THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

Screw preload analysis of direct-to-abutment connections in complete arch zirconia frameworks before and after thermomechanical aging

Aseel Altemimi, MChD/BChD, MS, FRCDC, DABP,[a] Fawaz Alzoubi, BDM, MA, EdD,[b] Liebert Parreiras Nogueira, PhD,[c] and Burak Yilmaz, DDS, PhD[d]

ABSTRACT

Statement of problem. Direct-to-abutment connections have been increasingly used for implant-supported fixed complete dentures (ISFCDs). However, the biomechanical performance of these connections and their screws under simulated clinical conditions has not been adequately investigated.

Purpose. The purpose of this in vitro study was to investigate the reverse torque values (RTVs) of ISFCDs connected to transmucosal abutments with and without the use of a Ti-base interface before and after thermomechanical aging (TMA). In addition, the study aimed to compare RTV according to the implant position and location (straight anterior and angled posterior) within each group.

Material and methods. Zirconia frameworks (N=24) for restorations supported by 4 implants were divided into 3 groups: frameworks with Ti bases and regular screws, direct-to-abutment frameworks with regular screws, and direct-to-abutment frameworks with modified screws. All frameworks were 3-dimensionally designed and subtractively manufactured. The RTVs of screws and preload efficiency (PE) were measured after tightening the screws. The frameworks were subjected to 1.2 million cycles at 90 N, 2 Hz with a dwell time of 30 seconds between 5 °C and 55 °C in distilled water with a total of 12 000 thermal cycles. RTV and PE measurements were repeated after TMA. Paired comparisons were performed using the Wilcoxon signed-rank test, and post hoc Mann-Whitney U tests with Bonferroni adjustment were used to evaluate RTV and PE loss after TMA. In addition, the Mann-Whitney U tests were used to compare the differences in preload loss between straight anterior and angled posterior abutments in each design. The Cohen r was used to estimate effect sizes for all group comparisons (α=.05).

Results. Before TMA, the median RTV was 13.3 Ncm, and the median PE was 88.3%. After TMA, the median RTV was 11.5, and the median PE was 76.7%, with significant loss of preload across the entire sample (z=6.06, P<.001). However, the Mann-Whitney U tests revealed that the losses were not significantly different between the standard Ti-base connection and either the direct-to-abutment connection with regular screws (P=.518) or the direct-to-abutment connection with modified screws (P=.664). Furthermore, no significant differences were observed between abutment positions in the Ti-Base connection with regular screws (P=.880) or between abutment positions in the direct-to-abutment connection with modified screws (P=.363). However, comparison of direct-to-abutment connections revealed significantly greater losses in angled posterior abutments with regular screws (z=−2.25, P=.025).

Conclusions. No significant differences in RTV and PE were observed between Ti-base and direct-to-abutment connections before and after TMA. Modified screw designs did not significantly affect preload before TMA in direct-to-abutment connections. However, they significantly minimized preload loss after TMA in angled posterior abutments only in the direct-to-abutment connection compared with that with regular screws in the Ti-base and the direct-to-abutment connections using regular screws. (J Prosthet Dent 2026;136:e290-e298)

Supported by Kuwait University Research [grant DG02/23], Kuwait.
There are no conflicts of interest to declare.
[a]Specialist, Post-graduate Prosthodontics, Kuwait Institute of Medical Specializations, Jahra Specialized Dental Centre, Andalous, Kuwait.
[b]Associate Professor, Department of General Dental Practice, Faculty of Dentistry, Kuwait University, Kuwait City, Kuwait.
[c]Researcher, Oral Research Laboratory, Institute of Clinical Dentistry, University of Oslo, Oslo, Norway.
[d]Associate Professor, Department of Reconstructive Dentistry and Gerodontology, University of Bern, Bern, Switzerland; Professor, Department of Restorative, Preventive and Pediatric Dentistry, School of Dental Medicine, University of Bern, Bern, Switzerland; Adjunct Professor, Division of Restorative and Prosthetic Dentistry, The Ohio State University College of Dentistry, Columbus, Ohio; and Adjunct Professor, Department of Prosthodontics, Faculty of Dentistry, Ankara University, Ankara, Turkey.
[1]A.A. and F.A. contributed equally to this article and share first authorship.

Clinical Implications

The direct-to-abutment connections performed similarly to conventional Ti-Base connections regarding RTVs and PE under simulated conditions. However, modified screw designs may significantly minimize preload loss over time in direct-to-abutment prostheses attached to angled posterior abutments. These findings will help reduce biomechanical complications, thereby improving the longevity of the prosthesis.

Several materials have been developed for the restoration of implant-supported fixed complete dentures (ISFCDs).[1-4] However, a metal substructure with acrylic resin or porcelain veneering is still commonly used.[1-4] The manufacturing process of these restorations involves several steps with potential errors. Moreover, fracture of the veneering material is a frequent complication.[2] Digital innovations and processes, including computer-aided design and computer-aided manufacturing (CAD-CAM), allow the use of monolithic materials such as zirconia for ISFCD fabrication.[1,2] The outcomes of zirconia-based, complete arch implant-supported restorations have been reported, with most studies reporting high success rates.[1-4] Conventionally, these restorations have titanium interfaces (Ti bases) cemented to the zirconia structure and attached to transmucosal abutments (multi-unit abutments) using screws. However, debonding of the Ti base from the restoration has been reported to be a complication.[5-7]

Recently, several clinicians and laboratories have used digital photogrammetry and cast-less workflows to connect ISFCDs directly to multi-unit abutments without the use of Ti bases (direct-to-abutment connections).[8] This workflow improves the accuracy of fit of the restorations by bypassing potential sources of error, particularly during Ti base cementation.[8] In addition, the direct-to-abutment approach offers several advantages, such as reduced costs, greater material thickness around the multi-unit abutments and screw channels, elimination of an additional interface, and narrower screw-access channels, making the design more streamlined. However, the performance of these restorations over time remains unknown.[8]

The feasibility of using commercially available modified screw designs with direct-to-abutment connections has not yet been evaluated. Particularly, the potential loss of torque, consequent screw loosening over time, and overall mechanical performance must be evaluated, as screw loosening is a common complication in implant prostheses[9-12] and a significant factor for understanding the biomechanical behavior of prosthetic designs and connections. Prosthetic screws are the primary components connecting the prosthesis to the transmucosal abutments in abutment-level prostheses. Typically, the screw is tightened to a certain torque (typically 15 Ncm) to create a screw-joint preload by generating tension, which is the main element of clamping forces.[13-16] The optimal preload is generated because of screw elongation (to the point of its yield strength) because of this tension.[17] To resist external stress forces, stable unaltered preload must be maintained as long as possible.[13,18]

Factors influencing preload include the applied torque, screw material,[19-21] screw-surface roughness, and screw and prosthesis design.[15,21,22] Under nonaxial or excessive occlusal loading, screw loosening may occur if the preload falls below the joint-separating forces.[13,22-26] The biomechanical characteristics of modified screw designs, such as the Rosen screw (Rosen Implant Solutions), have not been well documented.

Screw loosening and/or fracture might necessitate the removal of the entire restoration, causing significant damage.[19,27] Reverse torque values (RTVs) reflect abutment screw loosening[17]; hence, they have often been used to quantify the extent of loosening.

The use of Ti bases for single-implant restorations has been investigated[28]; however, studies evaluating the mechanical properties of this prosthetic attachment in ISFCDs are limited.[3,4] Furthermore, these studies evaluated implant-level prostheses and not direct-to-abutment connections. In addition, the author is unaware of a study investigating the usefulness of modified screw designs in direct-to-abutment zirconia ISFCDs. Therefore, this study aimed to investigate the RTV of screws connecting zirconia ISFCDs to transmucosal (multi-unit) abutments with and without the use of a Ti base (direct-to-abutment) before and after thermomechanical aging (TMA). In addition, because geometric differences between straight and angled multi-unit abutments can affect the integrity of the framework material at the abutment interface and RTV, this study aimed to investigate the effect of implant position and location (straight anterior and angled posterior) on the RTV within the groups. The null hypotheses were that no difference in RTVs would be found between direct-to-abutment and Ti-base connections and that within each of the 3 designs, the implant location (straight, anterior, and angled posterior) would not affect the RTVs of the screws.

MATERIAL AND METHODS

Twenty-four casts with 4 holes to accommodate 4 bone-level tapered implants (2 axial anterior and 2 tilted posterior) were 3-dimensionally designed and printed using cast resin (Asiga DentaModel; Asiga). The bases of

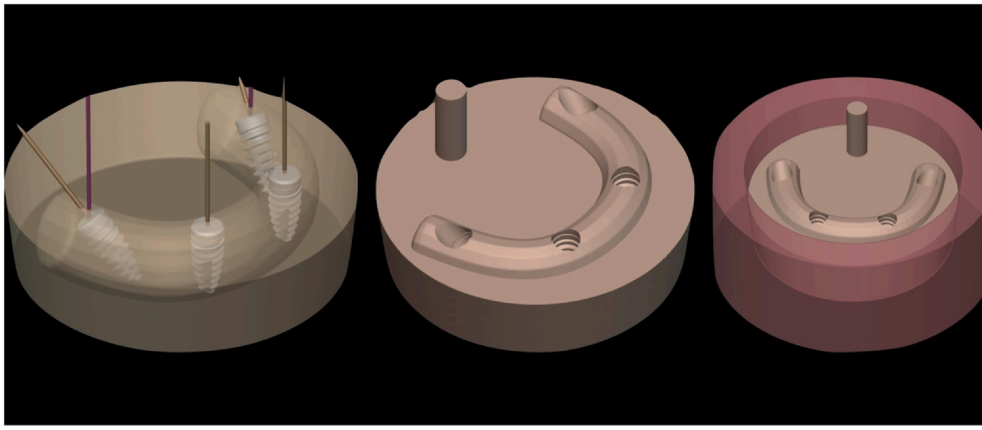

Figure 1. Casts designed to accommodate implants (*left*). Handle created to facilitate handling in and out of the water chamber of the mastication simulator (*center*). Diameter of cast base designed to fit closely in chamber to eliminate movement during thermomechanical aging (*right*).

the casts were designed to fit the exact dimensions of the thermomechanical chamber to minimize movement during TMA. Implants (4.1×10.0 mm Bone Level Tapered; Institut Straumann AG) were placed in the holes in the printed casts, leaving 1 mm of their crest exposed. Thirty-degree angled transmucosal abutments (Screw-Retained Abutment; Institut Straumann AG) were connected to each posterior implant in the cast for angle correction, and straight transmucosal abutments (Screw-Retained Abutment; Institut Straumann AG) were used for the anterior implants. All transmucosal abutments had the same gingival height (2.5 mm) (Figs. 1-4). All transmucosal abutment screws (*N*=96) were tightened twice, 10 minutes apart, using a torque of 35 Ncm as per the manufacturer's recommendation. The torque was measured using a calibrated electronic torque-limiting device (iSD900; NSK) (Fig. 5). Abutment-level scan bodies (DESS; Dental Smart Solutions) were attached to all transmucosal abutments and scanned using a laboratory scanner (UHD; Degrees of Freedom, CM Medical) to generate a standard tessellation language (STL) file to design the restorations using 2 CAD software programs (exocad; Align Technology and Blender for Dental; Blender Foundation). All prostheses were designed with a U shape with specific dimensions (8×8×8 mm) and interfaces to connect to their corresponding abutment-level casts based on the study groups and associated screws. The design and dimensions used were based on specific manufacturer recommendations for connectors for 3Y-TZP zirconia. To

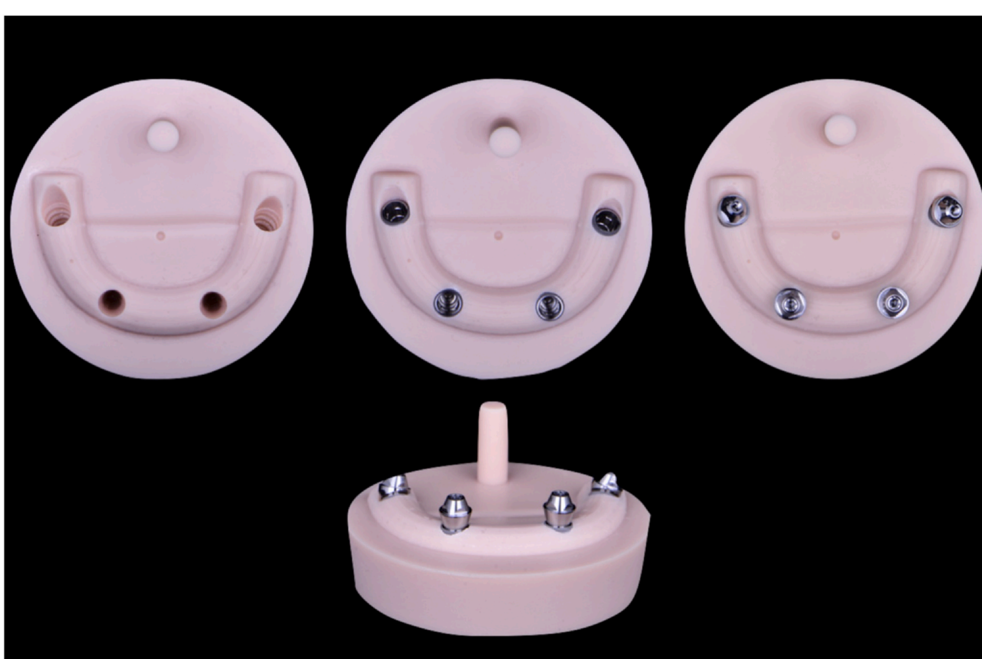

Figure 2. Casts after printing, implant installation, and transmucosal abutment attachment.

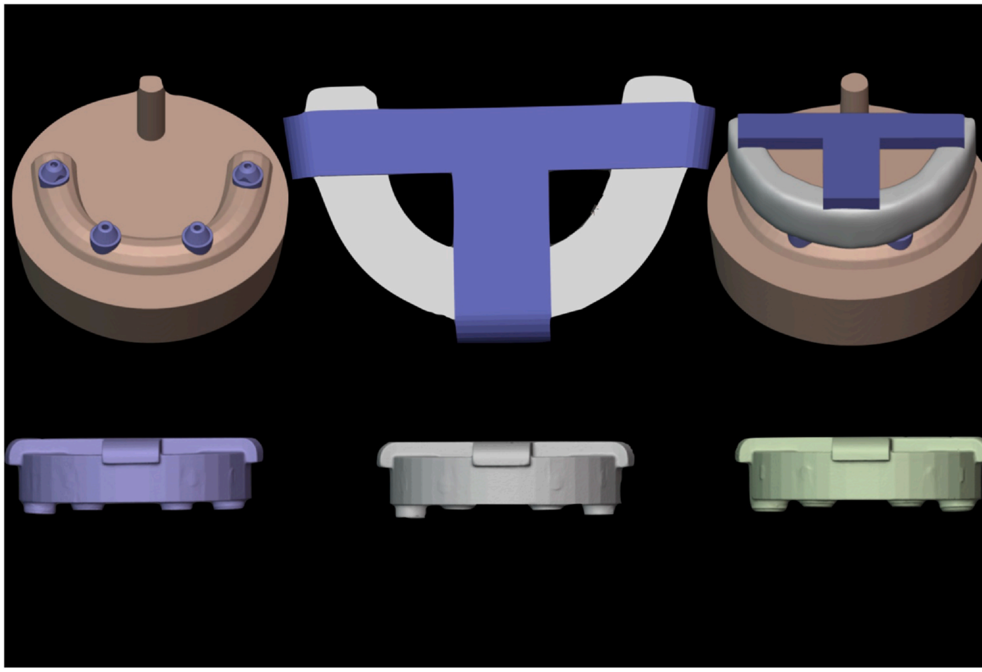

Figure 3. Framework designs.

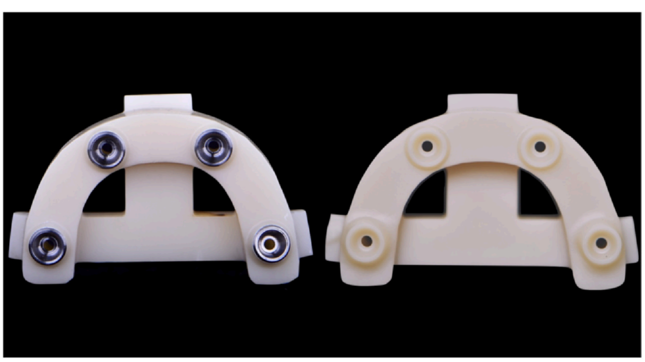

Figure 4. Frameworks after milling. ZrTiRS Group with Ti-base abutments (left) and ZrDiRS and ZrDiMS Groups with direct-to-abutment connections (right).

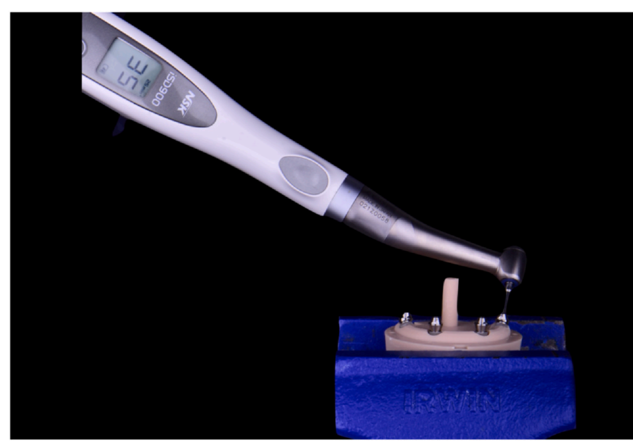

Figure 5. Transmucosal abutments tightened to 35 Ncm.

accommodate the loading indenter of the TMA machine, a T-shaped custom fixture was incorporated into the framework to direct forces along the long axis of each specimen. The design of this fixture was based on calculations to accommodate the anticipated center of mass and assure even distribution of load to all components of the framework. Monolithic 3Y-TZP zirconia blocks (Katana Zirconia YML; Kuraray Noritake) were used to manufacture the zirconia frameworks using a 5-axis milling machine (ARUM 5X-300 Pro; ARUM) and a CAM software program (HyperDent Classic; Follow Me Technology).

The specimens were divided into the following 3 groups: zirconia frameworks with Ti-base connections using regular screws (ZrTiRS), zirconia frameworks with direct-to-abutment connections using regular screws (ZrDiRS), and zirconia frameworks with direct-to-abutment connections using modified screws (ZrDiMS).

In the ZrTiRS Group, Ø4.6×4-mm Ti-base abutments (Variobase; Institut Straumann AG) were bonded to the zirconia frameworks using the bonding protocol introduced by Blatz et al.[29] The prosthesis was attached to the abutments using regular abutment screws (Straumann; Straumann Group). In the ZrDiRS Group, the design did not include Ti-base abutments, and the framework was designed to attach directly to the transmucosal abutments using regular abutment screws. In the ZrDiMS Group, a modified screw design (Rosen screw; Rosen Implant Solutions) was used. Laboratory screws were used during specimen preparation.

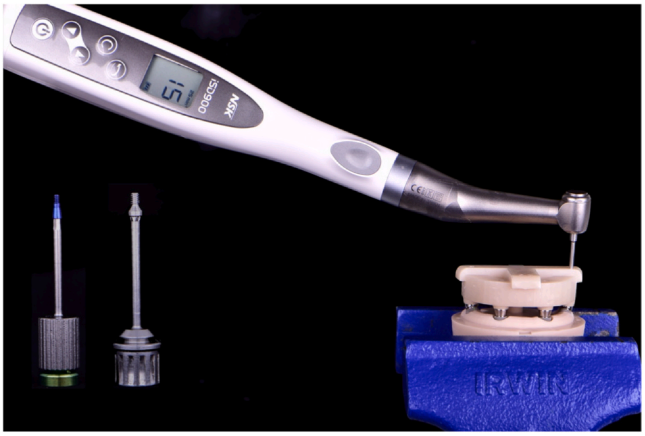

Figure 6. Prosthetic screws tightened to 15 Ncm in ZrTiRS and ZrDiRS groups and 2 (right) and ZrDiMS group (left).

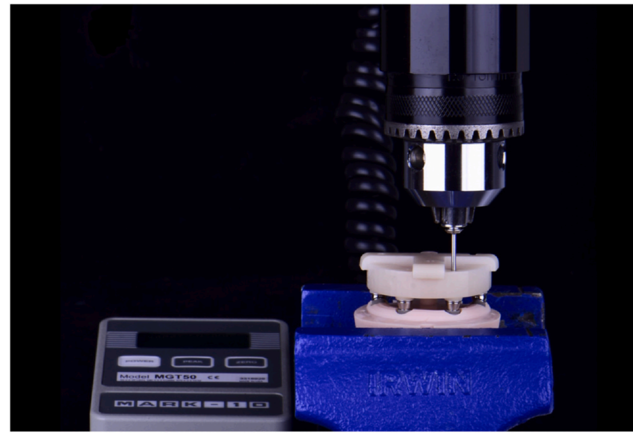

Figure 7. RTV measurement. RTV, reverse torque value.

Before tightening all new screws, a 1-screw Sheffield test[30] was performed to ensure passive seating of all specimens on their corresponding casts. Next, a triple-scan protocol and tactile evaluation were used to ensure that all frameworks had similar qualitative and quantitative fit. According to the triple-scan protocol, the cast with the corresponding transmucosal abutments on implants, the framework, and the framework secured to the cast using 1 screw were scanned separately.[31] The 3 images were superimposed using a best-fit algorithm software program (Geomagic; 3D Systems), and passive fit was verified before TMA. Frameworks with high outlier gap values on the triple scan or nonpassive sensation on tactile examination were discarded, and new ones were fabricated to ensure a similar gap and passive fit before loading.

In all groups, after fit confirmation using the 1-screw Sheffield test and triple-scan protocol, new prosthetic screws were tightened to 15 Ncm as per the manufacturer's recommendation. The screws were tightened twice, 10 minutes apart, using a calibrated electronic torque-limiting device (iSD900; NSK) before TMA (Fig. 6). The RTV of all 4 prosthetic screws was measured using a digital screw torque meter (MGT50; Mark-10) before TMA (Fig. 7). Finally, all frameworks were secured to the casts again using 4 new prosthetic screws and the same tightening protocol. The assemblies in all 3 groups are presented in Figure 8.

After TMA, RTV was measured using the digital screw torque meter and the same protocol as before TMA. The effect of TMA was evaluated by calculating the difference between the RTV before and after TMA (reverse torque difference [RTD]). In addition, preload efficiency (PE) before and after TMA was calculated using the equation PE (%)=(Removal torque/Tightening torque)×100. RTV was supplemented with PE to represent the residual preload in the prosthetic system.[32,33] The difference between the initial and final PE was calculated as PE difference (PED=Final PE–Initial PE). Negative RTD and PED values indicated preload loss, whereas positive values indicated preload gain.

The specimens were attached to a universal thermocycling/mastication simulator machine (CS-4; SD Mechatronik) and subjected to 1.2 million cycles at a force of 90 N at 2 Hz, with a dwell time of 30 seconds, at temperatures ranging from 5 °C to 55 °C in distilled water, and with a total of 12 000 thermal cycles. The load was delivered axially using a Ø6-mm-steel indenter

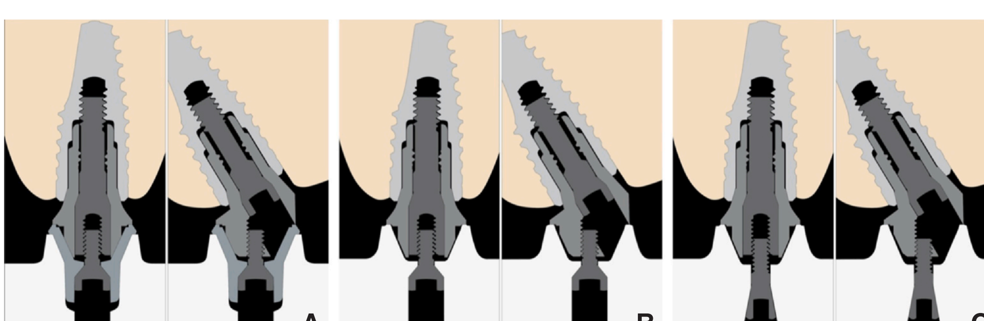

Figure 8. Illustration of all 3 group assemblies. A, ZrTiRS Group: Ti base with regular screws. B, ZrDiRS Group: Direct-to-abutment connection with regular screw. C, ZrDiMS group: Direct-to-abutment connection with modified screw.

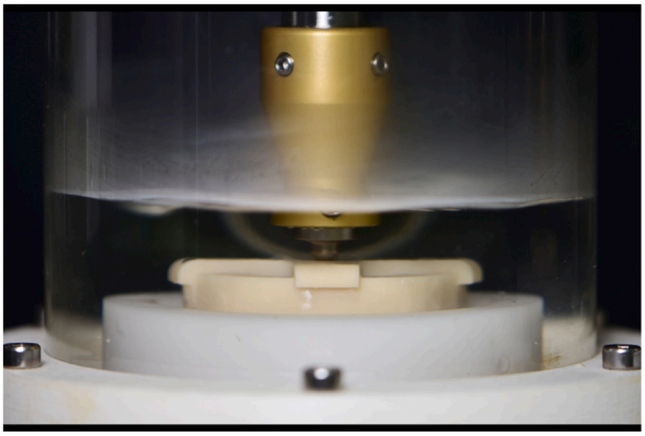

Figure 9. Specimen in TMA chamber during loading. TMA, thermomechanical aging.

directed toward the center of the custom T-shaped fixture on the zirconia framework with a vertical displacement of 2 mm at a speed of 60 mm/second and a horizontal displacement of 1 mm at 20 mm/second (Fig. 9). A custom fixture was used to ensure force dissipation and allow simultaneous loading of all parts of the restorations. The specimens were evaluated after approximately every 50 000 cycles to ensure the absence of damage or screw loosening. Any damaged specimens deemed unusable were excluded from the study and replaced with new specimens, and the frequency of screw loosening was recorded.

A priori power analysis had been conducted using a software program (G*Power v3.1; Heinrich-Heine-UniversitÄt DÜsseldorf) to determine the required minimum sample size. In addition, a pilot study was conducted before the power analysis. Assuming an effect size of f=.25, the estimated sample size for a statistical power >80% at a significance level of .05 was 24, with 8 specimens per group. The data were collected and analyzed using a statistical software package (IBM SPSS Statistics for Windows, v27.0. IBM Corp) and presented as medians with interquartile ranges. Because the difference in score distributions were skewed, nonparametric statistics were used for comparisons. The incidence of damaged frameworks and screw loosening was evaluated using the Kaplan-Meier method. Paired comparisons using the Wilcoxon signed ranks tests were used for RTV and PE before and after TMA. Post hoc Mann-Whitney U tests with Bonferroni adjustment were used to compare the losses in RTV and PE after TMA in each direct-to-abutment design versus losses in the standard Ti-base design. To evaluate the differences in preload loss between straight anterior and angled posterior abutments, the Mann-Whitney U tests were used within each of the 3 groups. The Cohen r was used to estimate effect sizes for all group comparisons (α=.05).

Table 1. Summary statistics for the entire sample (N=96)

Variable	Median (Ncm)	IQR (Ncm)	z (skewness/SE)
RTV			
Before TMA	13.3	3.5	1.81
After TMA	11.5	4	−1.49
RTD	−1.5	4	−4.29
PE			
Before TMA	88.3	23	1.81
After TMA	76.7	27	−1.49
Difference (PED)	−10	27	−4.29

IQR, interquartile range; PE, preload efficiency; PED, difference in PE after TMA; RTD, difference in RTV after TMA; RTV, reverse torque value; TMA, thermomechanical aging.

RESULTS

Neither framework damage nor screw loosening was noted in any of the specimens after TMA. Summary statistics presented in Table 1 include RTV and PE before and after TMA and differences in scores after TMA. Paired comparisons of RTV and PE before and after TMA using the Wilcoxon signed ranks test revealed significant loss of preload across the entire sample (z=6.06, P<.001). However, the Mann-Whitney U tests revealed that the losses were not significantly different between the 2 direct-to-abutment connections and the standard Ti-base connection (Table 2). No significant differences in RTV and PE loss were found between the screws in straight anterior and angled posterior abutments in the Ti-base connection and direct-to-abutment connection with modified screws groups (Table 3); however, significantly greater losses were observed in the angled posterior abutments in the direct-to-abutment connection with regular screws group (z=−2.25, P=.025, r=−0.40).

DISCUSSION

The null hypothesis that no difference in RTVs would be found between direct-to-abutment and Ti-base connections was not rejected. However, the null hypothesis that within each of the 3 designs, the implant location (straight, anterior, and angled posterior) would not affect the RTVs of the screws was rejected. No significant differences in RTV before and after TMA were observed between the direct-to-abutment and Ti-base connections, and using modified screw designs did not result in significant differences in RTV between the groups. Nonparametric comparisons were used to test the hypotheses in lieu of analyses of variance owing to the skewed data and heterogeneity of group variances.

No statistically significant differences in PE were observed between groups. However, the findings must be interpreted with caution and within the context of this study. Load distribution across implants and abutment screws with passive fit may compensate for

Table 2. Comparison of RTD and PED differences after TMA between Ti-base designs using regular screws and direct-to-abutment designs using regular and modified screw designs

	RTD (*n*=32)		PED (*n*=32)				
	Median (Ncm)	IQR (Ncm)	Median (Ncm)	IQR (Ncm)	*z**	*P*[a]	*r*[b]
Ti-base/regular screw (control)	−1.8	3.4	−11.7	23			
Direct-to-abutment/regular screw	−4	6.8	−26.7	45	−1.13	.518	−0.02
Direct-to-abutment/modified screw design	−1.5	2.4	−10	16	−0.97	.664	−0.02

IQR, interquartile range; PED, difference in preload efficiency after TMA; RTD, difference in reverse torque value after TMA; TMA, thermomechanical aging.

* Standardized Mann-Whitney *U* test; similar test results for RTD and PED;

[a] Bonferroni adjusted *P* value;

[b] Cohen *r* effect size.

Table 3. Comparison of RTD and PED after TMA between screws according to abutment and connection designs

		RTD			PED					
Design	Abutment position	*N*	Median (Ncm)	IQR	*N*	Median (Ncm)	IQR	*z**	*P*	*r*[a]
Ti-base/regular screw										
	Straight	16	−1.5	3.2	16	−10	21	−0.15	.880	−0.03
	Angled	16	−2.3	4.1	16	−15	27			
Direct-to-abutment/regular screw										
	Straight	16	−1.0	4.8	16	−6.7	32	−2.25	.025	−0.40
	Angled	16	−6.0	7.8	16	−40	52			
Direct-to-abutment/modified screw design										
	Straight	16	−1.5	3.3	16	−10	22	−0.91	.363	−0.16
	Angled	16	−1.3	3.4	16	−8.3	23			

IQR, interquartile range; PED, difference in preload efficiency after TMA; RTD, difference in reverse torque value after TMA; TMA, thermomechanical aging.

* Standardized Mann-Whitney *U* test; similar test results for RTD and PED.

[a] Cohen *r* effect size

decreased PE with modified screw designs, resulting in a 10% to 13% difference in mean PE. In clinical situations with single-implant crowns, this difference between the test and the control groups can have a greater impact on the screw stability, particularly in the long term, compared with that in the current ISFCD on 4 implants. However, the long-term performance of screws in crossarch splinted prostheses may be similar. Studies with long-term framework loading are required to validate these findings.

As mentioned earlier, the clamping force is the primary element for stable, unaltered preload between the screw head and prosthetic platform.[13-18] Factors that affecting this interaction may include the screw material,[19-21] screw design and surface roughness,[15,22] friction between the mating surfaces,[17] and abutment design.[34] Modification of these characteristics, such as the modified screw design used in this study, may impact the preload (through clamping forces). However, in this study, no difference was observed in RTV or PE and, hence, preload. This is important to validate any claims regarding the usefulness of modified screws in clinical practice.

The manufacturing accuracy, milling strategies, and machining of zirconia significantly affect the accuracy of the fit of the screw in the channel.[35] In Ti bases, screws fit into machined and properly offset channels with precalculated dimensions. However, in this study, the fit of screws without a Ti interface was highly dependent on these factors. This study did not investigate different milling strategies and dimensions of the screw channels in direct contact with the screw. As the biomechanics and preload of the modified screw design depend on the wedging effect it has on the zirconia channel, a slightly larger or smaller offset may affect the PE of the screws. The findings suggested that the screw design could influence preload. However, this study did not investigate the difference in preload between different modified screw designs for direct-to-abutment prostheses.

The findings in this study show that the potential added benefit in preload with modified screws designs in direct-to-abutment zirconia prosthesis connections is limited. Using modified screws with frameworks without Ti bases provides a cost benefit, and, in this study, this design provided preload outcomes similar to those in the control ZrTiRS (Ti-base) group. In addition, in direct-to-abutment connections, modified screws may protect the thin zirconia portion remaining under the screw head compared with regular screws. In the future, studies with longer fatigue loading durations are required to validate these findings. However, the wedging effect of these screws rather than the preload itself retains the restorations.

The null hypothesis that within each of the 3 designs, the implant location (straight, anterior, and angled posterior) would not affect the RTVs of the screws was rejected because significantly greater losses were observed in the angled posterior abutments with the direct-to-abutment design with regular screws compared with those in the straight anterior abutments (ZrDiRS Group). In contrast, no significant differences were observed between the straight anterior and angled posterior abutments in the other 2 groups (ZrTiRS and ZrDiMS Groups). The abutment-to-framework contact areas in both direct-to-abutment connections were similar; however, the modified-design screws were able to maintain the preload better than the regular screws in the posterior-angled abutments. One potential explanation for the improved outcomes could be the distinct design of the modified screws. In prostheses with Ti-base connections, clamping occurs between Ti and Ti-clamped surfaces. In contrast, in regular direct-to-abutment connections, the mating surfaces are Ti and zirconia, 2 materials with different ductility, which might impair the clampability of the system, leading to a higher preload loss.

Limitations of the study included the in vitro design; nevertheless, efforts were made to simulate the intraoral situation. However, longer loading durations are difficult to implement in in vitro settings because only 1 large-size framework can be loaded in fatigue loading machines. Furthermore, because of differences in the modulus of elasticity and other biomechanical parameters, the cast resin used in the current study may not simulate natural bone. Future studies should investigate the influence of different framework materials with higher loading forces with longer durations if possible.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. No significant differences in RTV and PE were observed between Ti-base and direct-to-abutment connections before and after TMA.
2. Modified screw designs did not significantly affect preload before TMA in direct-to-abutment connections. However, they significantly minimized preload loss after TMA in angled posterior abutments only in the direct-to-abutment connection compared with that with regular screws in the Ti-base and the direct-to-abutment connections using regular screws.

REFERENCES

1. Papaspyridakos P, Bordin TB, Kim YJ, et al. Technical complications and prosthesis survival rates with implant-supported fixed complete dental prostheses: A retrospective study with 1- to 12-year follow-up. *J Prosthodont.* 2020;29:3–11.
2. Bidra AS, Tischler M, Patch C. Survival of 2039 complete arch fixed implant-supported zirconia prostheses: A retrospective study. *J Prosthet Dent.* 2018;1192:220–224.
3. Barootchi S, Askar H, RavidÀ A, et al. Long-term clinical outcomes and cost-effectiveness of full-arch implant-supported zirconia-based and metal-acrylic fixed dental prostheses: A retrospective analysis. *Int J Oral Maxillofac Implants.* 2020;35:395–405.
4. Pozzi A, Arcuri L, Fabbri G, et al. Long-term survival and success of zirconia screw-retained implant-supported prostheses for up to 12 years: A retrospective multicenter study. *J Prosthet Dent.* 2023;129:96–108.
5. Pitta J, Todorovic A, Fehmer V, et al. Technical complication of a zirconia multiple-unit FDP supported by titanium base abutments - case report on a bonding failure and treatment alternative. *Int J Prosthodont.* 2021;34:518–527.
6. Pitta J, Burkhardt F, Mekki M, et al. Effect of airborne-particle abrasion of a titanium base abutment on the stability of the bonded interface and retention forces of crowns after artificial aging. *J Prosthet Dent.* 2021;126:214–221.
7. Karaokutan I, Ozel GS. Effect of surface treatment and luting agent type on shear bond strength of titanium to ceramic materials. *J Adv Prosthodont.* 2022;27:78–87.
8. Nagai T, Liu W, Yang CC, et al. Intraoral scanning for implant-supported complete-arch fixed dental prostheses (ISCFDPs): Four clinical reports. *J Prosthodont* 2024:1–12.
9. Taylor TD. Prosthodontic problems and limitations associated with osseointegration. *J Prosthet Dent.* 1998;79:74–78.
10. Zarb GA, Schmitt A. The longitudinal clinical effectiveness of osseointegrated dental implants: The Toronto study. Part III: Problems and complications encountered. *J Prosthet Dent.* 1990;64:185–194.
11. Goodacre CJ, Bernal G, Rungcharassaeng K, Kan JY. Clinical complications with implants and implant prostheses. *J Prosthet Dent.* 2003;90:121–132.
12. Johansson LA, Ekfeldt A. Implant-supported fixed partial prostheses: A retrospective study. *Int J Prosthodont.* 2003;16:172–176.
13. Shigley JE. Mechanical Engineering Design. 3rd ed. McGraw-Hill; 1977:240–2405.
14. Rangert B, Jemt T, Jörneus L. Forces and moments on Branemark implants. *Int J Oral Maxillofac Implants.* 1989;4:241–247.
15. Jörnéus L, Jemt T, Carlsson L. Loads and designs of screw joints for single crowns supported by osseointegrated implants. *Int J Oral Maxillofac Implants.* 1992;7:353–359.
16. Bickford JH. An Introduction to the Design and Behavior of Bolted Joints. 3rd ed. Marcel Dekker; 1995:515–5164.
17. Tsuge T, Hagiwara Y. Influence of lateral-oblique cyclic loading on abutment screw loosening of internal and external hexagon implants. *Dent Mater J.* 2009;28:373–381.
18. Weinberg LA. Reduction of implant loading with therapeutic biomechanics. *Implant Dent.* 1998;7:277–285.
19. Byrne D, Jacobs S, O'Connell B, et al. Preloads generated with repeated tightening in three types of screws used in dental implant assemblies. *J Prosthodont.* 2006;15:164–171.
20. Martin WC, Woody RD, Miller BH, Miller AW. Implant abutment screw rotations and preloads for four different screw materials and surfaces. *J Prosthet Dent.* 2001;86:24–32.
21. Tan KB, Nicholls JI. Implant-abutment screw joint preload of 7 hex-top abutment systems. *Int J Oral Maxillofac Implants.* 2001;16:367–377.
22. McGlumphy EA, Mendel DA, Holloway JA. Implant screw mechanics. *Dent Clin North Am.* 1998;42:71–89.
23. Ekfeldt A, Carlsson GE, Börjesson G. Clinical evaluation of single-tooth restorations supported by osseointegrated implants: A retrospective study. *Int J Oral Maxillofac Implants.* 1994;9:179–183.
24. Haas R, Mensdorff-Pouilly N, Mailath G, Watzek G. Brånemark single tooth implants: A preliminary report of 76 implants. *J Prosthet Dent.* 1995;73:274–279.
25. Rangert B, Krogh PH, Langer B, Van Roekel N. Bending overload and implant fracture: A retrospective clinical analysis. *Int J Oral Maxillofac Implants.* 1995;10:326–334.
26. Rangert BR, Sullivan RM, Jemt TM. Load factor control for implants in the posterior partially edentulous segment. *Int J Oral Maxillofac Implants.* 1997;12:360–370.
27. Hebel KS, Gajjar RC. Cement-retained versus screw retained implant restorations: Achieving optimal occlusion and esthetics in implant dentistry. *J Prosthet Dent.* 1997;77:28–35.
28. Al-Thobity AM. Titanium base abutments in implant prosthodontics: A literature review. *Eur J Dent.* 2022;16:49–55.
29. Blatz MB, Alvarez M, Sawyer K, Brindis M. How to bond zirconia: The APC concept. *Compend Contin Educ Dent.* 2016;37:611–617.
30. White GE. Osseointegrated Dental Technology. Quintessence Publishing; 1993:129.
31. Dönmez MB, Cakmak G, Schimmel M, Yilmaz B. Implementation of triple-scan protocol to evaluate the fit of complete-arch implant-supported fixed prostheses. *J Prosthodont.* 2024;34:441–445.
32. Cardoso M, Torres MF, Lourenço EJ, et al. Torque removal evaluation of prosthetic screws after tightening and loosening cycles: An in vitro study. *Clin Oral Implants Res.* 2012;23:475–480.

33. Paepoemsin TR, Reichart PA, Chaijareenont P, et al. Removal torque evaluation of three different abutment screws for single implant restorations after mechanical cyclic loading. *Oral Implantol.* 2016;9:213–221.
34. Alzoubi FM, Sabti M, Alsarraf E, et al. Preload evaluation of 2 implant-supported fixed partial denture abutment designs. *J Prosthet Dent.* 2022;128:1067.e1–1067.e6.
35. Kim JH, Lee H, Son SA, et al. Evaluation of the intaglio surface trueness and fit of zirconia crowns fabricated using different machining strategies with a chairside CAD/CAM system. *Int J Comput Dent.* 2024;27:191–198.

Corresponding author:
Dr Fawaz M. Alzoubi
Department of General Dental Practice
College of Dentistry
Kuwait University
Sabah Al Salem University City
P.O. Box 5969
Safat 13060
Shadadiya
KUWAIT
Email: Fawaz.alzoubi@ku.edu.kw

Acknowledgments
The authors thank Mr Shaji Micheal and Mrs Sreeja Saji from the Kuwait University bio-clinical sciences laboratory facility (Project No. SRUL 01/14) for the use of equipment and their contribution.

CRediT authorship contribution statement

Aseel Altemimi: Conceptualization, Methodology, Software, Validation, Data Curation, Writing – Original Draft, Writing – Review and Editing, Visualization. **Fawaz M. Alzoubi:** Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Writing – Review and Editing, Visualization, Project Administration, Funding Acquisition. **Liebert Parreiras Nogueira**: Software, Validation, Writing – Original Draft, Writing – Review and Editing. **Burak Yilmaz:** Conceptualization, Methodology, Formal Analysis, Data Curation, Writing – Original Draft, Writing – Review and Editing, Visualization, Supervision.

https://doi.org/10.1016/j.prosdent.2026.03.018