (FTIR) of all-ceramic crown materials. The FTIR spectra of the EE and the E.max CAD ceramic samples revealed a strong peak (wavenumber position at around 1,100 wavenumber) most likely related to silica (Fig. 1). The strong silica peak might overlap a phosphate peak as ceramics contain small amounts of phosphate.

In contrast, the FTIR spectra obtained for the Zirconium ceramic demonstrated a broad absorption band at wavenumber 690, which can be attributed to Zr–O stretches (Fig. 1). As reported in the literature, typical IR spectra of crystalline zirconia samples show various stretching frequencies around wavenumbers 508, 520, 580, and 740 [33,34]. There is a reported strong absorption band at wavenumber 471, which can be attributed to the tetragonal zirconia [35,36].

The FTIR spectra also determined that the all-ceramic materials do not show any characteristic H_2O/OH

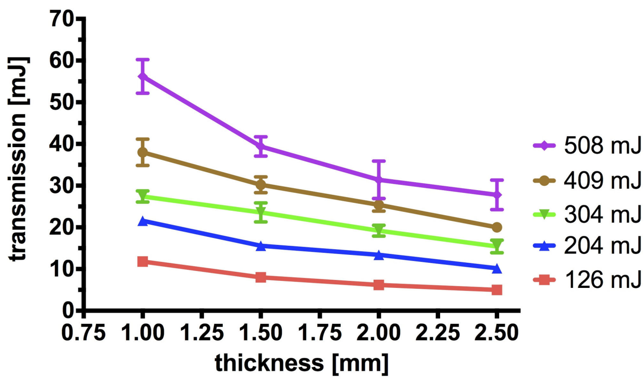

Fig. 2. E.max ZirCAD – energy transmission (average ± SD) at different energy levels and different sample thicknesses.

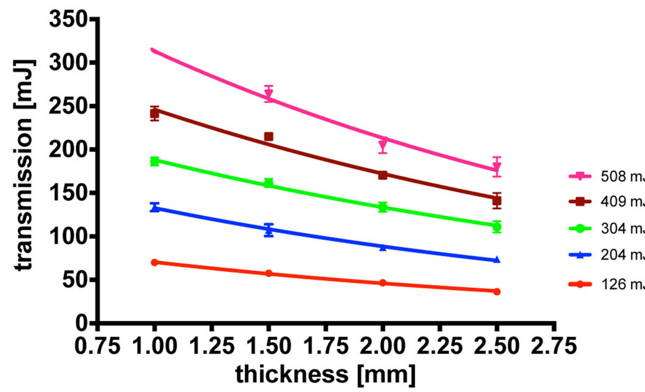

Fig. 3. E.max CAD – energy transmission (average ± SD) at different energy levels and different sample thicknesses with exponential curve fit.

absorption bands (wavenumber 3,750–3,640 and 3,600–3,400, respectively). Thus, with no distinct absorption around the Er:YAG laser emission wavelength of 2,940 nm (wavenumber 3,401) the FTIR results predicted that the Er:YAG laser irradiation will not be strongly absorbed by the tested all-ceramic materials but could be transmitted through the crown.

Energy transmission through all-ceramic crown materials. To calculate energy loss during transmission of the Er:YAG laser light through the all-ceramic materials, laser irradiation was directed perpendicular to the material surface with the laser tip in close proximity (10 mm distance to the sample surface) and the transmitted energy was measured on the opposing side behind the sample (18 mm distance to the energy meter). Three flat samples of each material were used to measure the energy transmission.

The laser was set to 5 different output energies of 126 mJ, 204 mJ, 304 mJ, 409 mJ, and 508 mJ per pulse, with a 10 Hz repetition rate. Figure 2 for E.max ZirCAD shows the average energy transmitted for the different laser energies (Mean ± SD) in relation to the ceramic thickness. EE and E.max CAD show energy transmission patterns similar to E.max ZirCAD.

E.max CAD transmitted the highest percentage of energy at any given thickness, followed by EEs and E.max ZirCAD. E.max CAD transmitted at 1 mm thickness 60.4% ± 4.2% of the irradiation energy and at 2.5 mm 20.5% ± 1.8%, EE transmission ranged from 48.6% ± 1.7% to 20.5% ± 1.8%, and E.max ZirCAD showed only a range from 9.9% ± 0.9% to 4.9% ± 0.6% transmitted energy.

Exponential regression curve fits have been calculated. The goodness of fit for the exponential regression curves varies from $r^2 = 0.9525$ to 0.9985. These good fits indicate that energy transmission with energy loss over thickness is exponential for all the tested ceramic materials.

The attenuation coefficient Σ was calculated for each ceramic material and within each material group for all different laser energies. For EEs the average attenuation coefficient was calculated at 0.387 ± 0.032 (Mean ± SD), for E.max CAD at 0.464 ± 0.068, and for ZirCAD at 0.565 ± 0.039. Within each material group the attenuation coefficient for the different applied laser energies was nearly identical. Figure 3 shows the exponential curve fit for energy transmission through E.max CAD. For the lowest energy the attenuation coefficient Σ was determined at 0.435 and 0.383 for the highest energy transmitted, with $r^2 = 0.9971$ and $r^2 = 0.9688$, respectively. The high r^2 values represent a very high goodness of fit for the exponential regression lines.

Bonding Cements

FTIR spectra of bonding cements. The FTIR spectra of all bonding cements (Variolink Veneer, Variolink II, Multilink, and SpeedCEM) revealed strong peaks that varied slightly in intensity. These peaks are most likely due to silica (1,100 wavenumber), as well as a C=O peak at 1,680/1,630 wavenumber. Moreover, the FTIR spectra demonstrated a broad H_2O/OH absorption band (wavenumber 3,750–3,640 and 3,600–3,400, respectively), which coincides with the Er:YAG laser emission wavelength (Fig. 4).

Multilink showed a distinct absorption peak at wavenumber 3,401 (identical with the Er:YAG laser emission wavenumber). In Figure 4 obvious peaks/elevations at wavenumber 3,401 are marked with an arrow.

Thus, all tested bonding cements absorb the Er:YAG laser irradiation. Ablation of the cements is likely to occur when irradiated.

Bonding cement ablation thresholds. The visual ablation threshold determination showed that when using an Er:YAG laser Variolink Veneer is ablated at fluences around 2.1–2.6 J/cm^2. Ablation fumes ("fuming") were the first sign of cement deterioration and ablation. Fumes from the cement surface were first seen at around 2.1 J/cm^2 and obvious ablation craters were detected at around 2.6 J/cm^2. All other cements needed fluences of between 2.3 and 2.6 J/cm^2 for "fuming" and 4.4–4.7 J/cm^2 to show ablation crater.

In summary, Table 1 shows the distance in millimeter between the 1,100 micrometer laser fiber tip and the

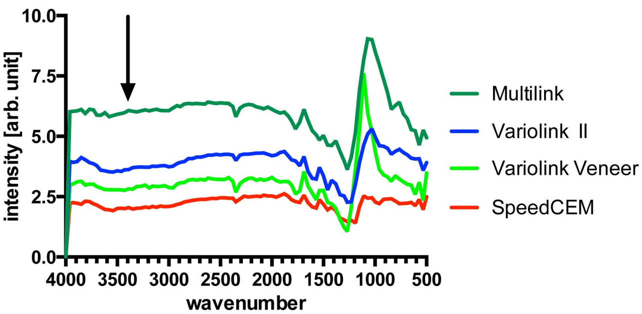

Fig. 4. FTIR spectra from Variolink Veneer, Variolink II, Multilink Automix, and SpeedCEM; the arrow marks the Er:YAG laser emission wavenumber 3,401.

sample surface at which first signs of ablation occurred when using the Er:YAG laser with 126 mJ per pulse, at a10 Hz pulse repetition rate. The corresponding fluence was calculated.

Cement ablation through ceramic material samples. For verification of energy transmission through the sample and possible subsequent ablation of the cement, standardized ceramic samples of E.max CAD and ZirCAD were placed on cement samples (Multilink Automix and Variolink Veneer). The distance to the ceramic surface at which first signs of ablation occurred was evaluated. The first signs of cement ablation through the standardized samples occurred at distances between the fiber tip and the ceramic surface of 5 mm with 126 mJ per pulse at the fiber tip.

Table 2 shows the tested ceramic material, thickness, cement type, and laser energy needed to create fuming and ablation craters, respectively, when transmitted through the ceramic material. The table shows also the corresponding fluences at the ceramic surface. For EE and E.max CAD at 1.0 mm thickness with 126 mJ per pulse ablation craters are immediately achieved when the laser light is sent through the ceramic. With increasing thicknesses higher energies are needed to achieve fuming and ablation.

As previously noted, E.max ZirCAD transmits the least energy of all the tested ceramics. E.max ZirCAD at 1.0 mm thickness in combination with Multilink Automix cement needed 500–600 mJ of irradiation energy for "fuming" to initiate the first sign of ablation and around 700 mJ per pulse are needed for ablation of the cement through the ceramic sample.

Using Multilink Automix cement with E.max ZirCAD at a 1.5 mm thickness requires 700 mJ energy per pulse to create fuming/deterioration of the cement. If Variolink Veneer cement is used instead of Multilink Automix, much stronger fuming/deterioration of the Variolink Veneer cement surface is observed in comparison to Multilink Automix cement.

DISCUSSION

The FTIR spectra of the EE and the E.max CAD ceramic samples revealed a strong absorption peak most likely related to silica and possibly a small amount of phosphate. In contrast, the FTIR spectra obtained from the Zirconium ceramic demonstrated a broad absorption band at small wavenumbers, most likely attributed to Zir–O stretches. The FTIR spectroscopy determined that all tested ceramics did not show any characteristic water absorption bands. Thus, with no distinct absorption around the Er:YAG laser emission wavelength of 2,940 nm (wavenumber 3,401) the FTIR results predicted that the Er:YAG laser irradiation will not strongly or even completely be absorbed by the tested ceramic materials, but will be transmitted through the ceramics.

The measurements of laser energy transmission through the flat ceramic samples showed that E.max CAD ceramic allowed the highest amount of energy to be transmitted. The E.max CAD material transmitted roughly between 21% and 60% of the irradiation energy, depending on the ceramic thickness. The transmission data for EEs are slightly lower, but in a similar range with 21%–49% energy transmission. In contrast, the Zirconia material E.max ZirCAD transmitted much less energy than the other two materials. Only 5% of the laser energy was transmitted through the 2.5 mm thick samples and up to 10% was transmitted at a 1 mm material thickness. Again comparable to the other ceramics, the energy transmission was inversely related to the sample thickness.

From the energy transmission perspective, debonding of cement through the EEs and E.max CAD ceramics will require less initial laser energy than the other ceramics. Transmitting enough energy through E.max ZirCAD in

TABLE 1. Determination of Ablation Thresholds for Variolink Veneer, Variolink II, Multilink Automix, and SpeedCEM using 2x Magnification Loops

	Distance fiber tip to sample for fuming [mm]	Distance fiber tip to sample for ablation [mm]	Fuming occurs at J/cm^2	Ablation occurs at J/cm^2
Multilink Automix	13.0	8.5	2.6	4.7
SpeedCEM	14.0	9.0	2.3	4.7
Variolink II	15.0	10.0	2.3	4.4
Variolink Veneer	18.0	13.0	2.1	2.6

TABLE 2. Irradiation Energies Transmitted Through Ceramic Materials EE, E.max CAD and E.max ZirCAD for Variolink Veneer and Multilink Automix Cements in Order to Achieve First Signs of Ablation (Fuming) and Ablation Craters, Respectively; Fluences at Ceramic Surface are Calculated When Fuming/Ablation Occurs

Sample #	Ceramic thickness	Cement type	Laser energy fuming occurs [mJ]	Fluence at ceramic surface fuming occurs [J/cm^2]	Laser energy ablation occurs [mJ]	Fluence at ceramic surface ablation occurs [J/cm^2]
Empress Esthetic						
A	1.0	Multilink Automix			126	9.5
A	1.5	Multilink Automix	126	9.5	204	15
A	2.0	Multilink Automix	126	9.5	204/304	15/23
A	2.5	Multilink Automix	204	15	304	23
E.max CAD						
A	1.0	Multilink Automix			126	9.5
A	1.5	Multilink Automix	126	9.5	204	15
A	2.0	Multilink Automix	126/204	9.5/15	304	23
A	2.5	Multilink Automix	204/304	15/23	409	30
E.max ZirCAD						
A & B	1.0	Multilink Automix	508/600	38/45	700	53
A, E, D	1.5	Multilink Automix	700 (strong fuming)	53		
E, D	1.5	Variolink Veneer	700 (very strong) fuming)	53		

order to ablate bonding cement appears to be more challenging. E.max ZirCAD transmitted roughly 75%–83% less energy than the leucite glass-ceramic and the LS_2, respectively. The observed differences in energy transmission in the infrared wavelength spectrum must originate in the different chemical composition of the all-ceramic materials. The Zirconia-oxide ceramic is clinically less translucent and appears opaque. Our energy transmission measurements have shown that this also seems to be true for the invisible near infrared wavelength spectrum.

The regression curve fits for energy transmission through the different ceramics showed an exponential energy loss with ceramic thickness for all the ceramics following the Lambert–Beer's law for light transmission through an absorptive/scattering medium at varying thicknesses. From the FTIR spectra it appears that the differences in energy transmission at the Er:YAG wavelength are not related to differences in absorption. These spectra did not show differences in absorption for the Erbium wavelength. Reflection of the surface and thus consequently transmission might depend on surface roughness. A rough surface might contribute to a larger, more distorted beam profile resulting in a lower fluence for debonding at the cement surface. Nevertheless, all materials were polished the same way. E.max CAD and ZirCAD were additionally fired; thus, there should be no major difference in refection due to surface roughness.

The large difference in energy transmission between the Leucite Glass Ceramics and the LS_2 on one side and the ZrO_2 on the other side are more likely due to different scattering behaviors within the ceramic and other material properties such as the ceramic composition. From a clinical perspective, Zirconia crowns are much less translucent. Those properties for the visible spectrum seem to occur also for the infrared spectrum. Zirconia is opaque because of its density, elemental chemistry, and high crystallinity [37], which result in a relatively high-refractive index (2.1–2.2) [38,39]. In contrast Leucite glass ceramics and Lithium- disilicate have a very low-refractive index of 1.4 in the visible range [40,41].

Er:YAG lasers are clinically indicated for removal of composite fillings. An Er:YAG laser removes cured composite resin in a slightly different way than ablating dental hard substances. Laser absorption occurs in the organic components of the resin. The ablation mechanism involved is explosive vaporization followed by a hydrodynamic ejection [42]. The rapid melting of the organic components creates large expansion forces due to the volume change of the material upon melting [43].

The FTIR of all tested bonding cements revealed a strong peak most likely related to silica and a C=O peak with a broad H_2O/OH absorption band. This absorption band coincides with the emission wavelength of an Er:YAG laser. In addition, the cement Multilink Automix showed a distinct peak at the Er:YAG emission wavenumber of 3,401 cm^{-1}. Thus, all tested bonding cements will absorb the Er:YAG laser irradiation and ablation of the cement will occur.

When testing the ablation thresholds of the various bonding cements, differences in the energies needed to start fuming of the cement as a first ablation sign and creating ablation craters were obvious. While Multilink Automix, SpeedCEM, and Variolink II needed roughly 4.4–4.7 J/cm^2 for ablation, Variolink Veneer started ablating at approximately 44% less energy. Selection of bonding cement with absorption properties suitable for laser removal might facilitate the removal of an all-ceramic crown if this is necessary post cementation. All-ceramics, which transmit minimal amounts of laser energy such as the Zirconia crowns tested, might benefit from cements with those higher absorption properties.

Testing whether enough laser light can be transmitted through ceramic samples such that ablation occurs in cement positioned directly under the ceramic samples confirmed the previously reported observations about ceramic energy transmission and the cement absorption characteristics to be correct. The surface of the all-ceramic samples were perpendicularly irradiated with the Er:YAG laser and ablation conditions for the bonding cement through the ceramic were evaluated. For the LS_2 E.max CAD ceramic, low energy settings with the thin ceramic samples were needed to cause cement fuming or ablation of the cement. Even at a ceramic thickness of 2.5 mm, which clinically might occur at occlusal surfaces, roughly 300 mJ irradiation energy were sufficient for fuming and roughly 400 mJ resulted in obvious ablation of the underlying Multilink Automix cement. As predicted, the clinically very opaque ZrO_2 ZirCAD, required laser energy settings at the high value of 700 mJ to cause obvious ablation with a 1 mm sample thickness. Thicker samples appeared to allow only enough energy transmission to achieve fuming of the underlying cement. When testing Variolink Veneer, the cement that needed lower energy for ablation, more intense fuming was observed with the same sample thickness. Future testing with all-ceramic crowns will determine whether fuming as interaction with the cement is sufficient to break the bond between the crown and the tooth and if the all-ceramic crown can be removed.

Limitations of this study are that we tested only two shades of ceramic samples, and only one shade of the bonding cements. One of the porcelain shades was visibly lighter than the other. While the perceived shade is dependent on optical properties in the visible spectral range, the Er:YAG wavelength is outside of this range and is unlikely to be influenced by the ceramic shade. Also, although we tested multiple bonding cements, the absorption tests were limited to only one shade. The cement shade might exert a slight influence on the absorption characteristics.

By visual examination no destruction of the ceramic restorative material has been observed; however, investigation of mechanical properties should confirm this observation.

Since the laser energies that were applied (up to 4.7 J/cm^2) were far below those known to be safe for removal of enamel or dentin (80 to 160 J/cm^2) [23–26] and up to 20 times lower than those used for composite removal [28,29,44], the all-ceramic crown removal process might also be safe for the pulpal tissue. Nevertheless, pulp temperature measurements during all-ceramic crown removal by laser will determine possible temperature increases and will assess pulpal safety. In the third phase of this proof-of-principle laboratory pilot series it will be evaluated whether the laser crown debonding procedure can be considered as appropriate for clinical use. Necessary requirements to ensure that the temperature rise in the pulp chamber stays within safe temperature limits for pulpal tissue will be discussed. Since the energies applied are far below those needed for ablation of dentin, no unnecessary destruction of tooth substance should occur. Following crown removal and caries removal, a new crown can be placed.

CONCLUSION

With respect to laser all-ceramic crown removal, it can be concluded that Er:YAG laser energy is transmitted through the all-ceramic materials tested, and the amount of transmitted energy depends on the ceramic thickness and composition. The bonding cement absorbs the energy transmitted through the crown and the remaining low fluences result in an ablation of the cement.

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