

Original Article



Effects of Axial Wall Modification on the Retention of Implant-Supported Zirconia Crowns in Short Titanium Abutments: An in Vitro Study

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Abstract

Introduction: Retention is a critical factor in the long-term success of cement-retained, implant-supported restorations. Insufficient retention may lead to prosthetic complications such as decementation, particularly in cases involving short abutments. Achieving adequate retention for abutments shorter than 4 mm is challenging because of the limited bonding surface. Various abutment design modifications have been proposed to enhance retention; however, comparative evidence on their effectiveness remains limited. This study aimed to evaluate the effect of different abutment design modifications on the retention of zirconia crowns cemented to short implant abutments.

Methods: Seventy-two implant abutments were digitally designed and divided into six groups ($n=12$). The control group had no modifications. Experimental groups included abutments with one axial wall removed, two opposing axial walls removed, an axial groove, a frustum-shaped groove, or a circumferential groove. Seventy-two zirconia crowns were fabricated using CAD/CAM technology and cemented with dual-cured resin cement under standardized laboratory conditions. Retention was measured using a pull-out test with a universal testing machine, recording the maximum force required to dislodge each crown.

Results: Mean retention values ranged from 155.93 N in the control group to 220.05 N in the circumferential groove group. Abutments with circumferential grooves and those with two opposing axial walls removed showed significantly higher retention than the control group ($P<0.05$).

Conclusions: Modifications to short abutment designs, particularly circumferential grooves and removal of opposing axial walls, significantly improved the retention of zirconia restorations, likely providing clinically relevant solutions for managing short implant abutments.



Introduction

Dental implants are widely accepted in dentistry, particularly for restoring edentulous areas.¹ Implant-supported crowns are attached to the implant abutment using either a screw-retained or cement-retained method. The choice between these two approaches is based on treatment planning, considering the specific advantages and disadvantages of each option.^{2,3} Screw-retained restorations are recommended in cases with limited interarch space, cantilever prostheses, or long-span fixed bridges. On the other hand, cement-retained restorations are often preferred for shorter fixed prostheses where the

margin is at or above the gingival level, for correcting unfavorable implant angulations, and for simplifying occlusal adjustments without requiring an access hole in the crown.⁴ While screw-retained restorations are prone to complications such as screw loosening, fractures, and esthetic limitations, cement-retained restorations also have challenges, including the risk of residual cement causing soft tissue inflammation.⁵ The success of cement-retained prostheses depends on sufficient retention and stability of the crown.⁶ Adequate retention and stability are therefore essential for the success of cement-retained prostheses.

Several factors affect the retention of cement-retained

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restorations on implants. Examples include abutment-related factors such as geometry, taper, surface area, height, surface roughness, retentive grooves, and the type and viscosity of the cement used.⁷ Generally, the retentive portion of a titanium abutment should be approximately 4–6 mm in height, as abutments shorter than 3.5 mm often fail to provide adequate retention for cemented crowns.⁸ In single-unit cement-retained restorations, particularly those with short crown heights, there is a higher risk of decementation. However, screw-retained restorations might exhibit esthetic challenges due to the access hole for the screw. Therefore, cement-retained restorations would be the preferred option in some cases, especially when short abutments are unavoidable.⁹ A significant geometric difference between natural teeth and implant abutments is the presence of an access hole and differences in the number of axial walls. Abutment design has a considerable impact on the retention of cemented crowns, as abutments with two opposing axial walls provide greater retention than those with a single continuous wall.¹⁰

Prior studies have evaluated different surface modifications to improve crown retention on short abutments, including adding grooves to the external surface of the abutment or the internal surface of the core.^{11–13} In this regard, using a circumferential transverse groove on the abutment increased the retention of cemented crowns.¹¹ In addition, increased retention was observed with milled and sandblasted abutments, as well as with abutments featuring retentive grooves.¹² Similarly, another study found higher retention in the frustum groove group than in the vertical groove group.¹³

Although most existing studies have focused on metal crowns, limiting their applicability to zirconia restorations, there is a lack of studies investigating the mechanical factors that influence the retention of cement-retained crowns on short titanium abutments. Therefore, our objective was to evaluate the effects of different mechanical modifications to the surface of short titanium abutments on the retention of zirconia crowns. These modifications included adding vertical grooves, frustum grooves, and circumferential transverse grooves, and removing axial walls. This study may provide insight into optimizing short abutment designs to improve the retention of zirconia crowns on short titanium abutments and to enhance the clinical longevity of cement-retained implant-supported restorations.

Methods

This in vitro study was conducted in 2022 at the Faculty of Dentistry, Tabriz University of Medical Sciences, Tabriz, Iran. Ethical approval was obtained from the Ethics Committee of Tabriz University of Medical Sciences (ethics code: IR.TBZMED.VCR.REC.1401.128). The study was conducted in accordance with international and national guidelines and regulations.

The sample size was calculated using the Power and Sample Size Calculator software. Based on the study by AlShaarani et al,¹³ with an expected mean difference of 130

units, a standard deviation of 114, a power of 80%, and an alpha of 0.05, 12 samples per group were required.

Abutment Design and Fabrication

Seventy-two custom straight titanium abutments were designed with a height of 3.5 mm, a diameter of 5.5 mm, a wall thickness of 1 mm, and a gingival height of 1 mm. The abutments were designed using the CATIA software. They were divided into six groups, and specific mechanical modifications were applied to the abutments as follows:

Control group (CG): No modification; abutments retained their original design.

Group 1 (G1: one wall removal): One wall (1/4 of the abutment's circumference) was removed up to 2 mm from the occlusal surface.

Group 2 (G2: two walls removal): Two opposing walls were removed up to 2 mm from the occlusal surface.

Group 3 (G3: axial groove): A vertical groove measuring 3 mm in height, 1.4 mm in width, and 0.7 mm in depth at the occlusal end (tapering to 1 mm in width and 0.5 mm in depth at the apical end) was created 0.5 mm from the finish line.

Group 4 (G4: frustum groove): A reverse vertical groove in the shape of a truncated cone (frustum) was created with dimensions similar to G3 but inverted.

Group 5 (G5: circumferential groove): A horizontal circumferential groove with a depth and width of 0.5 mm was placed 2 mm below the occlusal margin.

Modifications for CG, G3, and G4 were implemented into the design using CATIA software during the abutment's fabrication. Abutments in G1 and G2 were modified after fabrication using spark erosion with a custom electrode. All the abutments were milled from grade 5 titanium rods (Letherios, Italy) using CNC machines (HYUNDAI, Korea) (Figure 1). All the abutments were fabricated from the same batch of grade 5 titanium rods using identical CAD/CAM milling parameters. For groups 1 and 2, the wall-removal modifications were performed using a standardized spark erosion protocol with a custom electrode to ensure consistency of the intended abutment geometry among specimens. No additional surface treatment was performed after milling or spark erosion. The present study focused on the influence of abutment geometry on retention; therefore, micro-surface characteristics such as surface roughness were not evaluated.

Abutment Mounting

Fixture analogs were mounted in acrylic blocks using a surveyor to ensure proper parallelism. The abutments were attached to the analogs with a torque of 25 N/cm² using a ratchet. The screw access holes were sealed with wax during the laboratory steps for fabricating the copings (Figure 2).

Zirconia Crown Fabrication

Abutments were scanned using a 3Shape E3 scanner (3Shape, Denmark). Zirconia crowns were designed using Dental System software (3Shape, Denmark) with a cement gap of 0.025 mm at the margins and 0.045 mm elsewhere. A

retention stud was included in the proximal crown design for tensile testing. Crowns were milled from 14 mm thick monolithic zirconia blanks (VITA YZ T, Germany) using a CORiTEC 350i milling machine (Imes-Core, Germany) (Figure 3).

After milling, the crowns were cleaned in an ultrasonic bath with distilled water for 10 minutes and sintered in a VITA Zyrcomat furnace (Germany) following a long-term sintering protocol: gradual heating > 1.5 hours to a maximum of 1530°C, holding for 2 hours, and cooling to 400°C with the furnace closed.

Cementation Procedure

To simulate clinical conditions, the abutment screw access holes were filled with temporary filling material (Coltosol, Aria Dent, Iran) up to 1 mm below the occlusal surface. For the control, axial-groove, frustum groove, and circumferential groove groups, the access channels were filled to this level. However, in the one-wall and two-wall removal groups, because removal of the axial wall exposed part of the screw access channel, the temporary filling material was placed only to cover the screw head up to the level of the removed wall, reproducing the intended geometry of these modified abutments prior to cementation. Crowns were cemented using Embrace resin cement (Pulpdent, USA) per the manufacturer's instructions. Cement was mixed on a standard pad and applied as a uniform layer to the internal surface of each coping. The crown was initially seated with gentle finger

pressure to facilitate complete seating and extrusion of excess cement, followed by the application of a 5-kg static load for 5 minutes. Excess cement was removed with an explorer.



Figure 2. Mounting of analogs using a surveyor. This figure shows the mounting process of fixture analogs in acrylic blocks using a surveyor. The surveyor ensures parallelism and uniform alignment during the mounting procedure

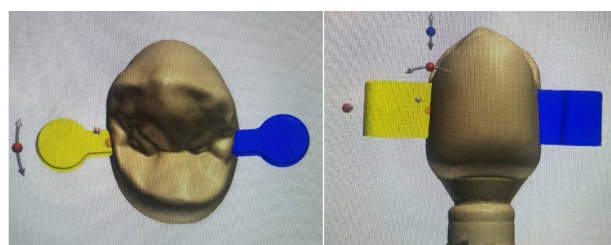


Figure 3. The design process of zirconia crowns using digital software. The abutments were scanned, and the crowns were designed with a proximal stud to facilitate pull-out testing

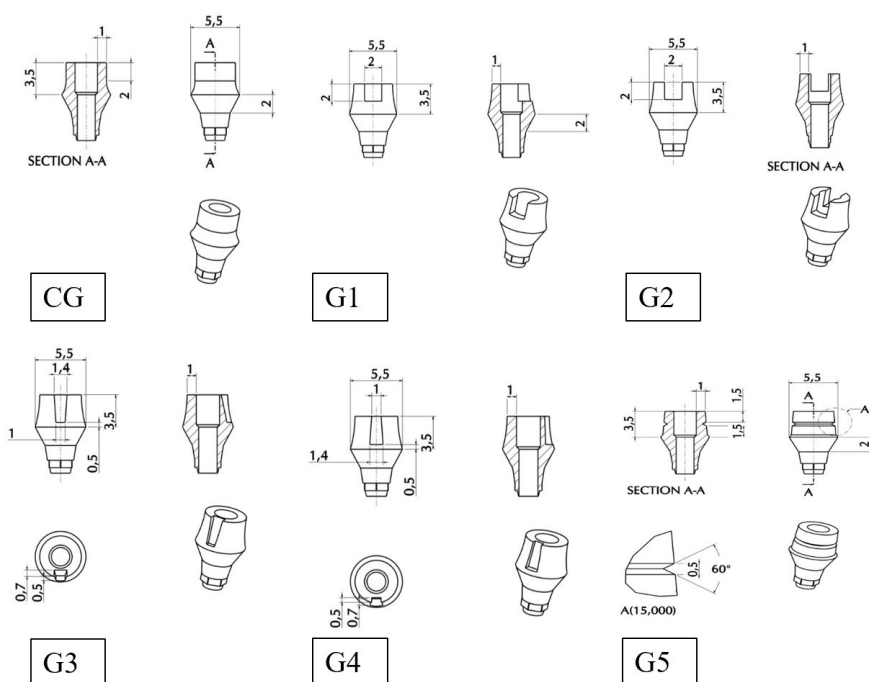


Figure 1. Design of abutments. The control group (CG) represents the original abutment design with no modifications. The G1 features an abutment design with one wall removed, specifically 1/4 of the circumference, with a height of 2 mm from the occlusal surface. In the G2, the abutment design includes the removal of two opposing walls, with each removed wall measuring 2 mm in height from the occlusal surface. G3 involves an abutment design with a vertical axial groove, 3 mm in height, tapering from 1.4 mm at the occlusal surface to 1 mm at the apical end, with a depth tapering from 0.7 mm at the occlusal to 0.5 mm at the apical end, positioned 0.5 mm from the finish line. G4 features an abutment with a frustum-shaped inverted vertical groove, with similar dimensions to G3 but in the opposite taper direction. G5 consists of an abutment with a horizontal circumferential groove, 0.5 mm in both depth and width, placed 2 mm below the occlusal surface

Retention Testing

Retention was evaluated by measuring the tensile force required to dislodge the zirconia crowns. This was performed using a universal testing machine (Hounsfield H25KS, UK) by attaching wires to the retention studs on the crowns.

Statistical Analysis

Data were reported as mean ± standard deviation (SD). The Kolmogorov-Smirnov test was used to verify the normal distribution of data, and Levene’s test was used to assess homogeneity of variance across groups. Statistical differences between groups were analyzed using one-way ANOVA at a significance level of $P < 0.05$. Statistical analyses were performed using SPSS 17.

Results

The retention of zirconia crowns varied significantly across the groups. The CG had the lowest mean retention value (155.93 N), while G5 showed the highest mean retention value (220.05 N). Groups G2 (201.94 N) and G3 (198.55 N), which involved modifications such as the removal of two opposing walls and the addition of axial grooves, also showed improved retention compared to the control. However, G1 and G4 showed intermediate retention values (Table 1).

The zirconia crown retention variable had a normal distribution ($P = 0.478$), and variances among the groups were homogeneous ($P = 0.130$). A statistically significant difference was observed between the mean retention values of the groups ($P = 0.003$).

The post hoc Sidak test revealed significant differences in zirconia crown retention between the control group and two modified abutment designs. Specifically, the retention in the two-wall removal group (G2) ($P = 0.035$) and the circumferential groove group (G5) ($P = 0.001$) was significantly higher than in the control group. Differences among the modified abutment groups themselves were not statistically significant (Table 2).

Discussion

The current study highlights the critical role of abutment design modifications in enhancing the retention of cement-

retained zirconia crowns, especially in cases of short abutments where limited interocclusal space is a challenge. This study evaluated the impact of various abutment wall modifications, including the removal of one or two walls, vertical grooves, frustum grooves, and circumferential grooves. Significant improvements in retention were observed with the removal of two opposing walls and the use of circumferential grooves. These findings showed that mechanical modifications to short titanium abutments can significantly improve the retention of zirconia crowns.

Our study showed significantly higher retention values in the two-wall removal and circumferential groove groups compared with the controls. Accordingly, Asutay et al.¹⁴ examined the effect of vent holes and horizontal grooves on the retention of metal frameworks in angled abutments. The study used non-eugenol cement and reported a significant increase in retention in the group with horizontal grooves, aligning with the findings of the current study. Similarly, Mishra et al.¹⁵ examined 60 implant abutments with different angles and reported a significant increase in retention with horizontal grooves on abutments ($P < 0.05$). Moreover, the retention of cast copings and cement remnants was evaluated in another study across four abutment groups: one horizontal groove, two horizontal grooves, vertical grooves, and a control group. A significant reduction in cement remnants was observed in groups with one or two horizontal grooves, and retention increased in the two-groove group, although the increase was not significant. The differences between our study and the study above might be explained by the use of different grooves, as they were created using burs in that study.¹⁶ Moreover, the categorization into different groups can also explain these differences. Lewinstein et al.¹¹ examined the effect of horizontal grooves and their number

Table 2. Results of post hoc Sidak test for the comparison of retention between the groups

Group 1	Group 2	Mean difference (Group 1-Group 2)	P value
Control	One wall removal	-38.40	0.144
	Two wall removal	-46.01	0.035
	Axial groove	-42.62	0.067
	Frustum groove	-35.71	0.223
	Circumferential groove	-64.12	0.001
One wall removal	Two wall removal	-7.61	1.000
	Axial groove	-4.22	1.000
	Frustum groove	2.69	1.000
	Circumferential groove	-25.72	0.750
Two wall removal	Axial groove	3.39	1.000
	Frustum groove	10.30	1.000
	Circumferential groove	-18.11	0.979
Axial groove	Frustum groove	6.91	1.000
	Circumferential groove	-21.50	0.917
Frustum groove	Circumferential groove	-28.41	0.607

Table 1. Retention values (Mean ± SD) of zirconia crowns across different abutment modification groups

Group	Mean (N)	Standard deviation (N)	95% confidence interval of mean (N)	Minimum (N)	Maximum (N)
CG	155.93	20.21	143.10 - 168.77	124.10	188.51
G1	194.33	36.32	171.25 - 217.41	137.06	250.10
G2	201.94	39.27	176.99 - 226.89	151.14	288.38
G3	198.55	36.59	175.30 - 221.80	149.92	263.48
G4	191.65	46.18	162.31 - 220.99	144.54	281.20
G5	220.05	28.65	200.81 - 239.30	177.54	280.11

CG: control group with no modifications. G1: abutments with one axial wall removed. G2: abutments with two opposing axial walls removed. G3: abutments with an axial groove added. G4: abutments with a frustum-shaped groove added. G5: abutments with a circumferential groove added

on the retention of Ni-Cr copings across four groups: control, one horizontal groove, two horizontal grooves, and three horizontal grooves. Using non-eugenol temporary and zinc phosphate cements, and following thermocycling, a pull-out test was conducted. For the temporary cement, retention increased with the number of grooves, while with zinc phosphate cement, a 60% increase in retention was observed with one groove, but additional grooves had no significant impact. These findings are consistent with our study, particularly due to the similarity in groove dimensions and milling methods. Additionally, another study examined the effects of axial and horizontal grooves on the retention of implant-supported cemented crowns across four groups, including no modification, one axial groove, two horizontal grooves, and three horizontal grooves. In contrast, our study used Ni-Cr crowns and temporary cement. The group with three horizontal grooves showed significantly higher tensile strength compared to other groups, which highlights that increasing the number of grooves increased strength. However, no significant increase in retention was observed in the group with axial grooves.¹⁷ Furthermore, the effects of axial features on the retention of cast crowns in short abutments across four groups of control, frustum groove, sagittal groove, and frustum groove with internal crown protrusion designs were investigated. Their findings showed that adding a frustum groove increased retention by 65%.¹³ Their study used different groove configurations and a different restorative material and fabrication approach, which likely contributed to the discrepancy between their findings and ours. In their work, the use of opposing grooves and directly waxed cast crowns may have altered the retention behavior compared with the CAD/CAM zirconia crowns used in the present study.¹³

Although the pull-out test provides a clear measure of axial retention, it does not replicate the complex oblique and cyclic forces present in the oral environment. Under oblique loading, the same design modifications may behave differently, and wall removal may also increase stress concentration in thinner regions of the abutment. Thus, while these modifications may improve retention, their potential effect on abutment strength and fracture resistance should be considered when translating the findings to clinical practice.

To contextualize our findings, several studies have assessed the effects of abutment wall modifications on crown retention, which clarify the interplay between wall removal, access channel filling, and crown design. In accordance with our findings, in the study by Tan et al,¹⁰ the effects of abutment wall removal on crown retention were evaluated by removing one wall, two opposing walls, two adjacent walls, and three walls. The results revealed that abutments with two opposing walls removed showed significantly higher retention compared to other groups, followed by abutments with three walls removed. The increased retention observed in abutments with two opposing walls removed can be attributed to the reduced hydraulic pressure of excess cement, which can lead to

more complete seating of the crowns during cementation. Additionally, the abutment access channel in this group was filled with less filler material compared to other groups, allowing it to act as a retention area and provide a pathway for excess cement to escape.¹⁰ This mechanism could also explain why the retention increase in the one-wall removal group in our study was not statistically significant. In this group, the abutment access channel was filled with a larger volume of filler material, potentially reducing the retention effect compared to the two-wall removal group. In addition, Derafshi et al.¹⁸ examined the effect of axial wall modifications on the retention of cast crowns. In their research, the first abutment group was the control group without any changes. In three other groups, part of one axial wall was removed to create three-walled abutments. The access channels in the first two groups were completely filled with composite resin, while in the third and fourth groups, the channels were only partially filled. Crowns in the first three groups were fabricated using a conventional design, while in the fourth group, crowns were designed with extensions into the abutment access channels. The results showed that the third group, which had a partially filled access channel and conventional crown design, had the highest retention compared to the other groups. Based on these findings, preserving the abutment's access channel and partially filling it is recommended for crowns on abutments with one wall removed to enhance retention.¹⁸ In our study, an increase in mean pull-out force was observed in the one-wall removal group compared to the control, but this difference was not significant. A reason for the discrepancy between the two studies could be the difference in abutment height. In the study by Derafshi et al,¹⁸ the abutments had a height of 5.5 mm, whereas the abutments in our study were shorter (3.5 mm). Therefore, this reduced height could explain the lack of statistical significance in retention improvement in our results.

Our study demonstrated that the horizontal groove group showed the highest retention compared to the control group. Emms et al.¹⁹ investigated the effects of access channel filling methods, axial wall height, and platform size on the retention of implant-supported crowns. The abutments were categorized into four groups: no modification, removal of one-third of the height of one axial wall (3 mm), removal of two-thirds of the height of one axial wall (6 mm), and complete removal of one axial wall (9 mm). The access channels were either partially or fully filled. It revealed that the highest retention was observed in the group where one-third of the axial wall height was removed. In addition, the method of filling the access channel significantly impacted crown retention.¹⁹ These findings highlight the importance of careful consideration of both abutment design modifications and access channel filling techniques to optimize retention.

The strength of our study is its focus on zirconia crowns, as most previous studies examined cast metal crowns fabricated through direct wax-up on the abutments. However, our study has some limitations that should be considered when interpreting the results. First, we did not

evaluate the effects of different cement types or varying numbers of grooves. Second, this study was conducted under static laboratory conditions without considering the complex intraoral environment, including thermal cycling, saliva, and biomechanical forces acting on the crowns. Therefore, further clinical studies are needed to confirm these findings in real-world scenarios. Third, the pull-out test assesses retention using a direct vertical force, which is relatively rare in the oral environment where crowns are subjected to lateral and angled forces. Thus, the impact of these more clinically relevant forces can also be considered in future research to better simulate intraoral conditions.²⁰ Another limitation is that micro-surface topography, including surface roughness after the post-fabrication spark-erosion procedure, was not quantitatively evaluated. Because the aim of this study was to investigate the effect of abutment geometry rather than surface characteristics, only the geometric modifications were standardized and assessed. Although all specimens were manufactured using standardized fabrication and modification protocols, minor variations in micro-surface topography cannot be excluded and may have influenced the measured retention values. Future studies should include profilometric or microscopic surface characterization to verify the consistency of modified abutment surfaces and to distinguish the independent effects of surface characteristics and abutment geometry on retention.

Conclusion

The findings of this study showed that modifying the abutment surface by introducing a horizontal groove significantly enhanced the retention of crowns on short abutments. Additionally, abutments with two opposing walls and a partially filled access channel demonstrated higher retention compared to the control group, suggesting them as the second most effective design. Horizontal grooves might be considered for the design of short abutments to improve crown retention and potentially extend the clinical lifespan of implant-supported restorations. From a practical standpoint, circumferential grooves are relatively straightforward to incorporate digitally during abutment design, whereas wall removal may require post-milling modification such as spark erosion. Therefore, both the biological and manufacturing implications should be considered when selecting the most suitable design for short abutments.

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Authors' Contribution

Conceptualization: Mahsa Kalantari, Ali Hafezeqoran, Roodabeh Koodaryan

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Writing–Review & Editing: Roodabeh Koodaryan, Ali Hafezeqoran, Fatemeh Bakhtiari, Mahsa Kalantari

Competing Interests

The authors declare no conflict of interest.

Consent for Publication

Not applicable.

Data Availability Statement

The data supporting this study's findings are available from the corresponding author upon reasonable request.

Ethical Approval

The Ethics Committee at the Faculty of Dentistry, Tabriz University of Medical Sciences, Tabriz, Iran, approved this study (Ethics Code: IR.TBZMED.VCR.REC.1398.222).

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