Effect of the combined zirconium dioxide surface treatment on the shear bond strength of a veneering ceramic to zirconium dioxide

Wpływ kondycjonowania powierzchni dwutlenku cyrkonu na zdolność wiązania ceramiki licowanej z dwutlenkiem cyrkonu

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Abstract

Background. Yttrium-stabilized tetragonal zirconia polycrystal (Y-TZP) is used as a core material in all-ceramic restorations. The delamination and chipping of a veneering ceramic are the most common complications in the case of zirconia-based restorations.

Objectives. The aim of the study was to investigate the effect of the combined treatment of the zirconium dioxide (ZrO₂) surface (airborne-particle abrasion with liner application) on the shear bond strength (SBS) of a veneering ceramic.

Material and methods. Thirty pre-sintered ZrO₂ cuboidal specimens (VITA YZ[®] HT) were sub-divided into 3 groups: group C consisted of 10 specimens without treatment at the sintering stage; group SZ₁ consisted of 10 specimens treated with airborne-particle abrasion (50-micrometer particles of aluminum oxide – Al₂O₃; Korox[®] 50), and then coated with a 0.1-millimeter liner (IPS e.max[®] Ceram ZirLiner) after sintering; group SZ₂ consisted of 10 specimens treated with airborne-particle abrasion (50-micrometer particles of Al₂O₃), and then coated with a 0.2-millimeter liner after sintering. Ceramic veneers (IPS e.max Ceram Dentin) were then applied using the layering technique. After that, the SBS tests were conducted.

Results. The results showed that the combined treatment of the ZrO₂ surface significantly affected SBS ($p < 0.01$). The highest mean value was shown in group C (12.441 ± 2.284 MPa), followed by group SZ₂ (7.889 ± 0.794 MPa), whereas the lowest mean value was observed in group SZ₁ (5.580 ± 0.843 MPa).

Conclusions. The combined treatment of the pre-sintered ZrO₂ surface significantly reduced the SBS of a veneering ceramic. However, the combined surface treatment with a liner thickness of 0.2 mm significantly enhanced the SBS of a veneering ceramic compared to the same combined treatment but with a liner thickness of 0.1 mm.

Key words: zirconium dioxide, ceramics, aluminum oxide

Słowa kluczowe: dwutlenek cyrkonu, ceramiki, tlenek glinu

Introduction

In restorative dentistry, metal-ceramic restorations have been used in fixed prosthodontic treatment for many years for preparing single crowns and fixed partial dentures. However, an increasing esthetic demand from patients and clinicians has led to a search for metal-free prosthodontic restorations.¹

As a result, various all-ceramic restorations have become available, such as lithium disilicate, infiltrated ceramics and – more recently – zirconium dioxide (ZrO_2 ; yttrium-stabilized tetragonal zirconia polycrystal – Y-TZP),² as they have great esthetic potential due to their improved optical properties, e.g., translucence, and the transmission and diffusion of light.³

The brittleness of these materials has led to an increased application of ZrO_2 -based ceramics, due to the fact that ZrO_2 exhibits mechanical properties that are most effective for producing restorations in the posterior oral region.⁴

The polycrystalline nature of Y-TZP reduces esthetic quality. Opaque ZrO_2 cores require the use of ceramic coatings with a high content of silica (SiO_2), such as feldspar, in order to enhance the esthetic properties of restorations.^{5,6}

Despite a high resistance to fracture exhibited by ZrO_2 -based restorations, the fracture of a veneer poses a problem. Clinical investigations have shown a greater percentage of failure (like chipping or delamination) of a veneering ceramic in restorations with ZrO_2 cores as compared to metal-ceramic restorations. Long-term clinical studies have concluded that bonding at the ZrO_2 –ceramic interface is weaker and adhesion is influenced by many factors, including improper design,⁷ a mismatch in the coefficient of thermal expansion (CTE),^{8,9} an improper technique of applying a ceramic veneer, and repeated firing cycles.¹ Other influencing factors comprise the rapid cooling of a ceramic veneer, which causes excessive residual tension within it, generating micro-fissures or leading to the debonding of a ceramic veneer in the presence of masticatory force.¹⁰ Delamination (adhesive failure) is more frequent than cases of chipping (cohesive failure). The reasons for that are poor interfacial adhesion and a great variation in mechanical properties between ZrO_2 and a veneering ceramic.^{11–13}

Various kinds of surface treatment and surface conditioning have been investigated to prevent the failure of a veneering ceramic.^{14–16} Each surface treatment technique refers to a single type of ZrO_2 surface treatment. To date, no technique has been recommended for optimal bonding between ZrO_2 and a ceramic veneer.

The objective of this study was to evaluate the effect of the combined treatment of the pre-sintered ZrO_2 surface on the shear bond strength (SBS) of a veneering ceramic. The null hypothesis tested was that the combined surface treatment of pre-sintered ZrO_2 has no effect on the SBS of a veneering ceramic.

Material and methods

Specimen preparation

Zirconium dioxide blanks (partially sintered Y-TZP, VITA YZ[®] HT; VITA Zahnfabrik H. Rauter GmbH & Co. KG, Bad Säckingen, Germany) were used to prepare 30 cuboidal specimens (3.687 mm in height, 19.664 mm in length and width) using a milling machine.¹⁷ Next, the specimens were randomly divided into 3 groups. Each group contained 10 specimens according to the applied ZrO_2 surface treatment. Group C contained 10 ZrO_2 specimens without treatment as a control group. Group SZ₁ contained 10 ZrO_2 specimens which were treated with airborne-particle abrasion and the application of a 0.1-millimeter-thick liner. Finally, Group SZ₂ contained 10 ZrO_2 specimens which were treated with airborne-particle abrasion and the application of a 0.2-millimeter-thick liner.

Group C

Ten ZrO_2 specimens were left without treatment after sintering (the control group). The ZrO_2 specimens were sintered in a furnace (VITA ZYRCOMAT[®] 6000 MS; VITA Zahnfabrik H. Rauter GmbH & Co. KG) according to the cycle recommended by the manufacturer (a high-speed sintering temperature of 1,450° for 80 min).

During sintering, the milled ZrO_2 specimens were subjected to volumetric shrinkage by about 20% based on the fact that the shrinkage factor for this type of ZrO_2 is 1.229. Following sintering, the dimensions of the specimens – approx. 3 ± 0.1 mm in height, and 16 ± 0.1 mm in length and width – were checked with a digital caliper.¹⁸ After sintering, the specimens were cleaned ultrasonically in distilled water in a digital ultrasonic cleaner (White-Sonic[®]; Whitepeaks Dental Solutions GmbH & Co. KG, Wesel, Germany) for 5 min to remove any surface residue, and then air-dried.

Group SZ₁

Ten ZrO_2 specimens were treated with airborne-particle abrasion (50-micrometer particles of aluminum oxide – Al_2O_3) (Korox[®] 50; Renfert GmbH, Hilzingen, Germany) before sintering, and then coated with a liner (IPS e.max[®] Ceram ZirLiner; Ivoclar Vivadent AG, Schaan, Liechtenstein) of a 0.1-millimeter thickness after sintering. According to the manufacturer, ZirLiner contains a glass ceramic and fluorapatite crystals ($\text{Ca}_5(\text{PO}_4)_3\text{F}$).

Airborne-particle abrasion was carried out before sintering. The working surfaces of the ZrO_2 specimens were abraded in the perpendicular direction (a 90° angle with the surface), with a crosswise motion of the nozzle at an air pressure of 0.5 bar for 15 s and a fixed distance of 10 mm between the nozzle and the surface of the specimen,

with 50-micrometer Al_2O_3 particles using a sandblasting device (EasyBlast[®]; BEGO, Bremen, Germany).¹⁹ Next, all the specimens were ultrasonically cleaned in distilled water for 5 min, and then air-dried. After that, sintering was carried out in a ZrO_2 sintering furnace (VITA ZYRCOMAT 6000 MS; VITA Zahnfabrik H. Rauter GmbH & Co. KG) according to the manufacturer's instructions.

For the standardization of the liner thickness (0.1 mm and 0.2 mm), a custom-made mold was fabricated. The mold consisted of a rigid base with 2 stainless steel metal straps: the 1st strap had a thickness of 0.1 mm and in its center there was a hole of a diameter of 4.5 mm; the 2nd strap had a thickness of 0.2 mm and the same 4.5-millimeter-diameter hole in the center. Through this hole, the standardization of the liner thickness was done on the surfaces of the ZrO_2 specimens. The liner was mixed with respective liquid (IPS e.max Ceram ZirLiner Build-Up Liquid allround; Ivoclar Vivadent AG). For standardization, the same amounts of powder and liquid were mixed for all specimens. For each specimen, 1 mg of powder was mixed with 2 drops of liquid to obtain the desired creamy consistency according to the manufacturer's instructions.¹⁷

Next, the liner was applied to the prepared surface using a brush; the brush was vibrated to achieve an even, greenish-color effect. Then, the liner was left to dry for 5 min.

When dry, the specimen was fired in a calibrated porcelain furnace (P3000; Ivoclar Vivadent AG) according to the manufacturer's instructions.

After firing, the thickness of each specimen was measured with a digital caliper with an accuracy of 0.02 mm in 3 different locations (the left end, the mid-point and the right end) and corrected with diamond rotary cutting instruments until the desired thickness of 3.1 mm (ZrO_2 + liner) was achieved.

Group SZ₂

Ten ZrO_2 specimens were treated with airborne-particle abrasion (50-micrometer particles of Al_2O_3) before sintering, and then coated with a 0.2-millimeter liner thickness after sintering. Airborne-particle abrasion was done before sintering, and the same procedure was performed as in group SZ₁. Next, the liner was applied according to the procedure mentioned for group SZ₁, except that the 0.2-millimeter strap was used in the custom-made mold.

Build-up of a ceramic veneer on the zirconium dioxide specimens

In order to build up a ceramic veneer on the ZrO_2 surface, a custom-made acrylic resin split cylindrical mold was fabricated.²⁰ The mold had 2 diameters (an outer diameter of 12.5 mm and an inner diameter of 4.5 mm) and was divided into 2 equal split parts with pins in the edge, through which the 2 parts of the mold were secured in position.

The mold was placed above the liner layer in the center of each specimen. The ceramic powder (IPS e.max Ceram Dentin A2; Ivoclar Vivadent AG) was mixed with an appropriate amount of respective liquid (IPS e.max Ceram Build-Up Liquid; Ivoclar Vivadent AG) according to the manufacturer's instructions. Then, the ceramic was added incrementally to the mold on the prepared ZrO_2 surface using the layering technique, condensing the ceramic material layer by layer. After each increment of the ceramic was placed, the excess moisture was removed with an absorbent paper tissue and the veneering procedure continued until the veneering ceramic measured 4 mm in thickness. The firing of the ceramic was performed according to the manufacturer's instructions. Due to the volumetric shrinkage which took place during the firing of the porcelain, additional porcelain was added following the abovementioned technique and was fired under the same conditions to achieve the desired dimensions of the ceramic (4.5 mm in diameter and 4 mm in length).¹⁸ After completing firing, the dimensions of the veneering ceramic were checked with a digital caliper, and then adjusted if needed using a straight headpiece. To evaluate SBS, each specimen was embedded in a silicon mold using cold-cured acrylic.²¹

Shear bond strength testing

Each specimen was attached to a universal testing machine (WDW-50; Laryee Technology Co., Ltd., Beijing, China). Load was applied to the specimen using a stainless steel chisel-shaped piston at a constant crosshead speed of 1 mm/min until failure. The specimen was regarded to be failed when the ceramic veneer was detached from ZrO_2 . The testing machine was automatically connected to computer software, which displayed the failure load force in newtons. The maximum force was recorded and SBS was calculated in megapascals by dividing the load force by the area of the bonded surface.

$$\text{SBS [MPa]} = \text{force [N]} / \text{bonded area [mm}^2\text{]} \quad (1)$$

where:

SBS – shear bond strength.

Scanning electron microscopy and energy-dispersive X-ray spectroscopy analyses

One failed specimen was selected from each group and cleaned in an ultrasonic cleaning bath for 5 min, and then air-dried. The interfacial surface was sputter-coated with gold. Next, the specimen was mounted on an aluminum holder and analyzed with secondary electrons. Images were observed under a field-emission scanning electron microscope (SEM) (Inspect S50; FEI Europe B.V., Eindhoven, the Netherlands) and photographs were taken at a magnification of $\times 200$ with an accelerating voltage of 20 KV to examine surface morphology.

The elemental composition of the same specimen at the fractured interfacial surface was qualitatively analyzed using energy-dispersive X-ray spectroscopy (EDS) and the weight percentage of each traced element was measured (XFlash[®] 6/10; Bruker Optik GmbH, Ettlingen, Germany). The mode of failure was examined under SEM at a magnification of $\times 29$; it was classified as:

- cohesive within the veneering ceramic;
- adhesive at the ZrO_2 –ceramic interface;
- or mixed.

The data was statistically analyzed using IBM SPSS Statistics for Windows, v. 21 (IBM Corp., Armonk, USA). The one-way analysis of variance (ANOVA) and the least significant difference (LSD) tests were applied to determine the significance of the differences between the groups. A p -value of ≤ 0.05 was considered statistically significant.

Results

The one-way ANOVA test showed that there was a highly significant difference ($p < 0.01$) in the mean value of SBS between the studied groups, as shown in Table 1. The highest mean value was shown in group C (12.441 ± 2.284 MPa), followed by group SZ_2 (7.889 ± 0.794 MPa), whereas the lowest mean value was observed in group SZ_1 (5.580 ± 0.843 MPa).

A further analysis of the data from the 3 groups was performed using the LSD test to examine the source of the differences between the tested groups. The LSD test showed a highly significant difference between group C and groups SZ_1 and SZ_2 . Likewise, the LSD test showed a highly significant difference between group SZ_1 and group SZ_2 .

The results for the failure modes after SBS testing are summarized in Table 2. The predominant mode of failure for groups SZ_1 and SZ_2 was cohesive, whereas mixed failure occurred in all groups in a low percentage. Adhesive failure was observed in group C in a high percentage, as shown in Fig. 1.

Table 1. Mean distribution of the shear bond strength (SBS) test among the tested groups

Group	n ($N = 30$)	$M \pm SD$ [MPa]	SE [MPa]	Range [MPa]		p -value
				min	max	
C	10	12.441 ± 2.284	0.722	9.52	15.97	0.0003*
SZ_1	10	5.580 ± 0.843	0.267	4.27	6.54	
SZ_2	10	7.889 ± 0.794	0.251	7.02	9.43	

Group C – control group (no treatment); group SZ_1 – airborne-particle abrasion + liner application (1 mm in thickness); group SZ_2 – airborne-particle abrasion + liner application (2 mm in thickness); M – mean; SD – standard deviation; SE – standard error; * statistically highly significant ($p < 0.01$); ANOVA.

Table 2. Modes of failure

Group	Adhesive failure n (%)	Cohesive failure n (%)	Mixed failure n (%)
C	5 (50)	2 (20)	3 (30)
SZ_1	1 (10)	9 (90)	0 (0)
SZ_2	1 (10)	7 (70)	2 (20)

Fig. 1. Modes of failure

A – adhesive failure; B – cohesive failure; C – mixed failure; magnification $\times 29$.

Surface morphology (SEM observation)

The SEM images of the specimens from group C revealed numerous scratch lines on the ZrO_2 surface with a thin layer of a veneering ceramic. These numerous scratch lines were produced by the milling machine

Fig. 2. Scanning electron microscope (SEM) images

A – group C; B – group SZ_1 ; C – group SZ_2 ; magnification $\times 200$.

during the preparation of the specimens (Fig. 2A). The images for group SZ₁ showed a rugged porous layer with areas of a veneering ceramic (Fig. 2B), whereas the SEM images for group SZ₂ revealed pronounced irregularities and rough texture, characterized by peaks and valleys (Fig. 2C).

Energy-dispersive X-ray spectroscopy

The chemical analyses within EDS were performed on the surface of the failed specimens after SBS testing. For group C, the elemental analysis showed the presence of Zr in the ceramic veneer layer and the elements characteristic of the veneering layer (mainly Si) in the ZrO₂ layer. The area of mutual diffusion between Zr and Si tended to increase. The EDS line-scan profile analysis showed the transition of the elements Na, Al, In, and P at the bonded interface of the Y-TZP specimens (Fig. 3).

Fig. 3. Energy-dispersive X-ray spectroscopy (EDS) and line-scan profile analyses for group C

The EDS analysis for groups SZ₁ and SZ₂ revealed that the remaining layers and the diffused particles on the surfaces contained SiO₂, Na, Al, K, and Ca, derived from the veneering ceramic and the liner material (Fig. 4,5).

Fig. 4. EDS and line-scan profile analyses for group SZ₁

Fig. 5. EDS and line-scan profile analyses for Group SZ₂

Discussion

Many factors may affect the SBS of a veneering ceramic to ZrO₂, such as the preparation of the surface, which may influence mechanical retention, the formation of flaws and structure defects at the ZrO₂–ceramic interface as well as the wetting properties and the volumetric shrinkage of the veneer.²² In addition, SBS may be affected by the residual stress generated by a mismatch in CTE.

The coefficients of thermal expansion for ZrO₂ and a veneering ceramic must closely match to obtain a strong interfacial bond. In the current study, the CTE of ZrO₂ ($10.5 \times 10^{-6} \text{ K}^{-1}$) was slightly higher than that of the veneering ceramic ($9.5 \times 10^{-6} \text{ K}^{-1}$). In case when the CTE of ZrO₂ is slightly higher than that of a veneering ceramic, beneficial residual compressive stress is created.^{23–25} An excessive difference in CTE may cause damage to a ceramic during cooling.

The ZrO₂ specimens were veneered using the layering technique. This technique is most widely used for applying veneering ceramics to the ZrO₂ surface.²⁶

The airborne-particle abrasion of the ZrO₂ specimens at the pre-sintering stage using 50-micrometer AL₂O₃ particles might be a favorable method of the surface treatment, as after sintering, the entire group treated at the pre-sintering stage showed a complete transformation of the monoclinic phase back to the tetragonal one, thus not subjecting ZrO₂ to early degradation.¹⁹ The objective of treating the ZrO₂ surface with airborne-particle abrasion is to create roughness and increase surface energy, and in consequence, to improve the strength of the bond with a veneering ceramic.

Liners are applied on the ZrO₂ surface mainly to mask its opaque white appearance before the application of a veneering ceramic and to enhance wettability, enabling the fabrication of lifelike restorations.^{27,28} ZirLiner is a ceramic liner; the manufacturer suggests that it enhances bonding with ZrO₂ and masks the opaque white color of ZrO₂. In a previous study, the application of ZirLiner alone did not improve the bonding of a ceramic veneer to the ZrO₂ surface.¹⁶

The results of this study rejected the null hypothesis, as the combined surface treatment of ZrO₂ resulted in a significant reduction ($p < 0.01$) in the SBS between the ZrO₂ surface and a veneering ceramic.

The highest mean SBS value appeared in group C (12.441 ± 2.284 MPa), followed by group SZ₂, and then SZ₁. The comparison between the groups using the one-way ANOVA showed highly significant differences with $p < 0.01$. The SEM images showed the bonded interface area and fracture surfaces with numerous porous defects for group SZ₁ (Fig. 2B). The formation of porosity and micro-gaps at the interface was a factor that reduced adhesion in the specimens through mechanical retention, which is comparable with the findings reported in the literature,^{6,12} where such formation occurred as well.

The comparison between group SZ₂ and group C showed a highly significant difference, which may be due to the fact that the liquid used for mixing the liner powder contained water. Tholey et al. provided an explanation for this; they found that ZrO₂ grains suffered from faceting (degradation) at the interface when adding a liner and a ceramic that was mixed with distilled water or liquid containing water at high firing temperatures.¹³ It is assumed that tensile stress was generated in ZrO₂ crystals due to the diffusion of water molecules, leading to lattice contraction and causing the transformation of the tetragonal phase to the monoclinic phase. This water-induced transformation could have an influence on ceramic failure in the clinical setting; however, the real effect is still unclear.⁹

The LSD test, performed to make comparisons between groups SZ₁ and SZ₂, showed a highly significant difference ($p < 0.01$) between the groups. Since the same roughening was used under the same conditions for both treated groups and nearly the same rough surface was obtained for both groups, the difference in SBS might be related to the different liner thicknesses applied. When the comparison between the SEM images for both groups was made, it turned out that the application of a 0.1-millimeter liner thickness yielded numerous porous defects (Fig. 2B). This indicated that the liner did not penetrate the irregular surface formed by sandblasting. However, applying a 0.2-millimeter liner thickness to the interface area (Fig. 2C) showed a reduction in the number and size of pores and defects. This indicates that the application of an increased liner thickness improves the wettability of the rough ZrO₂ surface produced by means of sandblasting.

In the present study, the analysis of the failure modes showed that the majority of the specimens exhibited combined failure or cohesive failure at a high percentage, whereas adhesive failure occurred at a low percentage, except for group C, which showed an adhesive mode of failure of 50%. This group revealed a high SBS value, whereas lower SBS values were recorded when failure occurred cohesively within a weak veneer material. The results of this study concur with those of Ereifej et al.²⁹ They stated that the samples which failed cohesively within a veneer presented low SBS values, whereas those having a mixed cohesive/adhesive fracture pattern or a cohesive fracture within the core showed higher SBS values.²⁹

The SEM observation for group C revealed that the residual veneer layer which remained on the surface of the ZrO₂ substructure was thin with a partial exposure of the ZrO₂ surface, indicating that the crack extended along the ZrO₂–ceramic interface (Fig. 2A). Thus, it can be concluded that the strength of the bond between ZrO₂ and the veneering ceramic was higher than the cohesive strength of the veneering ceramic. It means that the weakest link was not the interface, but the veneering ceramic itself.

It was also reported that the development and propagation of delamination was related to the mismatches in the elastic modulus and fracture toughness of ZrO₂ and porcelain.

A higher fracture toughness of ZrO_2 might induce a deflection of crack propagation from within the porcelain to along the core–veneer interface.³⁰ On the other hand, the results for groups SZ₁ and SZ₂ showed that the bond failure was predominantly cohesive or mixed. This may be due to performing sandblasting before sintering, which is illustrated by the shift of the failure modes, from mixed to cohesive.¹⁸

One of the limitations of this study was that the specimen design did not represent the clinical geometry of a ZrO_2 ceramic restoration. The study provided design that allowed for the SBS testing procedure.

In addition, the oral environment was not simulated with thermocycling, so further research is required to investigate its effect together with the combined surface treatment.

Conclusions

Within the limitations of the present in vitro study, both kinds of combined surface treatment studied significantly reduced the SBS of a veneering ceramic in comparison with the control group without treatment. The combined surface treatment of pre-sintered ZrO_2 using airborne-particle abrasion and liner application (0.2-millimeter thickness) significantly enhanced the SBS of a veneering ceramic to ZrO_2 as compared to the same combined treatment but with a liner thickness of 0.1 mm.

According to the results of the present study, creating the mechanical retention (scratch lines) of the ZrO_2 surface with a milling machine, as in the control group without air-abrasion and liner application, may be recommended for future research.

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References

- Aboushelib MN, de Jager N, Kleverlaan CJ, Feilzer AJ. Microtensile bond strength of different components of core veneered all-ceramic restorations. *Dent Mater.* 2005;21(10):984–991.
- Tinschert J, Natt G, Mautsch W, Augthun M, Spiekermann H. Fracture resistance of lithium disilicate-, alumina-, and zirconia-based three-unit fixed partial dentures: A laboratory study. *Int J Prosthodont.* 2001;14(3):231–238.
- Vidotti HA, Pereira JR, Insaurralde E, Pompéia Fraga de Almeida AL, do Valle AL. Thermo and mechanical cycling and veneering method do not influence Y-TZP core/veneer interface bond strength. *J Dent.* 2013;41(4):307–312.
- Martínez-Galeano G, Bautista-Lora A, Pacheco-Muñoz LF, Garzón-Rayó H. Liner effect on the bond strength of feldspathic ceramic to zirconia using a slow cooling protocol. *Rev Fac Odontol Univ Antioq.* 2015;27(1):63–75.
- Guess PC, Schultheis S, Bonfante EA, Coelho PG, Ferencz JL, Silva NR. All-ceramic systems: Laboratory and clinical performance. *Dent Clin North Am.* 2011;55(2):333–352.
- Dündar M, Özcan M, Gökçe B, Cömlekoğlu E, Leite F, Valandro LF. Comparison of two bond strength testing methodologies for bilayered all-ceramics. *Dent Mater.* 2007;23(5):630–636.
- Marchack BW, Futatsuki Y, Marchack CB, White SN. Customization of milled zirconia copings for all-ceramic crowns: A clinical report. *J Prosthet Dent.* 2008;99(3):169–173.
- Fischer J, Stawarczyk B, Tomic M, Strub JR, Hämmerle CH. Effect of thermal misfit between different veneering ceramics and zirconia frameworks on in vitro fracture load of single crowns. *Dent Mater J.* 2007;26(6):766–772.
- Daou EE. Bonding mechanism of porcelain to frameworks: Similarities and dissimilarities between metal and zirconia. *Br J Med Med Res.* 2016;16(3):1–16.
- Swain MV. Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures. *Acta Biomater.* 2009;5(5):1668–1677.
- Ozkurt Z, Kazazoglu E, Unal A. In vitro evaluation of shear bond strength of veneering ceramics to zirconia. *Dent Mater J.* 2010;29(2):138–146.
- Guess PC, Kulis A, Witkowski S, Wolkewitz M, Zhang Y, Strub JR. Shear bond strengths between different zirconia cores and veneering ceramics and their susceptibility to thermocycling. *Dent Mater.* 2008;24(11):1556–1567.
- Tholey MJ, Swain MV, Thiel N. SEM observations of porcelain Y-TZP interface. *Dent Mater.* 2009;25(7):857–862.
- Alghazzawi TF, Janowski GM. Effect of liner and porcelain application on zirconia surface structure and composition. *Int J Oral Sci.* 2016;8(3):164–171.
- Wang G, Zhang S, Bian C, Kong H. Interface toughness of a zirconia–veneer system and the effect of a liner application. *J Prosthet Dent.* 2014;112(3):576–583.
- Jabbar MK, Dulaimi SF. Effect of liner thickness and sandblasting of zirconia on the shear bond strength of veneering ceramic. *JODR.* 2018;5(2):40–51.
- Kareem IH, Al-Azzawi HJ. Effect of zirconia surface treatments on the shear bond strength of veneering ceramic. *J Bagh Coll Dent.* 2014;26(3):13–17.
- He M, Zhang Z, Zheng D, Ding N, Liu Y. Effect of sandblasting on surface roughness of zirconia-based ceramics and shear bond strength of veneering porcelain. *Dent Mater J.* 2014;33(6):778–785.
- Ebeid K, Willie S, Salah T, Wahsh M, Zohdy M, Kern M. Evaluation of surface treatments of monolithic zirconia in different sintering stages. *J Prosthodont Res.* 2018;62(2):210–217.
- Saka M, Yuzugullu B. Bond strength of veneer ceramic and zirconia cores with different surface modifications after microwave sintering. *J Adv Prosthodont.* 2013;5(4):485–493.
- Kirmali O, Akin H, Ozdemir AK. Shear bond strength of veneering ceramic to zirconia core after different surface treatments. *Photomed Laser Surg.* 2013;31(6):261–268.
- Aboushelib MN, Kleverlaan CJ, Feilzer AJ. Microtensile bond strength of different component of core veneered all-ceramic restorations. Part II: Zirconia veneering ceramics. *Dent Mater.* 2006;22(9):857–863.
- Craig RG, Powers JM, Wataha JC. *Dental Materials: Properties and Manipulation.* 8th ed. St. Louis, USA: Mosby; 2004:578–580.
- Aboushelib MN, Kleverlaan CJ, Feilzer AJ. Effect of zirconia type on its bond strength with different veneer ceramics. *J Prosthodont.* 2008;17(5):401–408.
- Alsarani M, De Souza G, Rizkalla A, El-Mowafy O. Influence of crown design and material on chipping-resistance of all-ceramic molars crowns: An in vitro study. *Dent Med Probl.* 2018;55(1):35–42.
- Gaspari L, Schaperl Z, Mehulić K. Shear bond strength in zirconia veneered ceramics using two different surface treatments prior veneering. *Coll Antropol.* 2013;37(1):121–125.
- Liu RY, Zhang YK, Zhou SY, et al. The effect of liner thickness on the color of Y-TZP based all-ceramic restorations. *Key Eng Mater.* 2013;544:380–383.
- Lee HS, Kwon TY. The application of a novel ceramic liner improves bonding between zirconia and veneering porcelain. *Materials (Basel).* 2017;10(9):1023.
- Ereifej N, Rodrigues FP, Silikas N, Watts DC. Experimental and FE shear-bonding strength at core/veneer interfaces in bilayered ceramics. *Dent Mater.* 2011;27(6):590–597.
- Liu D, Matinlinna JP, Pow EHN. Insights into porcelain to zirconia bonding. *J Adhes Sci Technol.* 2012;26(8–9):1249–1265.