Retention and marginal integrity of CAD/CAM fabricated crowns adhesively cemented to titanium base abutments – influence of bonding system and restorative material

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ABSTRACT

Purpose: To assess the influence of bonding system and restorative material on the marginal integrity and pull-off forces of monolithic all-ceramic crowns bonded to titanium base (Ti-base) abutments. Materials and Methods: A total of 108 Ti-bases were sandblasted and divided into 9 experimental groups (n = 12 each) according to the combination of crown material (polymer-infiltrated ceramic network [PI], lithium disilicate [LD], and zirconia [ZI]) and bonding system (Multilink Hybrid Abutment [mh], PANAVIA V5 [pv], RelyX Ultimate [ru]), with their respective primers. After bonding the crowns to the Ti-base abutments, the restorations were screw-retained on implants and thermomechanically aged (1,200,000 cycles, 49 N, 1.67 Hz; 5°C to 55°C). Marginal integrity and bonding failure were evaluated under a light microscope, and pull-off forces (N) were calculated. Chi-square tests for marginal integrity, as well as one-way and two-way ANOVA for the pull-off forces, were applied (α = .05). Results: PI presented higher marginal integrity than LD (P = .023). The bonding system pv revealed higher marginal integrity than mh (P = .005) and ru (P = .029). Differences in pull-off forces were found between restorative material and resin cement (P < .001), with the highest values for ZI + ru (598 ± 192 N), PI + pv (545 ± 114 N), LD + mh (532 ± 116 N), and PI + ru (528 ± 81 N). Specimens with marginal integrity revealed higher pull-off forces than those with alteration (P = .006). Specimens presenting bonding failures (micromovements) showed lower pull-off forces than those without bonding failures (P < .001). Conclusion: The tested CAD/CAM materials show favorable bonding performances with different bonding systems; nevertheless, a specific bonding system has to be recommended for each restorative material. Int J Prosthodont 2022. doi: 10.11607/ijp.7576
INTRODUCTION

The concept of CAD/CAM hybrid-abutment crowns, in which the crown is adhesively cemented directly to a prefabricated titanium base (ti-base) abutment and then directly screw-retained onto the implant, is becoming increasingly popular due to its implementation in digital workflows (1). These recent developments allow a fully digital data collection, design, and fabrication of the restorations, in a dental laboratory as well as chairside.

Although short-term clinical results of ti-base implant-supported restorations were promising (2–4), some doubts have been raised on the bonding stability of this type of restorations. Two laboratory investigations reported losses of retention of crowns from the ti-base abutments after a simulation of 5 years of clinical use (5, 6). In addition, some of the crowns that did not lose retention revealed the presence of marginal gaps and micro-movements between the two components (6).

For stable long-term results of hybrid-abutment crowns, good stability of the interface for bonding is desired. The bonding to titanium, ceramics, and hybrid ceramics has been widely investigated, and well-defined protocols for a reliable micro-mechanical and chemical bonding have been proposed (7, 8). However, most of the studies evaluating the bonding forces used shear or tensile bond strength tests on flat surfaces and did not consider the geometric aspects of a ti-base abutment. The height of the prosthetic part may provide additional mechanical stability and retention (9, 10). Other parameters may influence the long-term bond stability between the abutment and the all-ceramic crown in a clinical scenario. Functional load during chewing and temperature changes may result in thermo-mechanical stresses on the crown-abutment unit and may contribute to a degradation of the bond interface (11, 6, 12).

Currently, there are several restorative materials available in form of prefabricated ingots for the use in combination with ti-base abutments. In addition to their adhesive
mechanisms, the materials differ in their mechanical characteristics such as the elastic modulus, resulting in different degrees of plastic deformation and energy absorption (13).

At the ti-base abutments, the adhesive joint is located under the mucosa to avoid titanium visibility in different clinical situations. This might entail biological risks as the bond interface is displaced subgingivally and in case of degradation, a higher bacterial accumulation may be expected (14). Moreover, the marginal misfit of implant crowns leads to more crestal bone loss than accurately fitting crowns (15). As the ti-base concept is rather recent, more research is needed on these parameters to define this concept’s indications and limitations.

Therefore, the present study aimed to assess the influence of the bonding system and the restorative material on the marginal integrity and the pull-off forces of maxillary incisor monolithic CAD-CAM crowns bonded to ti-base abutments after thermal and mechanical aging. The following null hypotheses were defined: (1) the bonding system and the restorative material do not affect the external marginal integrity of the interface between ti-base abutments and crowns; (2) the bonding system and the restorative material do not affect the pull-off force between ti-base abutments and crowns.

**MATERIAL AND METHODS**

**Tested Materials**

The following restorative materials were used: (PI) polymer-infiltrated ceramic-network (VITA Enamic IS 16S, Vita Zahnfabrik) (LD) lithium disilicate (IPS e.max CAD Cerec/inLab LT A2 A16(S), Ivoclar Vivadent AG) and (ZR) 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) (CEREC Zirconia Meso S, Dentsply Sirona). To bond the crowns on the commercially available ti-base abutments (Conelog Titanium Base 4.3 mm GH 2.0 mm, CAMLOG Biotechnologies GmbH), the following bonding systems
were used: (mh) Multilink Hybrid Abutment (shade HO 0) (Ivoclar Vivadent AG) with Monobond Plus (Ivoclar Vivadent AG), (pv) Panavia V5 (shade Opaque) (Kuraray Co.) with Clearfil Ceramic Primer Plus (Kuraray Co.) and (ru) RelyX Ultimate (shade A3O) (3M) with Scotchbond Universal (3M).

Nine groups were defined according to the different restorative material and bonding system (Table 1).

**Preparation of specimens**

One-hundred eight conical connection titanium implants (Conelog, CAMLOG Biotechnologies GmbH) with 4.3 mm in diameter and 16 mm in length were used for the study. The implants were fixed in a standardized way in acrylic resin blocs and embedded with self-curing acrylic (Technovit 4071, Haraeus Kulzer) according to the ISO Norm 14801 (16) with 3 mm of the implants rough surface exposed to simulate bone loss.

All restorative materials were milled from ingots with an industrially prefabricated channel for the ti-base abutment to ensure standardized fit as provided by the manufacturers. Crystallization firing of the lithium disilicate and sintering of the milled zirconia crowns were performed according to the manufacturers’ specifications.

The design and fabrication procedures of the maxillary central incisor abutment-crowns have been published in detail in a previous publication (11). A modification was introduced by moving the cervical horizontal ring 1 mm coronally from the margin of the ti-base abutments (Fig 1). This modification allowed for controlled removal and polishing of the excess cement and the subsequent microscopical analysis of the external marginal gap.

**Bonding Crowns to Ti-Bases**

The ti-base abutments received a standardized airborne-particle abrasion pre-treatment with 50 μm aluminium-oxide (Cobra Aluoxyd, Renfert) at 2.5 bar air pressure with a 45-degree angle of incidence for 10 seconds (Fig 2) (11, 17). The lithium disilicate crowns were
etched with 5% hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar Vivadent AG) for 20 seconds, the polymer-infiltrated ceramic-network crowns were etched with 5% hydrofluoric acid (VITA CERAMICS ETCH, Vita Zahnfabrik) for 60 seconds, and the zirconia crowns were airborne-particle abraded with 50 µm aluminium-oxide at 2.5 bar air pressure.

All crowns and ti-base abutments were cleaned with alcohol in an ultrasonic bath (Micro 10+, Unident SA) for 4 minutes and dried with oil-free air after their respective pre-treatment. The corresponding primer for each bonding system was applied to the adhesive surface of the ti-base abutments and the crowns were bonded following the manufacturers’ specifications. During the hardening of the cement, the reconstructions were fixed with the force of finger pressure. A slight excess cement was left on the external margin and covered with glycerin gel to allow for complete polymerization. All specimens were left for auto-polymerization. No light-polymerization was conducted due to the different light-transmitting properties of the materials and the increased material thickness. After polymerization, the excess cement was removed and polished with a polishing set (Enamic Polishing Set, Vita Zahnfabrik).

The crowns were screw-retained onto the implants with 20 Ncm, and the access channels were closed with a polytetrafluoroethylene tape (Teflon, Chemours Co.) and a light-polymerization composite (Tetric EvoCeram, Ivoclar Vivadent AG).

**Marginal Gap Width Evaluation**

External marginal gap width (µm) (18) was measured vertically between the ti-base abutment and the crowns under a digital light microscope (200×) (VHX-6000, Keyence) after surface pre-treatment to verify a consistent adaptation among the specimens before bonding was performed (Fig 3).

**Marginal Integrity Analysis**
Analysis of the marginal integrity was performed before and after aging under a digital light microscope (200×) (VHX-6000, Keyence), and images of each specimen were registered in JPG format. The interproximal, oral and buccal sites were marked with a diamond drill on the titanium surface (Figs 4-5). Observed changes in the external margin after aging (e.g. fractures, crack lines, or gaps) were registered as alteration, while no changes were registered as integrity (alteration = 0; integrity = 1). The sum of the integrity for the 3 sites was calculated from 0 to 3, where 0 represents no marginal integrity and 3 full marginal integrity for each specimen. Specimens with a sum = 3 were classified as having full marginal integrity.

Aging

Aging was performed using chewing simulation (1,200,000 cycles; load: 49 N) and simultaneous thermocycling (5 °C to 55 °C; dwell time: 120 seconds) (Chewing Simulator CS-4.4, SD Mechatronik GmbH) with the specimens at a 30-degree angulation. Steatite balls were used as antagonists. Survival and mechanical integrity of the specimens was assessed after completing the aging procedure.

Bonding Failure Analysis

After aging, specimens were examined to detect loss of retention or presence of macro- or micro-movement between the crown and ti-base abutment. This examination was performed independently by 3 examiners (JP, FB, VF). A macro-movement was registered when a movement of the crown on the ti-base was perceptible with the naked eye. If no macro-movement was detected, specimens were additionally examined with aid of a light microscope (50×) (Olympus SZX9, Olympus) for detection of micro-movements (Pitta et al. 2020 JPD).

Pull-off Test
Pull-off forces (N) were measured in a universal testing machine (Shimadzu AGS-X series, Shimadzu) with a 10-kN load cell at a crosshead speed of 0.5 mm/min. An individualized holder was used to assure an axial pull-off force of the crown from the ti-base abutment. Maximum pull-off forces were recorded with a software (TRAPEZIUM X, V.1.4.4, Shimadzu). Failure modes were classified in type 1 - cement remained mostly on the abutment surface (> 90%), type 2 - cement remained on both abutment and crown surfaces (between 10-90%), type 3 - cement remained mostly on the crown (> 90%).

**Statistical analysis**

The collected data were statistically analyzed with dedicated software (IBM SPSS Statistics v25; IBM Corp). External marginal gap width and pull-off forces were tested using a Shapiro-Wilk test, to show a normal distribution for all. External marginal gap width mean values were calculated for each restorative material, and differences between the materials were analyzed using one-way ANOVA. Marginal integrity and bonding failure were analyzed using Chi-square tests. Student T-test, one-way ANOVA, or two-way ANOVA, followed by Tukey HSD post-hoc tests, were used to analyze differences in pull-off forces between groups. Significance level was set at $\alpha = .05$. Failure modes were evaluated descriptively.
RESULTS

Marginal Gap Width

The mean marginal gap width before bonding was 11.0 ± 1.48 µm for ZI, 13.0 ± 2.41 µm for PI and 15.25 ± 2.22 µm for LD, revealing significant differences of PI to LD and ZI (p < .001).

Marginal Integrity

Marginal integrity revealed to be significantly more frequent in buccal sites than interproximal sites (p < .001), while interproximal sites revealed more frequent marginal integrity than oral sites (p = .03). Moreover, percentage of specimens with full marginal integrity varied between 0% (T3; T4) and 92% (T2) per group, with significant differences found among the groups (p < .001) (Table 2).

When comparing the restorative materials, PI presented significantly more frequent full marginal integrity than LD (p = .023), but no difference was found between PI and ZI (p = .052) neither between LD nor ZI (p = .772).

When comparing the bonding system, “pv” revealed significantly more frequent full marginal integrity than “mh” (p = .005) and “ru” (p = .029). However, no differences could be found between “mh” and “ru” (p = .453).

Bonding Failures

After aging no fractures were detected at crown or abutment level. Moreover, no loss of retention or macro-movement was found between ti-base abutment and crown. Nevertheless, micro-movements could be detected. The percentage of bonding failures (micro-movements) varied from 0% (T2; T3) to 92% (T7) and the differences among the groups were statistically significant (p < .001). When analyzed by restorative material, PI showed significantly less micro-movements compared to LD and ZI (p = .002), while LD and ZI did not show significant differences between them (p > .05). Concerning the bonding
systems, “ru” revealed less micro-movement than “mh” (p < .001) and “pv” (p < .001). The bonding system “pv” has less micro-movements than “mh” but the difference is not significant (p > .05) (Table 3).

There was a significant association between integrity and bonding failure (p > .05). 95% of the specimens with full marginal integrity did not present any bonding failures whereas 61% of the specimen with marginal alteration of at least one site showed bonding failures.

**Pull-off Testing**

There were significant differences in pull-off force mean values between the different groups of restorative materials and bonding systems (p < .001) (Table 2). A strong interaction between restorative materials and bonding systems was found (p < .001) (Fig 6).

Pull-off forces mean values of groups T9 (ZI+ru), T4 (LD+mh), T2 (PI+pv) and T3 (PI+ru) ranged between 598 – 528 N and showed to be significantly higher than group T1 (PI+mh) (367 N). Values of groups T6 (LD+ru), T5 (LD+pv), T7 (ZI+mh) and T8 (ZI+pv) varied between 211 – 124 N and showed significantly lower values to all the previous mentioned groups (α = .05) (Fig 6).

Specimens with full marginal integrity revealed significantly higher pull-off forces (476 ± 189 N) when compared with specimens with marginal alteration (336 ± 207 N) (p = .006). Moreover, specimens presenting bonding failures revealed significantly lower pull-off forces (241 ± 170 N) than specimens without bonding failures (487 ± 171 N) (p < .001).

**DISCUSSION**

The present study showed that the marginal integrity as well as the pull-off forces were significantly influenced by the different restorative materials and by the different bonding system. Therefore, the two null hypotheses were rejected.
Uniform marginal gap adaptation of the crowns was verified before cementation, showing a range between 11 and 15.25 µm for the different materials. Even if the measurements revealed statistical differences between polymer-infiltrated ceramic-network and the other restorative materials, these results demonstrate a very good adaptation when compared to values ranging from 14 to 168 µm reported in the literature for all-ceramic restorations on implant abutments (19-21). Hence, it can be assumed that the differences in the current study are not clinically relevant.

Crack lines were found in the cement gap in a variety of specimens, with higher incidence in the oral aspects. This may be explained by the 30-degrees specimen angulation used in the chewing simulator, which resulted in tensile forces in the oral aspect and compressive forces in the buccal aspect. Although different resin cements were used, marginal degradation was frequently found for all the tested bonding systems. This finding confirms the results of a previous study which showed marginal degradation when resin cements were used (22). Other authors have also demonstrated the negative effect of thermocycling on the bond interface (23). In the present investigation an extended aging protocol combining simultaneous mechanical loading and thermocycling was applied.

Even though no macro-movements or loss of retentions were found after aging, a considerable number of micro-movements of the crowns towards the abutments could be registered. Micro-movements were suggested to be a possible first sign of debonding (6, 11). This hypothesis may be corroborated by the decreased pull-off force values found for specimens with marginal alteration and with bonding failures in the current investigation. With continued loading, the bonding interface may be progressively and negatively affected, hypothetically resulting in a decrease of the retention forces. No literature was found to underline this finding, but it seems to be different to results on tooth borne restorations where no such correlation could be found (24, 25). Mechanically, the frequent bonding failures
observed in the present study could also be justified by the limited crown/abutment height ratio. It is likely that restorations with increased abutment height could reduce the risk for debonding, as the bonding surface is increased, and the crown might be stabilized better against non-axial forces during mechanical loading (9, 10, 26, 27, 28, 29). In the present study, the anatomic design of the crown would have allowed the use of a ti-base abutment height of approximately 10 mm, which hypothetically could have given increased support and increased bond stability. Unfortunately, no such ti-base abutment height is currently available for the use with prefabricated ingots in a chair-side workflow.

Regarding the tested restorative materials, it was noticeable that the polymer-infiltrated ceramics network crowns were generally more resistant to marginal alteration and less prone to exhibit micro-movements. This improved marginal integrity and bond interface performance could be explained by the fact that this material has a higher elastic modulus (30) and may absorb more energy which leads to an increased damping of occlusal forces than oxide or silicate ceramics (31). This observation was also confirmed in another recent investigation (12).

The results of the pull-off forces showed increased values (over 500 N) for the three different restorative materials depending on the bonding system used. None of the bonding systems performed generally better than the others at all materials, which means that for each restorative material a different bonding system may be recommended. Even though, the primers of the three tested bonding systems contained silane, which is proven to be beneficial in adhesion to silicate ceramics (32), and 10-methacryloyloxydecyl-dihydrogen-phosphate (10-MDP) that is essential for a durable bond to zirconia and to titanium (33, 34), their performance diverged significantly (35). A possible explanation might be related to the different primer compositions, concentrations and chemical formulations in each bonding system (36).
The standardization of the testing conditions is one of the strengths of the current investigation. It has been shown that insufficient standardization leads to a larger dispersion of the pull-off forces (37). Parameters of the specimen fabrication were kept as constant as possible by using a standardized airborne-particle abrasion device (11), ingots with a prefabricated channel to fit the ti-base abutment, and auto-mixing cement syringes to provide controlled mix of the cements. Marginal gap width has been demonstrated to have a significant influence on the retention of crowns on abutments (38), which in this study was controlled by an external marginal gap width evaluation prior to bonding.

A possible limitation of this study is the bulky design of the crowns, which did not allow for light-polymerization and consequently a higher degree of conversion for dual-polymerization bonding systems (39). Future research should focus on the geometry, especially on the influence of the height of ti-base abutments on the long-term stability of this type of implant restorations.

CONCLUSIONS

The novel CAD/CAM materials show favorable bonding performances with different bonding systems, nevertheless for each restorative material a specific bonding system has to be recommended, as none of the systems performed equally good with each of the different materials. Clinical long-term evaluations are needed to determine the clinical effect of using different cements.

ACKNOWLEDGMENTS

The authors would like to thank to Eng. Eric Vittecoq (HEPIA Genève) for his support in developing the pull-off test set-up. The authors also thank to Oral Reconstruction Foundation (ORF21802) for funding the study and Camlog Biotechnologies GmbH, Ivoclar

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Vivadent AG, Dentsply Sirona and VITA Zahnfabrik for the support with their respective material.

REFERENCES


Fig 1: Design and dimensions (mm) of a specimen.

Fig 2: Standardized airborne-particle abrasion device with a 45-degree angle of incidence.
Fig 3: Marginal gap width evaluation before bonding. (specimen in photo: LD)

Fig 4: Marginal integrity analysis, before (left) and after aging (right) with marginal integrity
(specimen in photo: group T2 (PI + pv))

Fig 5: Marginal integrity analysis, before (left) and after aging (right) with visible alteration
(specimen in photo: T8 (ZI + pv))
Fig 6: Interaction between the restorative material (PI: polymer-infiltrated ceramic-network; LD: lithium-disilicate; ZI: zirconia) and the bonding system (blue: Multilink Hybrid-Abutment; red: Panavia V5; green: RelyX Ultimate) on the pull-off forces, significant different pull-off forces means (P < .05) are indicated by different uppercase letters.