Lasers in Surgery and Medicine

Laser All-Ceramic Crown Removal—A Laboratory Proof-of-Principle Study—Phase 2 Crown Debonding Time

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Background and Objectives: The removal of all-ceramic crowns is a time consuming procedure in the dental office. Little research has been done in alternative removal techniques for all-ceramic crowns. The objective of the second phase of this proof-of-principle laboratory pilot study was to evaluate whether Ivoclar Vivadent all-ceramic crowns can be efficiently removed from natural teeth without damage to the underlying tooth structure using an Erbium laser.

Study Design/Materials and Methods: The ceramic materials used were IPS E.max CAD Lithium-disilicate (LS_2) (E.max CAD) and IPS E.max ZirCAD Zirconium-oxide (ZrO_2) (ZirCAD) (Ivoclar, Vivadent, Liechtenstein). Molars, either as stand-alone teeth or placed in an artificial row of teeth, were prepared to receive all-ceramic crowns. Copings and full contour crowns with either featheredge or regular margins were produced. The all-ceramic crowns were bonded to the teeth with Ivoclar Multilink Automix. The time for Er:YAG laser debonding of each crown was then measured. The Er:YAG (LiteTouch, Syneron, Yokneam, Israel) was used with an 1,100 μm diameter fiber tip with energies up to 600 mJ per pulse (wavelength 2,940 nm, 10 Hz repetition rate, pulse duration 100 μs at 126 mJ/pulse, and 400 μs at 590 mJ/pulse). The irradiation was applied at a distance of 10 mm from the crown surface following a defined pattern. Air-water spray was applied to the crowns at a rate of 67 ml/minute.

Results: All of the all-ceramic crowns were successfully debonded with the laser. On average, an all-ceramic E.max CAD crown was debonded in 190 ± 92 seconds (average ± SD). The debonding time for ZirCAD featheredge crowns was 226 ± 105 seconds and for ZirCAD crowns with regular margins it was 312 ± 102 seconds. No crowns fractured and no damage to the underlying dentin was detected. The bonding cement deteriorated due to the Er:YAG irradiation. Additionally, no carbonization at the dentin/cement interface was observed.

Conclusion: Er:YAG laser energy can successfully be used to efficiently debond all-ceramic full contour crowns from natural teeth without damage to the underlying tooth structure. Lasers Surg. Med.

Key words: all-ceramic crowns; Er:YAG laser; laser debonding; crown removal; debonding time; zirconium-oxide; lithium-disilicate

INTRODUCTION

Dental crowns are indicated when tooth structure has been weakened due to caries, large fillings, fractures or root canal treatments. Porcelain fused to metal (PFM) crowns in which porcelain is layered on top of a metallic alloy still dominate the tooth-colored restoration market.

Nevertheless, in the last few decades tremendous advances in the physical properties and methods of fabrication of ceramic materials have led to the increasing use of all-ceramic tooth colored crowns [1]. In addition, advances in bonding techniques which allows gluing the all-ceramic crown to the tooth, have also increased the utilization of all-ceramics in dentistry [2,3]. The increasing demand for esthetic, tooth-colored restorations has resulted in an increased use of dental ceramics for both visible anterior crowns as well as posterior teeth [4,5]. Using all-ceramic crowns for posterior teeth requires materials, which can withstand high occlusal forces. Newer ceramic materials such as Lithium-disilicate (LS_2) and especially Zirconium-oxide (ZrO_2), which has the highest fracture resistance amongst ceramics, have made all-ceramic crowns a practical alternative to PFM crowns [1,2,6].

Recent advances using anatomically shaped CAD/CAM fabricated monolithic crowns without additional porcelain veneering can fulfill esthetic as well as functional requirements. Monolithic crowns do not experience chipping of the veneering porcelain. Additionally, other failures such as fatigue failures can often be prevented [3,5,7–9]. Consequently, these systems are considered as potential replacements for metal-ceramic restorations [3].

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When the removal of a PFM crown is indicated, the relatively soft PFM crown is sectioned with a diamond or tungsten carbide bur [10]. The edges are then torqued apart and the halves are quickly removed. In contrast, high-strength all-ceramic crowns are very difficult to cut and remove. While the flexure strength of a PFM crown is at 120 MPa.[11], bonded leucite-reinforced porcelain has a flexure strength of 200–220 MPa [12–15], and a full contour LS_2 crown offers a flexural strength in excess of 360 MPa (CAD/CAM fabricated) and 400 MPa (pressed) [16]. Ultimately, a full contour zirconia crown has a strength of more than 1,000 MPa [11]. Consequently, the removal process is very time consuming. Diamond burs become dull quickly, and sparks typically occur due to extended contact time between the crown material and the diamond bur [17].

When cutting a porcelain crown, another major difficulty arises the moment the dentist wants to differentiate if the bur is still cutting in porcelain, has already reached the bonding cement or is already deep in the tooth dentin structure. Since all three materials in question are relatively white, visual differentiation is difficult [18]. A dentist who does not want to cut unnecessarily deep into healthy tooth structure will often pause for evaluation.

Little research has been conducted to develop alternative techniques for all-ceramic crown removal. With the introduction of pulsed lasers into dentistry, there may be a practical application of these lasers for removing all-ceramic crowns. The Er:YAG laser is safe for ablation of dental hard tissues [19–22] as well as composite resin [23–25]. As previously shown, these short-pulsed lasers are a promising method for the debonding of veneers while avoiding overheating of the dental pulp. If the luting cement is rapidly ablated, then heat conduction by the slow process of thermal softening [26–28] can be avoided [29].

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 the underlying healthy tooth structure. The debonding process of veneers (IPS Empress Esthetic and e.max Press HT) is very time efficient, with an average removal time of 100 seconds per veneer [30,31].

The objective of the second phase of this proof-of-principle laboratory pilot study presented here was to evaluate whether Ivoclar Vivadent all-ceramic crowns with high flexural strength made from fracture resistant ceramics like LS_2 and ZrO_2 can efficiently be removed from natural teeth using an Erbium laser. For that reason, in the second phase of this pilot study we tested only IPS E.max CAD and IPS E.max ZirCAD and did not test the leucite glass-ceramic Empress Esthetic, which provides roughly 50% of the flexural strength of LS_2 and has the lowest flexural strength of all materials tested in phase 1 of this laboratory study. The Empress Esthetic all-ceramic crowns offer a relatively low challenge for removal. The aim of this study was to prove that all-ceramic crowns with high flexural strength will be debonded and removed from teeth in a timely fashion and without unnecessary damage to the underlying tooth structure by using an Erbium laser.

To the best of our knowledge, this is the first scientific publication demonstrating the efficient laser debonding of all-ceramic crowns.

MATERIALS AND METHODS

To test the hypothesis that Ivoclar Vivadent LS_2 and ZrO_2 all-ceramic crowns can be removed from natural teeth with Erbium laser light without damaging the underlying dentin, we performed multiple laser crown debonding tests.

In a pre-test, we first studied the removal time for LS_2 and ZrO_2 all-ceramic copings, and secondly, we evaluated the debonding of all-ceramic regular full contour crowns from stand-alone single molars. Finally, we evaluated the removal time for all-ceramic full contour crowns positioned in an artificial row of teeth.

Ceramic Materials

The ceramic materials used in this study were IPS E.max CAD shade LT A2 (LS_2) (E.max CAD) and IPS E.max ZirCAD shade MO0 (ZrO_2) (ZirCAD) (Ivoclar, Vivadent, Liechtenstein). Ivoclar Vivadent Inc., Amherst, NY, USA produced the all-ceramic copings and full contour crowns for this study.

Pretest–All-Ceramic Copings and Full Contour Crown Debonding from Stand-Alone Teeth

For a pre-test, all-ceramic copings and full contour crowns were used to explore basic parameters for laser crown debonding. Copings consist of a very thin base of one material covering the prepared tooth. Later, for clinical use, copings can be layered with other ceramics to create a full contour crown. To accept copings and full contour crowns, molars were prepared with a taper of 4–8°. Impressions were made with Ivoclar Virtual extra light and heavy body polyvinylsiloxane (PVS) materials. For this pretest part of the study, all teeth were mounted on a small stand with no adjacent teeth.

Four E.max CAD (shade LT A2) and four ZirCAD (shade MO0) copings were produced and cemented onto the corresponding teeth (procedure see below). The delivered E.max CAD copings showed a uniform wall thickness of 1 mm. The ZirCAD copings presented with 0.5 and 1.0 mm wall thicknesses.

Next, eight molars were prepared to receive all-ceramic full contour crowns. For the crown design and production, a uniform thickness was specified for all crowns. The margin width was specified to be 1 mm, and the thickness at the contact points was to be 1.5 mm. The non-functional cusps were designed with 1.5 mm thicknesses, and a 2.0 mm thickness was requested for the functional cusps.

All-ceramic Full Contour Crown Debonding from Teeth Positioned in an Artificial Row of Teeth

In this last study section, we tested the removal of E.max CAD full contour crowns, ZirCAD crowns with featheredge margins, and ZirCAD crowns with regular margins. For this part of the study, all teeth were mounted in an artificial row of teeth.

A total of forty molars were prepared for this part of the laser crown removal study. Twenty molars were assigned to the E.max CAD group and twenty to the ZirCAD ceramic group. As with the pre-test, all teeth were prepared with a taper of 4–8°. For all twenty E.max CAD crowns and ten of the ZirCAD crowns uniform thicknesses were specified. The thickness at the contact points was prescribed to be 1.5 mm. The non-functional cusps were designed with 1.5 mm thicknesses and the functional cusps with a 2.0 mm thickness. The preparation and design allowed for a width at the margin of 1 mm. For the remaining 10 ZirCAD crowns, a "featheredge" preparation was utilized. The featheredge crowns were still designed as full contour crowns but were prepared and produced with wall thicknesses of 1 to 1.5 mm. The cervical margin width was 0.3–0.5 mm. Impressions were made with Ivoclar Virtual extra light and heavy body PVS materials. The E.max CAD crowns were fabricated in shade LT A2, and the E.max ZirCAD crowns were produced in shade MO0.

After manufacturing of the crowns, the crowns for all study parts were measured to confirm their thicknesses (Mitutoyo micrometer, model # IDC-112E, Mitutoyo America, Aurora, IL). The mesial, distal, buccal, and lingual walls as well as the occlusal surfaces were measured. Each measurement was performed three times at the thickest area of the individual surface and averaged for each surface.

At delivery, the crowns were surface conditioned with a primer (Monobond plus), placed and seated with an adhesive cement (Ivoclar Multilink Automix [Yellow Shade]) according to the manufacturer's instructions. According to the manufacturer's instructions, silane was not used, thus a possible chemical bonding was not achieved.

After cementing, the E.max CAD crowns were stored in a normal saline solution at 37°C for a range of 4–21 days. The ZirCAD crowns were stored for 1–15 days in a normal saline solution.

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 400 μs at 590 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 measured with an energy meter (Energymax 400, Molectron Detector, Inc., Portland, OR).

During the laser irradiation, the sapphire tip was used at a distance of (5 to) 10 mm from the ceramic surface. The Er:YAG laser was used at different set energies (between 304 mJ and 590 mJ per pulse, pulse repetition rate of 10 Hz) depending on material and material thickness according to earlier laser energy transmission measurements (reported earlier). Air-water spray from a dental unit syringe was directed at the crown surface. The water flow was repeatedly applied at a rate of 67 ml of water per minute.

The irradiation time, until an all-ceramic crown was debonded, was measured. To test whether the crown was already sufficiently debonded, we initially checked the first time after 1 minute of systematic irradiation. A plier was placed on the buccal and lingual surfaces of the crown and a dislodging force in the occlusal directions was applied. If no movement was detected when using light forces, we continued with the laser debonding process. If the debonding was sufficient, the crown came straight off with a slight pull from the plier. Alternatively, the time was measured until a crown lifted-off from the tooth on its own due to ablation pressure during the irradiation process.

After debonding, the underlying tooth structure was inspected for visible damage using 2.5 power magnification. We also clinically inspected the bonding cement and its adherence to dentin and the all-ceramic crown.

Laser Debonding Procedure

The following describes the laser irradiation pattern for debonding of all-ceramic full contour crowns:

Laser irradiation began on the occlusal surface and for 30 seconds the irradiation fiber was moved in direction from buccal to lingual in a back and forth motion while irradiating the area from one contact point to the other. When the tip reached at the opposite contact point, the same irradiation pattern going from buccal to lingual was repeated until reaching the original contact point (painting the surface with imaginary 1 mm wide stripes). When the tip arrived at the original contact point the irradiation direction was changed from mesial to distal (and back) and the occlusal area was irradiated from contact point to contact point. The next step was to irradiate the buccal line angels/cusps for a maximum of 30 seconds. The irradiation then continued down the buccal surface for a maximum of 30 seconds, hitting the cervical margins only once. Next, the lingual line angles/cusps and lingual surface were irradiated in the same fashion as the buccal surface (line angle/cusps first then down in to the cervical margin) for a maximum total time of 1 minute. The irradiation on the buccal and lingual surfaces was also applied up and down from the incisal margins to the cervical margins. Finally, the interproximal areas were irradiated by going far into the interproximal area, painting up and down and lining up the irradiation direction with the direction of the neighboring tooth (fiber almost parallel to the neighboring tooth) – from both, the lingual and buccal side (1 min max).

This protocol results in approximately 3.5 minutes of total irradiation time. The irradiation energy started out with 550 mJ per pulse (1,100 micron fiber tip). – The irradiation distance depended on whether changes in transparency or a grey coloration occurred due to the deterioration of the bonding cement. If changes occurred immediately, the irradiation distance was increased and the speed of "painting" was increased so that the total debonding time was reduced. Typically, the irradiation tip stayed 10 mm away from the ceramic surface. An air- water spray from a syringe was aimed at the fiber tip and the crown surface at an angle of roughly 45 degrees. Staying at a distance from the ceramic surface prevents sparking during the debonding procedure. Some crowns popped off on their own during irradiation, while some needed a gentle pull with a plier.

When removing the ZirCAD crowns, additional time was spent on the irradiation of the contact points. Each contact point was irradiated from the occlusal ridge side. Additionally, from the lingual and buccal surfaces, the irradiation was directed to the contact point from a direction beyond the contact point. Irradiation of the area below the contact point down to the cervical margin was applied

RESULTS

Pretest—All-Ceramic Crown Debonding from Stand-Alone Teeth

Laser debonding of all-ceramic copings from stand-alone teeth. Four E.max CAD copings with approximately 1 mm wall thicknesses (thickness at margins up to 1.3 mm) were debonded with the Er:YAG laser applying 300 mJ laser energy per pulse. The time needed to debond was 2–3 minutes per coping. No fractures of the copings or any alteration or destruction of underlying tooth substance were observed. All copings were easily pulled off with a plier or popped off on their own.

Zirconia copings with a wall thickness of 0.5 mm were debonded using a laser pulse energy of 300 mJ for approximately 2 minutes. Zirconia copings with wall thicknesses of 1.0 mm were debonded using energies of 500 mJ per laser pulse in less than 5 minutes per coping. Again, after debonding, the crowns did not show any signs of deterioration and no changes of the underlying dentin were observed. In all cases, the cement appeared deteriorated and was easily "scratched off" from the tooth as well as from the inside of the crown with a dull instrument (Fig. 1a and b).

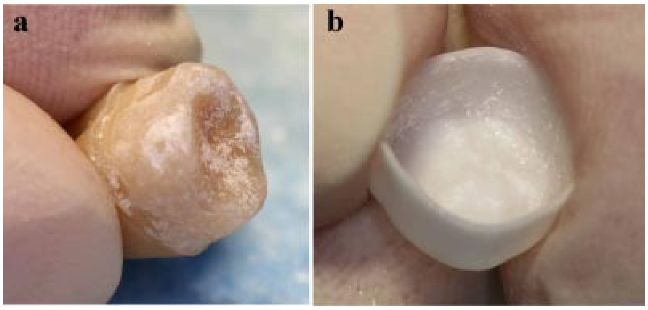

Fig. 1. Zirconia coping with 0.5 mm thickness; (a) Tooth surface immediately after laser debonding of the E.max ZirCAD coping. The cement appears whitish and sticks mainly to the tooth surface; (b) Inside of the ZirCAD coping appearing almost clean.

Laser debonding of all-ceramic full contour crowns from stand-alone teeth. The E.max CAD crowns presented with an axial wall thicknesses of 1.5–2 mm, margins with 1 mm thickness, and occlusal surfaces with a 2 mm thickness (two of shade A2 and two of shade A4). All of the full contour crowns were laser debonded. The debonding times were 2:00, 2:30, 2:15, and 3:30 (min:sec), using laser energies of approximately 500 mJ per pulse. Afterwards, several of the crowns were re-cemented and again laser debonded. A few bonded crowns had been kept in normal saline solution for 2–7 weeks. No obvious differences in laser debonding time or effort were observed.

Laser Debonding of All-Ceramic Full Contour Crowns from Teeth Located in an Artificial Row of Teeth

Laser debonding of all-ceramic E.max CAD full contour crowns in an artificial row of teeth. All 20 Ivoclar E.max CAD all-ceramic full contour crowns that were cemented on single molars and then positioned in an artificial row of teeth were successfully laser debonded and removed. Figure 2 shows the mounting sleigh with the adjacent teeth in place (one bicuspid and one molar). The fixation screws are partially visible in the back.

The laser energy was set to 560 mJ but varied between 500 and 590 mJ during the experiments due to issues with the laser. All crowns were removed in one piece and no crown fractured during the debonding process. On later examination, one crown showed a tiny hairline fracture at the margin.

The actual average thicknesses of the removed crowns was 1.91 ± 0.25 mm (average ± Standard Deviation [SD]) for the occlusal, 1.68 ± 0.15 mm for the buccal, 1.75 ± 0.26 mm for the lingual, and 1.82 ± 0.21 mm for the mesial and distal surfaces.

Calculating the laser debonding/removal time for the 20 E.max CAD crowns on average, an all-ceramic crown was debonded in 190 ± 92 seconds (average ± SD). The range of irradiation time for debonding varied from 85 seconds to 420 seconds. Eight of the 20 crowns were removed in a range 85–150 seconds.

Laser debonding of all-ceramic zirCAD featheredge full contour crowns in an artificial row of teeth. The actual average thicknesses of the featheredge full contour ZirCAD crowns was 0.90 ± 0.1 mm for occlusal, 0.96 ± 0.05 mm for buccal, 0.95 ± 0.05 mm for lingual, and 0.98 ± 0.04 mm for mesial and distal surfaces (average ± SD). At the gingival margins, these crowns showed a minimum thickness of 0.6 mm with an average of 0.67 ± 0.05 at the thinnest cervical margin area. The

Fig. 2. Mounting sleigh for artificial row of teeth with adjacent teeth in place next to an E.max CAD crown.

maximum thickness at the gingival margins was in average 0.9 ± 0.05 mm.

All 10 Ivoclar ZirCAD featheredge full contour crowns cemented on molars and then positioned in an artificial row of teeth were successfully laser debonded and removed. All crowns were removed in one piece and no crown fractured during the debonding process. No changes in the underlying dentin were observed.

Regarding the removal time for the featheredge crowns the range of irradiation time for debonding of ZirCAD featheredge crowns varied from 160 seconds to 492 seconds. The average removal time was 226 ± 105 seconds (average ± SD).

Since this was a proof-of-principle study, the average removal time calculation included all those cases where the laser had to be readjusted during the removal attempt (the laser energy had fallen to less than 450 mJ per pulse). If those time delays were excluded, the average removal time would be reduced to 196 ± 50 seconds.

Laser debonding of all-ceramic ZirCAD full contour crowns (regular margins) in an artificial row of teeth. The average thicknesses of the full contour ZirCAD crowns (with regular cervical margins) was 1.89 ± 0.18 mm for occlusal, 1.6 ± 0.08 mm for buccal, 1.55 ± 0.05 mm for lingual, and 1.57 ± 0.07 mm for mesial and distal surfaces (average ± SD). All 10 Ivoclar ZirCAD full contour crowns cemented on molars and then positioned in an artificial row of teeth were successfully laser debonded and removed. All ZirCAD crowns were removed in one piece and no crowns fractured during the debonding process. No changes in the underlying dentin were observed. Figure 3 shows a ZirCAD full contour crown after removal. The contact points received less laser energy and the cement is deteriorated, while the other areas received more energy and show slightly carbonized cement at the cement/crown interface.

The individual removal time for the ten ZirCAD crowns varied between 210 and 501 seconds. On average, a ZirCAD full contour crown was laser debonded in 312 ± 102 seconds.

Fig. 3. ZirCAD full contour crown after laser debonding and removal. The pictures show the tooth from the mesial contact point side; No darkening of the cement at the contact points, slight darkening at the cement crown interface.

Again, if the removal times would be excluded where laser readjustment was needed during the removal, the average ZirCAD full contour crown removal time would be reduced to 253 ± 69 seconds.

Bonding Cement after Laser Debonding

In all cases of laser crown debonding and removal, the bonding cement was almost completely deteriorated. In most cases, the majority of the cement remained on the axial walls of the teeth and on the occlusal inside surface of the crown. The cement was friable and easily crumbled. If the cement had not already "fallen off" when the crown was taken off, it was effortlessly removed from the tooth as well as the inside of the crown using a dull spatula.

If carbonization of the cement occurred, it was only visible at the crown-cement interface. No carbonization of the cement or any other discoloration occurred at the cement-dentin interface or of the dentin itself. Carbonization at the cement-crown interface occurred more often when removing the zirconia crowns.

DISCUSSION

In a previous study, we had shown that ceramic veneers can easily and efficiently be debonded from extracted teeth with an Er:YAG laser [30,31]. Debonding of veneers occurred without damage to the underlying tooth structure. In addition, in phase 1 of this proof-of-principle study [reported earlier], we also demonstrated that flat ceramic samples made from Ivoclar Vivadent's all-ceramic crown materials, LS_2 and ZrO_2, allow transmission of Er:YAG laser energy. Moreover, we had shown that thicker ceramics typically used in crowns will require higher laser energies than thin veneers for laser debonding. Lastly, in comparison to the LS_2 ceramic, the ZrO_2 based ceramic crowns might pose another challenge for laser debonding since Zirconia transmits up to 80% less Er:YAG laser energy than LS_2. Since the FTIR spectra from LS_2 and Zirconia did not reveal a stronger absorption of Zirconia at the Erbium wavelength [previous paper], it can be assumed that the light is more scattered. The observed carbonization at the cement ceramic interface allows the speculation that with removal of zirconia crowns, the cement fumes as described, consequently heats up and deteriorates, and it is less likely that an explosive ablation takes place. Nevertheless, the previous tests had shown that Zirconia might allow enough laser energy transmission for a debonding effect. In phase 1 of this proof-of-principle study, we also had shown that different bonding cements require only small laser energies for deterioration or ablation. In summary, we hypothesized that typical all-ceramic crowns transmit Er:YAG laser energy, the transmitted energy will be absorbed in the bonding cement, the bonding cement will deteriorate, and debonding of all-ceramic full contour crowns will be possible (Las Surg Med, previous paper).

In phase 2 of the laboratory proof-of-principle study presented here, we demonstrated that all-ceramic full contour crowns can be debonded with an Er:YAG laser and consequently can easily be removed.

It appears that full contour E.max CAD crowns allow sufficient energy transmission for debonding. Removal of full contour E.max CAD crowns from stand-alone teeth took only 120–210 seconds. To reach and deteriorate the bonding cement at the typically thicker contact point area, higher laser energy settings are required for sufficient transmission of energy. Specifically, when the crown to be debonded is placed in simulated natural conditions with adjacent teeth, the contact points are difficult to reach with the laser energy. Furthermore, to reach the contact points angulation of the fiber is needed, which reduces the effective fluence at the cement surface. After developing an effective irradiation pattern, the removal of such crowns placed in an artificial row of teeth took on average only 190 seconds. While crowns came off as quickly as 85 seconds, the longest removal took five times longer.

The prolonged times needed to debond were typically due to laser energy transmission problems with the laser system itself. Damage of the mirror in the laser handpiece, but more frequently overused and deteriorated fiber tips were the reasons for delivering insufficient energy to the crown. When it became clinically apparent (see below) that the energy delivery was too low, adjusting the energy and/or replacing the fiber tip resulted in sufficient debonding energy. Afterwards, the debonding process was successfully completed for each crown.

As expected from the transmission measurements previously reported in phase 1 of this study (Las Surg Med previous paper), the laser debonding of Zirconia crowns was slightly more challenging. Since E.max ZirCAD transmits roughly 80% less laser energy than E.max CAD, we started with debonding of very thin-walled copings. For clinical use in dentistry, copings are layered with veneering ceramics, which transmit laser energy much better than Zirconia. The first goal was to test whether we could remove a Zirconia coping. While using 300–500 mJ laser energy, Zirconia copings with thicknesses of 0.5 and 1.0 mm were debonded in 2– 5 minutes, respectively.

The thinnest full contour all-ceramic Zirconia crowns were the featheredge crowns, where the tooth preparation is at a minimum. These crowns showed extremely thin "featheredge" margins, challenging the material properties. Nevertheless, we were able to laser debond and remove all featheredge Zirconia crowns, which presented with walls that were significantly thicker than the copings. Furthermore, the laser debonding of featheredge Zirconia crowns successfully occurred where teeth were placed in an artificial row of teeth. The debonding of the Zirconia featheredge crowns, which were designed as full contour crowns, took an average of 226 seconds. The debonding of these crowns required only 36 seconds more than the average debonding time for the full contour E.max CAD crowns. If considering only those debonding cases without the need for laser adjustment as described above, the all-ceramic featheredge full contour crown removal needed only 6 seconds longer than the debonding of the E.max CAD crowns.

As a final challenge, the debonding of full contour Zirconia crowns with regular thick margins was tested. The debonding of these all-ceramic E.max ZirCAD crowns occurred despite their much thicker walls. The laser debonding time of these crowns from teeth located in an artificial row of teeth took with an average of 312 seconds, which was slightly longer than the debonding of the featheredged Zirconia crowns. Not considering cases where laser adjustment was needed during debonding, the average removal time dropped to 253 seconds. Thus in summary, the debonding of a full contour Zirconia crown took only 2 minutes longer than the removal of a fully comparable LS_2 crown. Not considering cases which needed laser adjustment, the time difference was only 1 minute.

Since this was a proof-of-principle study, the primary aim was to show that all-ceramic crowns can be debonded and secondly, debonding in a reasonable amount of time could be achieved. There was an obvious learning curve regarding the debonding irradiation scheme. In practice, the debonding time will trend towards the shorter debonding times.

Porcelain has been known to take up water when in the mouth over time [15,32,33]. Since Er:YAG laser energy is predominantly absorbed in water, any stored water in the porcelain could lead to fractures of the porcelain during laser debonding. Consequently, due to the laser induced water expansion, pieces of the crown might fracture off, allowing for an easier crown removal. Storing the all-ceramic crowns in saline solution for up to 21 days did not have any obvious influence on fracture incidence. Only a tiny hairline fracture was observed at one E.max CAD crown margin.

Since Multilink cement is a dual-cure cement, which polymerizes with and without light application, polymerization occurs quickly and completely and will not influence the light absorption properties of the cement over time. Water uptake in composites over time is also known [34–36]. Since the Erbium lasers are highly absorbed in water, absorption of water into the cement will raise the absorption of the bonding layer. As a result, for debonding less laser energy should be necessary. The ceramic crowns should come off more easily. Most probably due to the short storage time an obvious change in laser crown debonding time was not observed.

Er:YAG lasers are clinically indicated for removal of composite fillings. Laser absorption occurs in the organic components of the resin. The ablation mechanism involved is explosive vaporization followed by a hydrodynamic ejection [37]. The rapid melting of the organic components creates large expansion forces due to the volume change of the material upon melting [38]. An indicator for delivering sufficient energy for debonding is the clinically observed change in translucency/opacity of the all-ceramic due to the alteration of the bonding cement. The ceramic appears to slightly change color to a greyish more opaque tone, but only the perceived translucency has been reduced; the material is unlikely to have changed its physical properties. This kind of translucency change might be similar to the color change observed in the semiconductor industry during the performance of the Laser-lift-off procedure where the observed color change is a clear indicator that lift-off is occurring through the used sapphire [39,40].

Also, the carbonized cement will influence the perceived shade. This described change in perceived translucency was easily observed with the E.max CAD material, but also occurs to a lesser extent with the ZirCAD material.

Due to the divergent beam profile when the laser exits the fiber, varying the distance of the fiber tip to the ceramic surface allows for controlling the fluence at the cement layer. Fluences that are too high result in unnecessary burning of the cement at the ceramic-cement interface. This could be observed in some cases with the E.max CAD crowns. Consequently, the ceramic opacity rapidly changed. With the highly scattering Zirconia, which is more difficult to see through, most likely the transmitted energy was not sufficient high enough for an explosive ablation of the cement but lead only to fuming, with deterioration of the cement and carbonization of the cement at the cement zirconia interface. While with the highly energy transmitting LS_2 crowns, the debonding process is an explosive ablation of the cement, with the very low energy transmitting zirconia crowns the debonding occurs more likely due to fuming and consequently heat deterioration of the cement.

In general, to prevent any heat damage, and specifically in case of more translucent LS_2 ceramic crowns it appears advisable to apply the lowest fluence necessary to debond the all-ceramic crown and to slightly retract the fiber when strong darkening becomes visible.

Nevertheless, as described in phase 1 of this proof-of-principle study, “fuming of the cement” due to Er:YAG laser irradiation occurs at low energy levels as a first indicator of deterioration of the cement. Since the Zirconia crowns were thick and only a low amount of energy was transmitted, fuming appears to be sufficient to break the bond between the crown and the tooth. Therefore, all the tested types of all-ceramic crowns were removed. The crumbled, friable consistency of the cement after debonding also supports the assumption that the bonding cement is severely altered. A dull spatula or a hand scaler can be used to remove the deteriorated cement followed by polishing with a prophy cup and pumice to clean the tooth.

Since the laser energies reaching the inner side of the crown (2 up to 5 J/cm^2) were far below those known to be safe for removal of enamel or dentin (80–160 J/cm^2) [19–22] and up to 5-times lower than those used for composite removal [24,25,41], the all-ceramic crown removal process should be safe for the pulpal tissue. Nevertheless, pulp temperature measurements during laser all-ceramic crown removal will evaluate possible temperature increases and will serve to 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.

The applied energies, specifically those reaching the inside of the crown, were far below those needed for ablation of dentin, and consequently the underlying tooth structure stayed intact and unaltered. Following laser crown debonding and caries removal, a new crown if needed could be fabricated and placed.

Limitations of this study are that we tested only one shade of each of the two different all-ceramic full contour crowns. 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. For both ceramics, we tested only one bonding cements with only one shade. The ceramic composition obviously influences the transmission much stronger than the shade. In this study ceramic thicknesses were also limited to the typical range of wall thickness for all-ceramic crowns, extreme thicknesses were not tested. In this proof-of-principle study we did not test layered ceramics due to our emphasis on monolithic crowns. Nevertheless, we assume that layered full ceramic crowns might be even easier to remove. The layered feldspathic porcelain has a much lower flexural strength and might easily fracture off during the laser crown debonding procedure. Subsequently, the remaining thin porcelain coping should be easy to remove.

CONCLUSION

With respect to laser all-ceramic crown removal, it was determined that sufficient Er:YAG laser energy was transmitted through LS_2 and zirconia crowns to debond those all-ceramic crowns. Ivoclar Vivadent E.max CAD and ZirCAD all-ceramic full contour crowns were easily laser debonded and removed. Although the bonding cement deteriorated due to the irradiation, no destruction, removal or alteration of the underlying remaining dentin was identified.

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