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Marginal Discrepancy and Internal Fit of Bi-Layered and Monolithic Zirconia Fixed Dental Prostheses: An In Vitro Study

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Abstract: This in vitro study evaluated the influence of restoration design (bi-layered vs. monolithic) and manufacturing technique on the marginal discrepancy and internal fit of 3-unit zirconia fixed dental prostheses (FDPs). Mandibular second premolars and second molars were prepared as abutments in a 3-unit zirconia bridge to develop four groups (*n* = 10 FDPs): MZ: Monolithic zirconia FDPs, ZL: zirconia framework veneered by the hand-layering technique, ZP: zirconia framework veneered by the heat-pressed technique, and CAD-on: zirconia framework veneered by CAD/CAM lithium-disilicate glass–ceramic. All the zirconia FDPs were cemented to their corresponding die replicas using dual-cure resin cement and were subjected to compressive cyclic loading at a load range for half a million cycles using a universal testing machine. FDPs were sectioned mesiodistally to measure the marginal gap and internal fit using scanning electron microscopy. The measurements were taken at pre-assigned points of each abutment. Data were statistically analyzed via a Kruskal–Wallis test ($\alpha = 0.05$). No significant differences were found between the monolithic and bi-layered zirconia groups in terms of the marginal discrepancy. However, there was a significant difference in the marginal gap between the zirconia groups. The marginal gap between monolithic and bi-layered zirconia FDPs was within the clinically acceptable range (<100 µm). Comparable mean values of the marginal gaps of 3-unit monolithic and veneered zirconia FDPs were found. Therefore, the FDP design and veneering methods did not affect the marginal discrepancy. However, the mean internal gap varied among the experimental groups. As the current in vitro investigation demonstrated equivalent mean values of marginal gaps of both 3-unit monolithic and bi-layered zirconia FPDs, the use of monolithic 3-unit zirconia FPDs would be a viable alternative fabrication technique.

Keywords: marginal; internal; zirconia; CAD/CAM; prostheses

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1. Introduction

The increased esthetic demands for all-ceramic restorations have enhanced the development of durable ceramic materials coupled with the use of computer-aided design and computer-aided manufacturing (CAD/CAM) technology in dentistry [1,2]. Zirconia has become a favorable choice among all-ceramic materials because of its superior mechanical properties exhibiting a flexural strength of approximately 1000 MPa [3]. However, despite the outstanding mechanical properties of zirconia, its application has been limited to the manufacturing of substrates of crowns and fixed dental prostheses (FDPs) owing to its high opacity [4]. Tooth-colored and highly translucent zirconia has been developed and increasingly utilized in full-contour (monolithic) single crowns and multi-unit restorations [5,6]. Increased translucency in zirconia was achieved by reducing the alumina additive to 0.05% by weight while maintaining the yttrium oxide stabilizer at 3 mol% (equivalent to 4.5–5.6 wt%). Further improvement in translucency was observed when the yttrium oxide content exceeds 4 mol% (less than 10 wt%), in conjunction with an increase in cubic phase zirconia. These changes facilitate the use of zirconia as a monolithic restoration material without an additional veneer layer [7].

Survival and success rates of the zirconia restorations were evaluated according to their mechanical and biological outcomes. Several studies indicate that the most common mechanical failure of zirconia-based restorations is chipping (cohesive failure) within the veneer layer [8–12]. In addition to the mechanical complications, biological complications including periodontal problems, loss of vitality, and secondary caries have been reported [13,14]. A systematic review indicated that secondary caries and loss of vitality result from an improper fit of all-ceramic restorations [13].

A well-fitted margin is essential for reducing plaque buildup, preventing recurrent caries, and potentially prolonging the restoration's lifespan [15]. Research studies suggest that a marginal opening of 50 µm to 100 µm is clinically acceptable [16,17]. However, the quality of the restoration fit can be affected by factors like impression, fabrication, and luting thickness. A study by May et al. [18] found that increasing the thickness of the resin cement decreased the failure load of feldspathic porcelain crowns. This is because a thicker layer of cement can result in a higher concentration of stress [19]. Additionally, research by Rezende et al. [20] demonstrated that thicker cement spaces can lead to high-stress concentration, specifically under the occlusal area of bi-layered zirconia crowns. Conversely, insufficient cement space can hinder the proper seating of the restoration, potentially resulting in a larger marginal gap, which can lead to biological complications [21]. Therefore, maintaining a cement thickness layer within the range of 50 µm to 100 µm is considered advantageous for ensuring the long-term performance of zirconia restorations.

Veneering porcelains are manually layered onto the zirconia substructure, although the press veneering porcelain technique is considered a viable alternative [22]. In addition to manual layering and pressing techniques, CAD/CAM veneering techniques for fabricating zirconia restorations have been developed to improve the chipping resistance of zirconia restorations [23]. Torabi et al. [24] evaluated the marginal gap of zirconia copings for single crowns before and after veneering with three different veneering techniques. The mean marginal gap, prior to veneer application, was 35 µm; this value increased after the veneering process to 63, 50, and 51 µm when using layering, pressing, and CAD-on veneering techniques, respectively.

The production methods of zirconia prostheses significantly affect the marginal integrity of monolithic and bi-layered zirconia FDPs [2,25]. Zirconia blocks are available as both pre-sintered and fully sintered blocks. From fully sintered zirconia, the desired restoration with the final dimensions can be milled with accurate fit results because fully sintered zirconia does not shrink upon sintering. Pre-sintered zirconia blocks can be milled to an enlarged size, where a shrinkage of approximately 25% occurs during the final sintering process of these blocks. This shrinkage must be compensated for at the milling stage [26,27]. Schriwer et al. [28] emphasized that zirconia restorations fabricated from fully sintered blocks using the hard machining method exhibited superior fit tolerance and marginal adaptation compared with zirconia produced by soft machining. This improper fit could be attributed to the shrinkage that occurs in the pre-sintered zirconia after sintering. In a recent study that evaluated the marginal discrepancy of monolithic zirconia produced using different CAD/CAM systems, the marginal fit of all groups was within the clinically acceptable range [29]. It was concluded that monolithic zirconia milled using 5-axis and dry milling exhibited excellent marginal adaptation.

As monolithic zirconia has been used to overcome the technical complications of veneer ceramics in layered zirconia restorations, the marginal and internal discrepancy data of monolithic 3-unit zirconia FDPs compared with bi-layered FDPs are limited. Therefore, this study aimed to evaluate the influence of the restoration design (monolithic vs. bi-layered) and manufacturing technique on the marginal discrepancy and internal fit of layered and monolithic zirconia FDPs. The null hypothesis that was tested was that the restoration design and manufacturing technique had no significant effect on bi-layered and monolithic zirconia restorations.

2. Materials and Methods

Tooth preparation was performed on an epoxy resin mandibular second premolar and second molar. The prepared teeth were used to prepare replicas using a highly filled epoxy resin (Viade Products Inc., Camarillo, CA, USA) to serve as abutments for the 3-unit zirconia restorations (n = 10 FDPs) in each group (Figure 1). Considering a pilot study, the sample size was calculated using G*Power software to maintain 80% power and 95% precision (α = 0.05).

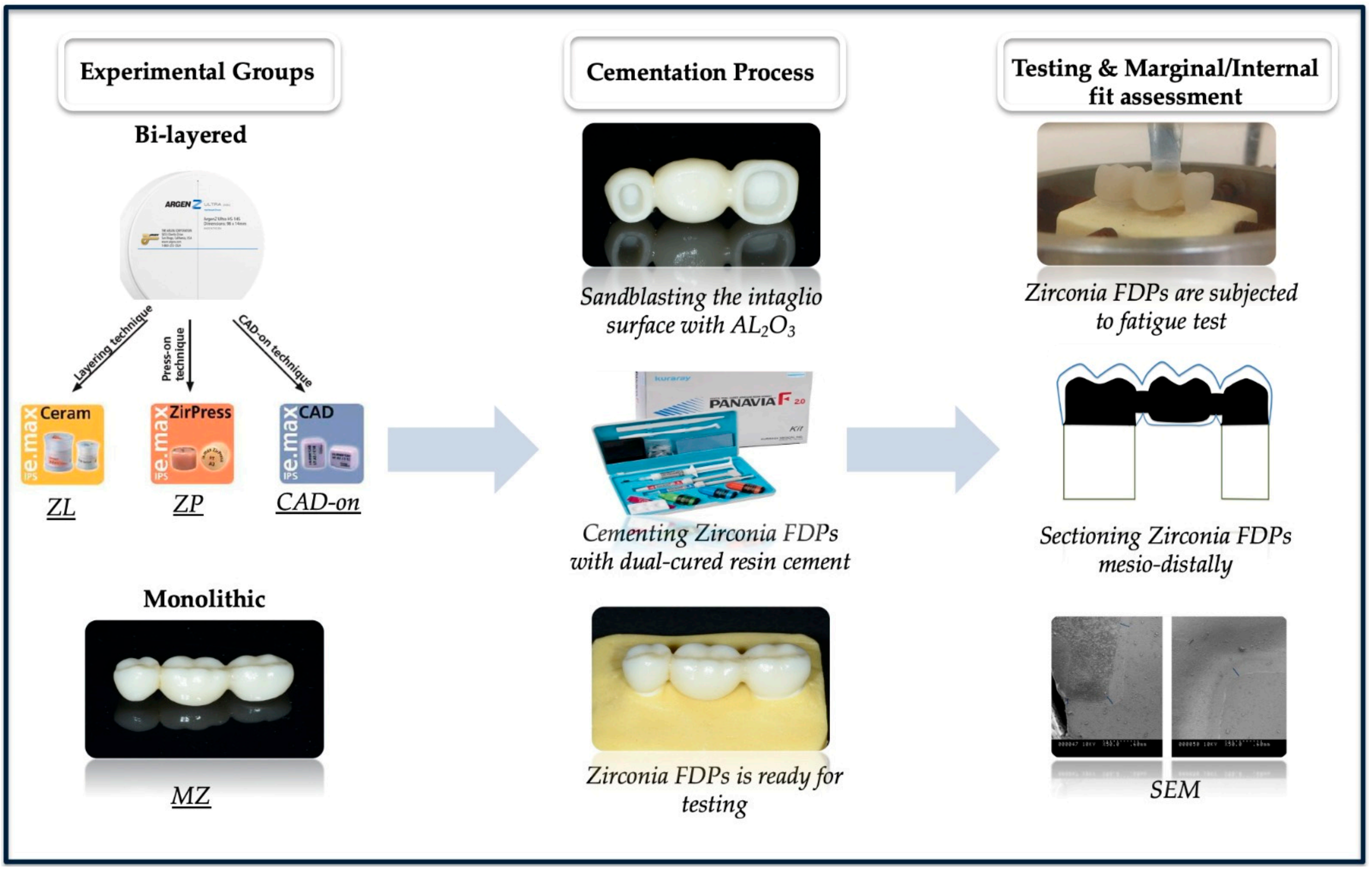

Figure 1. Flow diagram showing fabrication process and marginal/internal gap assessment.

2.1. *Zirconia Frameworks Fabrication*

The prepared teeth replicas were digitally scanned, and the framework was designed using the cut-back technique at 0.5 mm minimum thickness abutment copings and a connector size of 9 mm^2. An Argen Z, (Argen Z Ultra, Argen Corporation, San Diego, CA, USA) disc was milled using CAD/CAM system (Roland DWX-50, DG Corp, Osaka, Japan), and the final sintering was performed according to the manufacturer's recommendations.

2.2. *Veneering Process*

2.2.1. Conventional (Layering) Veneering Technique (ZL)

The milled and sintered frameworks were cleaned under running water to remove any remaining debris. A conventional hand-layering technique (IPS e.max Ceram, Ivoclar

Vivodent, Schaan, Liechtenstein) was utilized for veneer application. The veneer layer was then sequentially built to the desired shape and thickness following the manufacturer's recommendations.

2.2.2. Pressed-on Veneering Technique (ZP)

A fully anatomical wax pattern was fabricated on the zirconia framework. The thickness and shape of the wax pattern were maintained for all the specimens using a silicon impression of a fully anatomical bridge. A sprue was attached to the restoration to proceed with investing (IPS PressVEST, Ivoclar Vivadent, Schaan, Liechtenstein) and then burned out. Finally, the IPS e.max Zirpress Ivoclar Vivadent ingots were pressed into the mold using a press furnace followed by a glaze layer.

2.2.3. CAD-on Veneering Technique (CAD-on)

The prepared tooth replicas were digitally scanned, and the framework and veneer were designed using the split file technique. The zirconia framework was milled with 0.5 mm minimum thickness abutment copings and a connector size of 9 mm^2 (Argen Z Ultra, Argen Corporation, San Diego, CA, USA). The veneer was milled using a lithium-disilicate glass–ceramic (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein). Both the milled framework and the milled veneering ceramic were fused together using low-fusing glass–ceramic (IPS e.max CAD crystal/connect Ivoclar, Vivodent, Schaan, Liechtenstein). A fusion ceramic agent was applied to the intaglio surface of the veneer, and a vibration device was used for full seating of the veneer onto the framework, followed by crystallization and glazing firing.

2.3. Monolithic Zirconia (MZ)

This group comprised monolithic 3-unit zirconia bridges (Argen Z Esthetic, Argen Corporation, San Diego, CA, USA). The restoration was designed and milled according to the manufacturer's recommendations with a minimal occlusal thickness of 1.5 mm. The pre-sintered bridge was sintered in a special furnace, followed by a glazing step.

2.4. Marginal and Internal Fit Measurements

All frameworks were tried on the tooth replica abutments to ensure proper fitting. The intaglio surface of zirconia FDPs was grit etched with aluminum oxide. Subsequently, the zirconia FDPs were cemented to the abutment replicas with Panavia F2.0 resin cement (Kuraray, Okayama, Japan) according to the manufacturer's recommendations. Prior to cyclic loading test, specimens were stored in water at 37 °C for 24 h. The specimens were subjected to compressive cyclic loading prior to marginal and internal fit measurements. The cyclic loading test was performed in water at 37 °C using a universal testing machine (Instron, Canton, MA, USA), with a load range of 50–600 N for up to 500,000 cycles. All specimens were examined under light microscope. Minor and moderate chipping within the veneering porcelain was recorded for both ZL and ZP groups, whereas ZM and CAD-on specimens survived the fatigue test with no failure. However, no specimen was excluded from the study, neither due to debonding nor due to fracture. After completion of the compressive cyclic loading test, the specimens were sectioned mesiodistally to determine the internal fit tolerance by measuring the cement film thickness and margin gap under a scanning electron microscope (SEM) at 50× magnification. Measurements were performed at ten pre-assigned points via a single examiner for each abutment (Premolar and Molar). The measurement points were defined as follows: 1: marginal gap (MG), 2: cervical (C), 3: axial (A), 4: axio-occlusal (AO), and 5: occlusal (O) (Figure 2). Image analysis software (ImageJ, National Institute of Health) was used to measure the marginal and internal fit from SEM images (Figure 3).

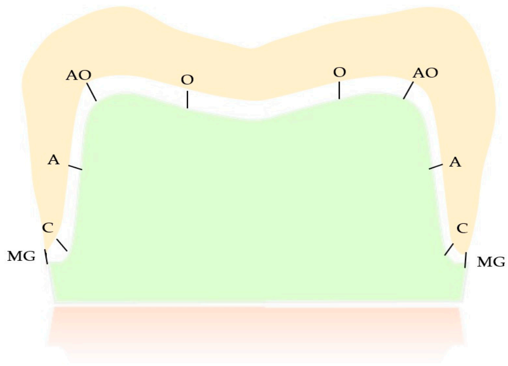

Figure 2. Schematic representation of the measurement points: marginal gap (MG), cervical (C), axial (A), axio-occlusal (AO), occlusal (O).

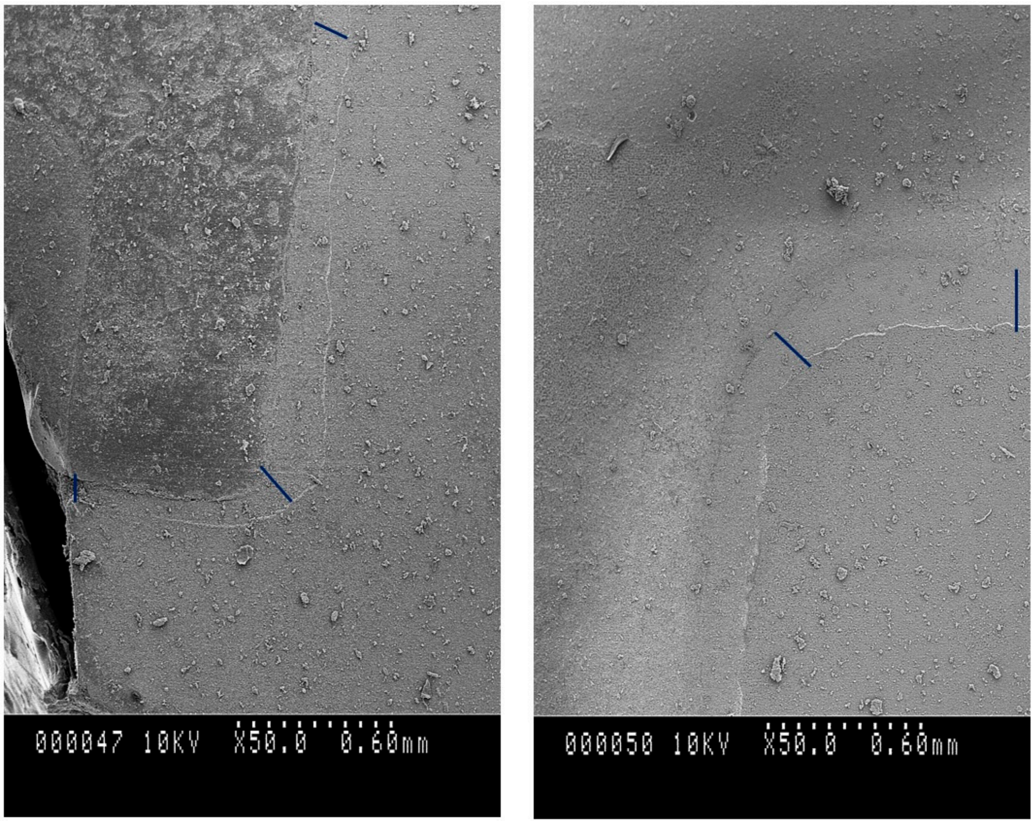

Figure 3. SEM images representing the measurement locations.

Previously, normality test was conducted, and the data were not normally distributed. Therefore, the marginal and internal discrepancies were statistically analyzed using Kruskal–Wallis test followed by Mann–Whitney U test at ($\alpha = 0.05$).

3. Results

The results of the marginal adaptation of the investigated groups are shown in Table 1 and Figure 1. The marginal gap for the experimental groups was within the acceptable clinical range (50–100 µm) (Figure 4). The marginal gap value for premolar and molar abutments varied among the groups in the range of 65.17–84.33 µm. The Kruskal–Wallis test indicated no significant differences between the groups for each abutment, premolar (p = 0.76) or molar (p = 0.86), in terms of the marginal gap.

Table 1. Marginal and internal gap discrepancy measurements (μm).

Groups		Median (μm) (IQR 25th–75th)				
		Marginal	Cervical	Axial	Axio-Occlusal	Occlusal
MZ	Premolar	76.50 (50.75–88.25)	113.00 (83.50–143.00)	90.50 (74.25–112.75)	131.00 (81.25–174.00)	145.00 (76.50–213.50)
	Molar	76.00 (58.25–99.75)	116.50 (102.50–136.00)	80.00 (58.00–97.50)	87.50 (79.75–120.00)	150.00 (115.00–230.00)
ZL	Premolar	69.00 (63.00–79.25)	114.00 (108.50–132.00)	119.00 (89.50–125.25)	147.50 (95.75–191.75)	142.00 (118.50–228.50)
	Molar	81.00 (70.00–96.50)	129.50 (109.75–14,025)	106.50 (82.00–122.00)	175.50 (144.50–217.0)	161.50 (147.25–267.25)
ZP	Premolar	64.50 (54.00–74.50)	103.50 (88.00–143.00)	120.00 (104.0–130.00)	140.50 (122.75–174.0)	153.00 (129.25–187.25)
	Molar	77.00 (58.00–88.00)	127.00 (117.50–135.50)	119.00 (117.25–132.0)	186.00 (139.00–225.0)	167.50 (151.00–240.25)
CAD-on	Premolar	61.30 (47.25–80.00)	109.00 (97.50–139.00)	85.00 (72.50–93.75)	122.00 (95.00–137.00)	144.00 (123.50–182.50)
	Molar	75.50 (49.00–97.00)	118.50 (102.50–144.25)	86.00 (81.25–105.00)	128.50 (108.25–139.0)	163.00 (133.75–249.25)

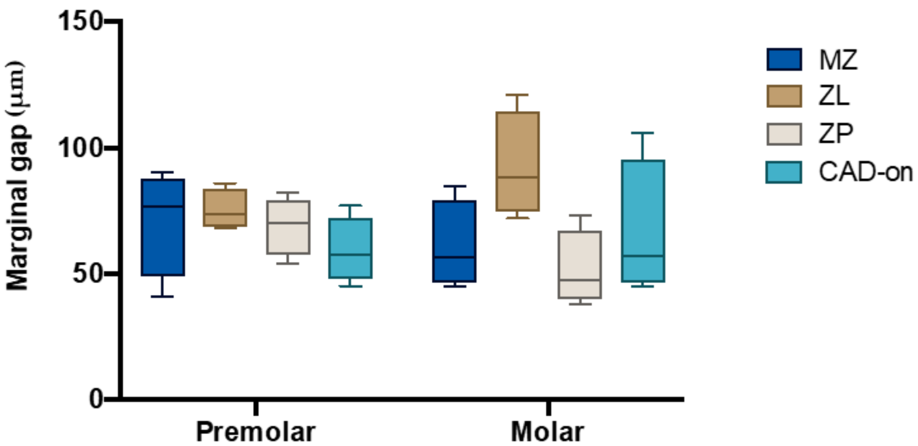

Figure 4. Boxplot representing the marginal gap (μm) measurement of zirconia FDPs.

The internal gap was evaluated at cervical, axial, axio-occlusal, and occlusal points. The internal fit results of both the monolithic and bi-layered zirconia FDPs are presented in Table 1. The lowest internal gap value was observed at the axial points, whereas the highest gap value was found in the occlusal area in all groups.

The Kruskal–Wallis test indicated a significant difference between the groups in the axial and axio-occlusal areas ($p < 0.001$) of both the molar and premolar (Figure 5). In the axial area, the Mann–Whitney U test showed a significant difference in premolar abutment between the ZP and CAD-on groups. At the molar abutment, the Mann–Whitney U test indicated a significant difference between the MZ and ZP groups and between ZP and CAD-on. For the axio-occlusal area, the Mann–Whitney U test showed a significant difference in the molar abutment only between the MZ and ZL, MZ and ZP, ZL and CAD-on, and ZP and CAD-on groups. However, the Kruskal–Wallis test showed no statistically significant difference at the cervical and occlusal measurement points for both premolar and molar abutments.

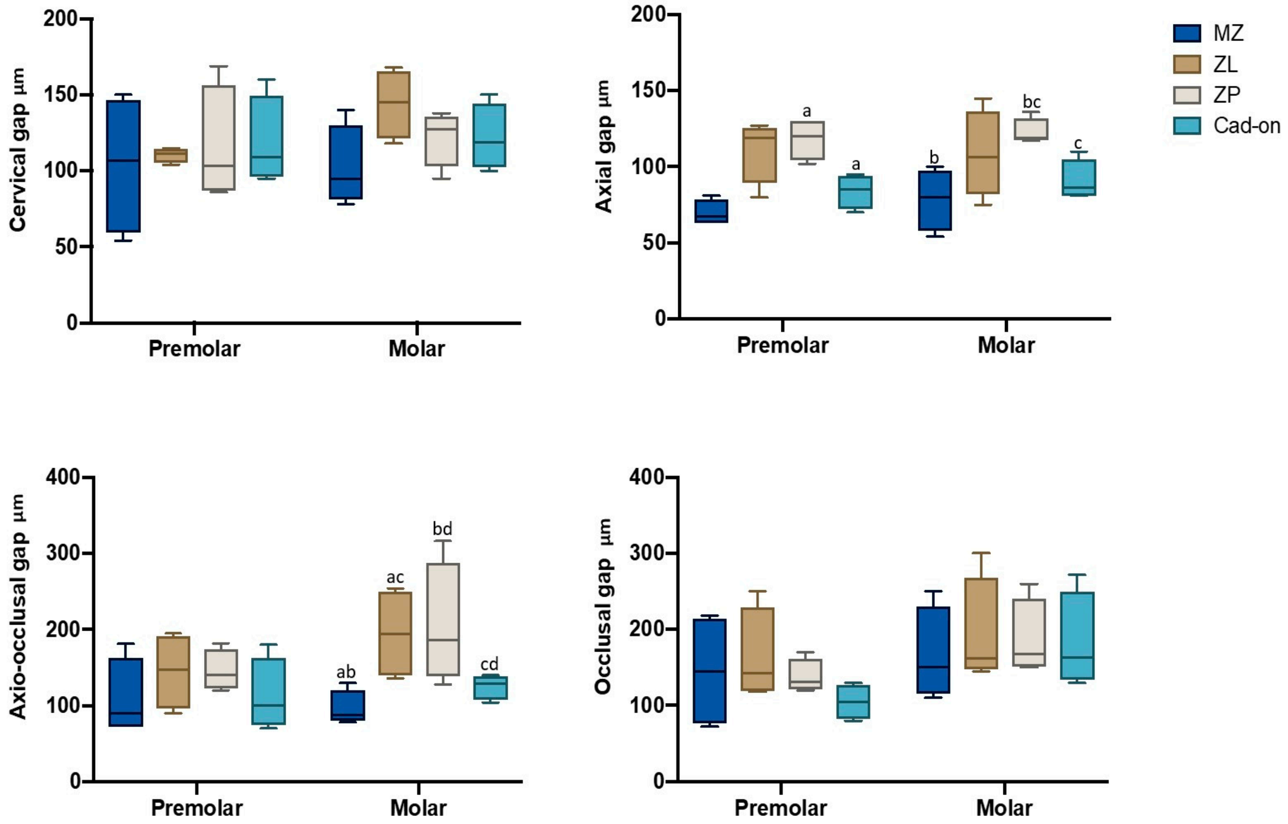

Figure 5. Boxplot showing the internal gap measurement at axial, cervical, axio-occlusal, and occlusal areas of zirconia FDPs for both abutments. The same letter indicates significant differences between the groups.

4. Discussion

A proper fit of zirconia FDPs is essential to ensure excellent long-term longevity and performance. Thus, this in vitro study evaluated the marginal and internal fit of monolithic and bi-layered zirconia FDPs. With respect to the marginal discrepancy, no significant difference was observed between the groups; therefore, the null hypothesis could not be rejected. The marginal openings between 50 and 100 µm are considered to be clinically acceptable [16,17]. In this study, the marginal gap for monolithic and bi-layered 3-unit zirconia FDPs was within the acceptable clinical range. In contrast, there was a significant difference in terms of internal discrepancy; therefore, the null hypothesis stating that 3-unit zirconia FDPs design and manufacturing techniques affected the internal fit was rejected.

The marginal and internal fit of zirconia restorations can be affected by various factors, including impression procedures, fabrication processes, and cementation [29–34]. The precision of the impression technique affects the fit of the dental restorations. Studies have compared the fitting accuracy of zirconia restorations using digital and conventional impression methods [29,35]. In a systematic review, Chochlidakis et al. [36] concluded that the marginal discrepancy of all-ceramic restorations manufactured using the digital impression method is statistically similar to those constructed using the conventional impression method. In this in vitro study, digital impressions were used to fabricate the 3-unit monolithic and veneered zirconia restorations. The marginal gap ranged between 65.17 µm and 84.33 µm. Consistent with our study, Su and Sun [31] compared the marginal and internal fit of 3-unit zirconia FDPs fabricated using digital and conventional impressions. They revealed that the marginal gaps were 63–76 µm for digital and conventional impressions, respectively. In contrast, Wettstein et al. [37] found that the internal gap of 3-unit zirconia FDPs fabricated using digital impression differs from that of conventional metal–ceramic restorations. The variation between the results of the current investigation and those of previous studies can be attributed to the performance of different CAD/CAM systems.

The veneering technique and material used affect the fitting of zirconia restorations. The influence of the veneering process on zirconia restoration has been investigated in previous studies for both zirconia crowns and FDPs in previous studies [25,26]. In an in vitro study evaluating the marginal discrepancy of zirconia copings before and after veneering procedures, investigators found a significant increase in the marginal opening after the veneering process [26]. In this study, the marginal gap in the ZL, ZP, and CAD-on groups were 77.25, 69.92, and 68.42 µm, respectively. The highest mean value of the marginal opening was observed in the zirconia group that was veneered manually (ZL). A possible explanation for this finding could be the influence of the number of firing cycles. Manual veneering usually requires between four and five firing cycles, while between two and three firing cycles are needed for pressed-on and CAD-on techniques. In addition to the number of firing cycles, the coefficient of thermal expansion mismatch between the veneering material and the zirconia framework is another factor. This difference causes stresses in the veneering layer during cooling from the glass transition to room temperature [27]. As veneering methods negatively affect the marginal adaptation of bi-layered zirconia FDPs, information regarding the influence of glazing firing on monolithic zirconia restorations is limited. To the best of our knowledge, only one study has emphasized that the glazing procedure does not affect the marginal discrepancy of single monolithic crowns [38].

The marginal fit of zirconia restorations is affected by cementation. A systematic review indicated that cementation dramatically increased the marginal gap value [16]. Kale et al. [38] measured the vertical marginal discrepancy of monolithic zirconia crowns before and after cementation. The marginal gap increased from 38 µm in the pre-cementation stage to 60 µm after cementation. This increase could be attributed to the pressure applied during cementation to gain full seating of the crown, which most likely resulted in an uneven cement layer. The measurements at the marginal gap in the current study were performed after the cementation process because all specimens were subjected to a compressive cyclic loading for half a million cycles that represented five years of chewing function. In addition, the measurement method utilized cross sectioning using scanning electronic microscopy, which was not possible prior to the fatigue test.

Previous investigations have reported that the largest internal gap occurs in the occlusal area of zirconia FDPs [12,14]. The acceptable average occlusal gap has been reported to range from 100 to 200 µm [39]. In the present study, the mean occlusal gap in each group was in the acceptable occlusal range. The lowest mean occlusal gap was revealed as 145 µm for monolithic zirconia FDPs, whereas the highest was 192 µm for zirconia FDPs veneered manually. Bayramoğlu et al. [40] indicated that the internal gap at the occlusal area of zirconia restoration was 204 µm compared with the occlusal gaps of traditional veneered metal–ceramic and pressed-on metal–ceramic restorations, which were 397 and 285 µm, respectively. The reasons for obtaining high occlusal and axial gaps could be attributed to defects in the scanner resolutions, which led to reduced scanner accuracy along with milling device limitations [39].

The results of the current investigation showed no significant difference between monolithic and bi-layered zirconia FDPs with respect to the marginal adaptation. The mean marginal opening of the monolithic zirconia FDPs was 74.92 µm. Suárez [41] et al. compared the marginal fit of monolithic 3-unit zirconia FDPs with that of bi-layered zirconia FDPs. The marginal gap was 76.2 (36.3) µm and 77.4 (38.9) µm for veneered and monolithic zirconia FDPs, respectively. These results are consistent with the findings of the present investigation. In this study, the marginal gaps for both monolithic and layered zirconia FDPs were within the acceptable clinical range and less than 100 µm. By contrast, Schoenberger et al. [42] examined and evaluated the fit of highly translucent and regular zirconia manufactured using different CAD/CAM systems (Cercon vs. Ceramill). The authors found a significant difference between the zirconia brands fabricated using different

CAD/CAM systems. One possible explanation for the different results of these studies is the use of different CAD/CAM systems.

The study findings have practical relevance for dental professionals and laboratories engaged in the manufacture of zirconia FDPs. Understanding how different restoration designs and manufacturing procedures impact fit and marginal discrepancy might help clinical decision making and patient outcomes. The results of this present in vitro study should be interpreted with caution for several reasons. Monolithic and bi-layered zirconia restorations were fabricated under ideal conditions using the same cast model, which does not imitate clinical procedures. In addition, the marginal and internal fits of the zirconia restorations were measured by a cross-sectioning technique using scanning electron microscopy. This technique allows the fit of the restorations at certain points to be measured. Another limitation of our study is the use of resin tooth replicas rather than extracted teeth. Using resin tooth replicas allowed us to standardize the size and preparation of the teeth, ensuring consistent conditions for testing the marginal discrepancy and internal fit of zirconia FDPs. However, resin tooth replicas have some inherent shortcomings and do not perfectly duplicate the complexity of natural teeth. The results of our investigation, particularly in relation to marginal integrity, may be influenced by the way resin tooth replicas respond to load and stress in comparison with natural teeth. Clinical investigations are needed to verify the result of this study on the effect of restoration design (monolithic vs. bi-layered) and manufacturing technique on the marginal and internal fit.

5. Conclusions

Within the limitations of the present study, the following conclusions could be drawn:

- The restoration design (bi-layered vs. monolithic) has no effect on the marginal discrepancy.
- The marginal fits of 3-unit monolithic and veneered zirconia FDPs are within the acceptable clinical range.
- The internal fit at the occlusal area showed the highest cement film thickness for both veneered and monolithic zirconia FDPs.

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