Purpose: To evaluate the effect of cementation protocols on the bonding interface stability and pull-out forces of temporary implant-supported crowns bonded on a titanium base abutment (TiB) or on a temporary titanium abutment (TiA).

Materials and Methods: A total of 60 implants were restored with PMMA-based CAD/CAM crowns. Five groups (n = 12) were created: Group 1 = TiB/SRc: crown conditioned with MMA-based liquid (SR Connect, Ivoclar Vivadent); Group 2 = TiB/50Al-MB: crown airborne particle-abraded with 50-µm Al₂O₃ and silanized (Monobond Plus, Ivoclar Vivadent); Group 3 = TiB/30SiOAl-SRc: crown airborne particle-abraded with 30-µm silica-coated Al₂O₃ (CoJet, 3M ESPE) and conditioned with MMA-based liquid (SR Connect); Group 4 = TiB/30SiOAl-MB: crown airborne particle-abraded with 30-µm silica-coated Al₂O₃ (CoJet) and silanized (Monobond Plus); and Group 5 = TiA/TA-PMMA: crown manually enlarged, activated, and rebased with PMMA resin (Telio Lab, Ivoclar Vivadent). Specimens in the TiB groups were cemented using a resin cement (Multilink Hybrid Abutment, Ivoclar Vivadent). After aging (120,000 cycles, 49 N, 1.67 Hz, 5°C to 55°C, 120 seconds), bonding interface failure was analyzed (50x). Pull-out forces (N) (0.5 mm/minute) and modes of failure were registered. Chi-square and Kruskal-Wallis tests were used to analyze the data (α = .05).

Results: Bonding failure after aging varied from 0% (Group 5) to 100% (Groups 1, 2, and 4) (P < .001). Mean pull-out force ranged between 53.1 N (Group 1) and 1,146.5 N (Group 5). The pull-off forces were significantly greater for Group 5 (P < .05), followed by Group 3 (P < .05), whereas the differences among the remaining groups were not significant (P > .05).

Conclusion: The cementation protocol had an effect on the bonding interface stability and pull-out forces of PMMA-based crowns bonded on a titanium base. Airborne particle abrasion of the crown internal surface and conditioning it with an MMA-based liquid may be recommended to improve retention of titanium base temporary restorations. Yet, for optimal outcomes, conventional temporary abutments might be preferred.
implant temporary titanium abutments either by the dental technician or clinician. This is a time-consuming and handcrafted process that is highly susceptible to human error. 

Recent improvements in digital dental technology, however, have provided alternatives that are able to compensate for some of these provisional materials’ shortcomings. Namely, CAD/CAM technology has enabled the fabrication of restorations from preprocessed thermoplastic and thermostet resin blocks, with rather promising features. Controlled and standardized manufacturing processes of CAD/CAM resin blocks at a high temperature and pressure have enhanced their mechanical properties, color stability, and marginal accuracy, but at the same time, adversely affected their reparable. The latter property is important when the surface requires modification for esthetic or cementation purposes.

Among other types, CAD/CAM PMMA blocks with pre-milled screw-access channels are available for implantology purposes. The role of the channel is to fit on the titanium base abutment (TiB). TiBs are prefabricated pieces connecting the implant and superstructures. In vitro investigations have demonstrated that TiBs provide an enhanced mechanical stability, regardless of whether they are combined with ceramic or temporary resin material. However, loss of retention of a TiB-supported temporary restoration is a clinically encountered problem that has not been addressed thus far. A TiB-related cementation protocol and its associated problems, particularly for temporary restorations, have scarcely been explored. Theoretically, the cement and material type of the temporary restoration, as well as the abutment geometry and configuration, could all affect the retention of the temporary implant-supported restoration. The height and geometry of the TiB are abutment-related independent factors (uncontrollable by the clinician) that could affect the restoration retention and fit, whereas surface treatment of the abutment surface and the crown and cement type are some dependent variables (controllable by the clinician) that could additionally influence the stability of the superstructure.

Therefore, the aim of this in vitro study was to evaluate the effect of various cementation protocols on the bonding interface stability and pull-out forces of PMMA-based CAD/CAM temporary implant-supported single crowns bonded on a TiB or on a temporary titanium abutment (TiA) after artificial thermomechanical aging. The null hypotheses were: (1) the type of surface treatment of the PMMA crown inner surface would not affect the bonding interface stability or the axial pull-out forces of temporary crowns bonded to TiBs; and (2) the bonding interface stability and the axial pull-out forces of PMMA crowns would not be different on a TiB compared to a TiA.

MATERIALS AND METHODS

Sixty temporary crowns were fabricated from a PMMA-based unfilled CAD/CAM block (Telio CAD CER/inLAB LT A16 [S], Ivoclar Vivadent) using a milling unit (CEREC MC XL, Dentsply Sirona). The crown outer shape and design were the same as previously used, while the internal fit was defined by the pre-milled channel of the block. Five groups (n = 12) were established; in four groups, TiBs (CONELOG Titanium Base CAD/CAM crown, gingival height 2.0 mm, Camlog) were tested, and in one group, a conventional TiA (CONELOG Temporary Abutment crown, Camlog) was used as a control. Sample size calculation was done based on a previous study applying a similar methodology.

The temporary abutments were cut at the level of the screw-access channel of the crown. The final height obtained was 9 mm. The TiB did not need any adjustment and presented a bonding height of 4.7 mm.

All abutments (TiBs and TiAs) were airborne particle-abraded with 50-μm Al2O3 particles (Cobra Aluoxyd, Renfert) for 20 seconds at a pressure of 2.5 bar and from a distance of 10 mm, cleaned in an ultrasonic alcohol bath (Micro 10+, Unident Swiss) for 4 minutes, and silanized (Monobond Plus, Ivoclar Vivadent) for 60 seconds. Subsequently, the surfaces were gently air dried with oil-free air, and the crowns were cemented or rebased on the respective abutments according to their group. The materials used and their respective compositions are described in Table 1.

The groups were:

- **Group 1 (TiB/SRc):** The internal surfaces of the crowns were conditioned with a methyl methacrylate (MMA)-based liquid (SR Connect, Ivoclar Vivadent) for 30 seconds, gently air dried, and immediately light polymerized for 40 seconds (Bluephase, Ivoclar Vivadent). The crowns were then cemented using a resin cement (Multilink Hybrid Abutment, Ivoclar Vivadent).

- **Group 2 (TiB/50Al-MB):** The internal surfaces of the crowns were airborne particle-abraded with 50-μm Al2O3 particles (Cobra Aluoxyd, Renfert) for 10 seconds at a pressure of 2.5 bar and from a distance of 10 mm, cleaned in an ultrasonic alcohol bath for 3 minutes, and silanized (Monobond Plus, Ivoclar Vivadent) for 60 seconds. The crowns were then cemented using a resin cement (Multilink Hybrid Abutment).

- **Group 3 (TiB/30SiOAl-SRc):** The internal surfaces of the crowns were airborne particle-abraded with 30-μm silica-coated Al2O3 particles (CoJet) and subsequently cleaned in an ultrasonic alcohol bath for 3 minutes. Thereafter, the protocol continued as in Group 1.
• Group 4 (TiB/30SiOAl-MB): The internal surfaces of the crowns were airborne particle–abraded with 30-μm silica-coated Al₂O₃ particles for 10 seconds at a pressure of 2.5 bar and from a distance of 10 mm and immediately cleaned in an ultrasonic alcohol bath for 3 minutes. Thereafter, the treatment protocol continued as in Group 2 from the moment of silanization.

• Group 5 (TiA/TA-PMMA): The screw channels were manually prepared by drilling to fit the crowns on the TiA. The internal surfaces of the crowns were then conditioned (Telio Activator, Ivoclar Vivadent) for 4 minutes and rebased with PMMA (shade Dentin A2, Telio Lab, Ivoclar Vivadent). The crowns were polymerized in a water bath at 45°C and a pressure of 2.5 bar for 15 minutes (Ivomat, Ivoclar Vivadent).

Upon polymerization (7 minutes for Groups 1, 2, 3, and 4; 15 minutes for Group 5), resin cement or PMMA excess were cleaned, and the crowns were screwed onto their respective dental implants (diameter of 4.3 mm; length 16 mm; CONELOG, Camlog Biotechnologies) with a torque of 20 Ncm, as recommended by the manufacturer. The screw access channel was then sealed with polytetrafluoroethylene (PTFE) tape (Teflon, Chemours) and composite resin material (Tetric EvoCeram A3, Ivoclar Vivadent), and the implants were embedded in a vertical position in a custom-made acrylic resin block with a self-curing acrylic (Technovit 4071, Kulzer), in accordance with ISO 14801.14

Next, tests were conducted for all specimens with thermal cycling (5°C to 55°C, dwell time 120 seconds) and a chewing simulation (120,000 cycles, 49 N, 1.67 Hz, CS-4.8, SD Mechatronik). A steatite ball (diameter of 6 mm) was used as an antagonist indenter. The specimens were loaded 2 mm below the incisal edge at a 30-degree
angle to the palatal surface of the abutment crowns. The vertical indenter movement for each chewing act was 2 mm.

Following the aging procedure, bonding interface stability was analyzed by two independent observers (J.P., F.B.) under ×50 magnification (SZX9, Olympus). Bonding failure was registered when a movement between the TiB and the crown was observed.

Axial pull-out forces were measured in Newtons (N) with a Universal Testing Machine (AGS-X Series, Shimadzu) using a 10-kN load cell at a crosshead speed of 0.5 mm/minute (Fig 1). To ensure even force distribution between the crown and the holder, a 0.5-mm–thick tin foil (Dentaurum) was used. For each sample, the maximum pull-out force (N) was recorded using specific software (Trapezium X, V.1.4.4, Shimadzu). Failure modes were classified as: type 1 = cement remained predominantly on the abutment surface (> 90%); type 2 = cement remained on both abutment and crown surfaces (between 10% and 90%); type 3 = cement remained predominantly on the crown (> 90%).

Bonding failures and pull-out force data were computed in a statistics software (SPSS Statistics version 25, IBM). Bonding failure percentages after artificial aging and failure modes after pull-out test were assessed using Pearson chi-square test. A nonparametric Kruskal-Wallis test followed by Dunn-Bonferroni adjusted post hoc test was used to analyze the data of pull-out forces (N), as normality was not proven by Shapiro-Wilk test. Level of significance of $\alpha = .05$ was set for all tests.

RESULTS

After chewing simulation, Groups 1, 2, and 4 showed 100% bonding failure, while Groups 3 and 5 presented 83.3% and 0% bonding failures, respectively (Table 2). The differences between the groups were statistically significant ($P < .001$). The mean pull-out force ranged between 53.1 N (Group 1) and 1,146.5 N (Group 5) (Table 3). The forces were significantly greater for Group 5 ($P < .05$), followed by Group 3 ($P < .05$), whereas the differences among Groups 1, 2, and 4 were not statistically significant ($P > .05$). The failure modes were distributed among type 1 or type 2 for Groups 1, 2, and 4, while Group 3 presented exclusively type 3 failures (Table 3; Fig 2). Only the differences between Group 3 and the remaining groups were significant ($P < .001$). In Group 5, loss of retention between the crown and abutment was not observed after the pull-out test. The forces registered at the moment of failure in this group corresponded to the maximum axial pull-out force attained before breakage of the abutment screw.

DISCUSSION

This investigation demonstrated that the type of surface treatment of the PMMA crown internal surface affected the bonding interface stability and the pull-out force of temporary crowns bonded to a TiB. When a modified manufacturer protocol was applied by introducing previous airborne particle abrasion of the internal surface of the crown with 30-µm silica-coated alumina particles, the pull-out forces improved compared to the other cementation protocols. Thus, the first null hypothesis was rejected. Moreover, the use of temporary implant-supported single crowns bonded to a TiA provided higher bonding interface stability and higher pull-out forces when compared to temporary implant-supported single crowns bonded to TiBs. Therefore, the second null hypothesis was also rejected.

In the current investigation, four different cementation protocols involving variations on the chemical and mechanical surface treatments of the PMMA crowns supported by TiBs were tested. After an aging procedure equivalent to 6 months of use in the oral cavity (120,000 chewing cycles),$^{15}$ corresponding to the average life span of a temporary restoration, almost every sample supported by a TiB showed a micromovement between the crown and TiB. This movement might represent the initial failure of the bonding interface, which could possibly evolve into a complete loss of retention under occlusal forces in a clinical scenario. For instance, the only TiB group that revealed some stable bonding interfaces
(26.7%) was Group 3. In this protocol, the only modification to the recommended manufacturer instructions was the introduction of tribochemical particle abrasion of the inner surfaces of crowns using 30-μm silica-coated Al₂O₃ particles. This simple surface morphologic modification not only improved the bonding interface stability, but also enhanced pull-out force and altered the failure mode. The pull-out forces of Group 3 were significantly greater than all the other TiB groups. Moreover, in Group 3, the cement remained predominantly on the crown surfaces (type 3 failure), suggesting good bonding between the materials, contrary to what was found in the other TiB groups (failure types 1 and 2).

These results indicate that exclusively surface conditioning with MMA-based liquid, as suggested by the manufacturer, is insufficient to attain adequate retentive strength of the PMMA crown to a TiB surface through Bis-GMA–based resin cement. This could be explained by two simultaneously acting factors. One is the high density of the PMMA block with a high degree of conversion and insufficient free radicals for copolymerization. The highly cross-linked PMMA surface probably impeded the penetration of the MMA-based liquid and prevented the secondary interpenetrating polymer network (IPN) bonding. The second might be related to the too-short time allowed for wetting the PMMA surface (30 seconds), which was most likely insufficient to initiate the swelling phenomenon necessary for the secondary IPN bonding. The application of airborne-particle abrasion surface treatment (Group 3) most likely removed the outer dense layer on the PMMA crown, hence facilitating the penetration of the MMA-based liquid deeper into the surface, which enhanced the softening of the PMMA with the monomer.

Although the values were much lower than when a TiA was used (Group 5), the values appear to be comparable to those obtained for lithium disilicate hybrid abutment crowns bonded to TiBs that did not undergo airborne particle abrasion after 1,200,000 chewing cycles. This finding supports the use of the modified cementation protocol when incorporating a mechanical treatment of the internal surface of the temporary crown if the use of a TiB is desired for a short-period span. In addition, when a universal primer containing silane was applied after tribochemical airborne-particle abrasion treatment of the PMMA crown surfaces (Group 4), very low interface stability and pull-out forces were achieved. This finding reinforces the importance of using an MMA-based liquid to condition a pre-abraded PMMA surface. The conventional technique with use of a TiA demonstrated more stability and higher axial pull-out forces than any group using TiBs. Even with no bonding system used (as the crowns were rebased directly on the temporary abutment), the stability of this complex was considerably improved. In fact, the values obtained from the pull-out test corresponded to the maximum elasticity tolerance of the screw, and not to the retention between the abutment and crown. This means that the real retention force values could be expected to be even higher than the registered ones. The explanation for these findings may be related to the abutment geometry and macrodesign. The prosthetic height of the TiA (9 mm) was almost double that of the TiB (4.7 mm). This results in an increased surface contact area.
Fig 2. Representative specimens from Groups 1 (a and b), 2 (c and d), 3 (e and f), and 4 (g and h) showing remaining cement on titanium-base abutments (a, c, e, g) and crowns (b, d, f, h).
between the crown and the abutment. Other important aspects are the presence of macroretention features on the temporary abutments, as well as the type of rebasing material. The use of a PMMA-based material to rebase a PMMA-based crown resulted in achieving only one interface (metal PMMA). The MMA monomer (Telio Activator) was allowed to wet the PMMA surface of the crown for 2 to 4 minutes, which is a sufficient contact wetting time. In addition, the rebasing material was allowed to polymerize in a water bath with increased temperature (60°C to 70°C), which accelerates the diffusion rate of the monomers into the PMMA crown. In other words, the swelling and dissolving of the PMMA phase of the crown was achieved, and the secondary IPN bonding between the PMMA-based crown and PMMA-based luting material was obtained.

In all test groups, a Bis-GMA–based resin cement was used to bond the crowns to the TiB, whereas in the control group, the PMMA crowns were relined with PMMA resin on the TiA. These protocols represent clinically relevant procedures in digital and analog workflows, respectively. A possible alternative would be to reline the crowns with PMMA resin directly on the TiB. An eventual limitation of this technique can be related to the reduced cement gap, which might preclude sufficient space for a cohesive resistance of the relining PMMA resin. This problem could be prevented by reopening the crown intaglio and then relining it, which would allow enough space for the PMMA resin to cure. However, a fully digital workflow would not be possible anymore, as the crown would need to be repositioned and fixed in a physical model in a conventional manner by a dental technician. Hence, future research and development of higher TiBs appears to be necessary to improve the stability of these temporary solutions and improve their applicability in a digital workflow.

CONCLUSIONS

The cementation protocol had an effect on the bonding interface stability and pull-out forces of PMMA-based CAD/CAM temporary implant-supported single crowns bonded to a TiB. Supplementing manufacturer instructions by introducing airborne-particle abrasion with 30-μm silica-coated Al₂O₃ particles of the crown internal surface and conditioning with an MMA-based liquid may be recommended to improve retention if use of a TiB is desired for temporary restorations. Yet, for optimal outcomes, conventional temporary abutments might be preferred.

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