






## RESEARCH ARTICLE

# Influence of Thermal Aging on the Marginal/Internal Fit of Incisor Veneered and Monolithic Zirconia Crowns

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## ABSTRACT

**Objectives:** The aim of the study was to evaluate and compare the effect of thermal aging on the marginal and internal adaptation of veneered and monolithic zirconia (MZ) crowns.

**Materials and Methods:** A maxillary central incisor abutment was digitally designed, fabricated using resin, and scanned for crown design. MZ (IPS e.max ZirCAD Prime Esthetic) and veneered zirconia (VZ; coping: Everest, KaVo; layering: IPS e.max Ceram) crowns were fabricated ( $n = 10$ ). STL files were analyzed in Geomagic Design X to calculate root mean square (RMS) values within the selected marginal and internal regions before and after 10,000, 30,000, and 50,000 thermal cycles with superimposition. Data were analyzed using Shapiro–Wilk and Mann–Whitney  $U$  tests. The comparison of thermal aging treatments was evaluated using the Friedman and post hoc Wilcoxon signed-rank tests ( $p < 0.05$ ).

**Results:** Significant differences were found between MZ and VZ crowns ( $p < 0.05$ ). In the MZ group, marginal gaps increased from  $104\ \mu\text{m}$  (T0) to  $115\ \mu\text{m}$  (T3), and internal gaps from  $122\ \mu\text{m}$  (T0) to  $146\ \mu\text{m}$  (T3). In the VZ group, marginal gaps increased from  $82\ \mu\text{m}$  (T0) to  $128\ \mu\text{m}$  (T3) and internal gaps from  $136\ \mu\text{m}$  (T0) to  $204\ \mu\text{m}$  (T3). VZ crowns showed higher dimensional changes than MZ crowns.

**Conclusions:** Thermal cycling significantly affected the fit of zirconia crowns. VZ crowns exhibited greater dimensional changes after 30,000 and 50,000 thermal cycles, while MZ crowns maintained superior marginal fit during the same periods.

**Clinical Significance:** This study highlights the influence of thermal aging on the marginal and internal adaptation of veneered and MZ crowns. VZ may be more susceptible to marginal or internal discrepancies after thermal aging, when compared with the MZ.

## 1 | Introduction

Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) are commonly used in dentistry for their exceptional biocompatibility, low plaque accumulation, abrasion resistance, color stability, and outstanding mechanical qualities [1]. Zirconia demonstrates a high degree of fracture toughness in contrast to the inherent brittleness of ceramics. A process called

“transformation toughening,” which involves a stress-induced phase change within the material, specifically the transition from the tetragonal to the monoclinic phase, is responsible for this toughening mechanism [2, 3]. When zirconia is exposed to a moist environment at low temperatures between  $65^\circ\text{C}$  and  $300^\circ\text{C}$ , a condition known as “low-temperature degradation” (LTD) takes place [4, 5]. This degradation process initiates at isolated surface grains and progressively spreads

from the surface into the bulk material, resulting in surface roughening and reduced mechanical strength [6]. These microstructural changes can compromise the dimensional stability of zirconia restorations and potentially affect marginal adaptation over time [7].

Porcelain veneering has traditionally been employed to enhance the esthetic properties of zirconia-based restorations. Although zirconia substructures are stronger, the esthetic result may be impaired by their opacity. In addition, a common complication associated with bilayered zirconia restorations is veneering ceramic chipping [8–10]. Monolithic zirconia (MZ) restorations, which give greater translucency while preserving zirconia's mechanical qualities, have been created to overcome these drawbacks [11–14]. Several changes have been made to achieve this improved translucency, such as adding 0.2mol% lanthanum oxide, raising the yttria content, or decreasing the alumina percentage [15–17]. These restorations, however, are directly exposed to the intraoral environment, which includes temperature, pH, and humidity changes that can be impacted by the LTD phenomenon [18, 19].

The success of ceramic crowns is closely related to their marginal and internal fit. Even though CAD/CAM technology has a better marginal fit than traditional techniques, the milling process can cause LTD, which increases zirconia's monoclinic phase concentration [20]. This effect is more noticeable in places with thin cervical margins where the monoclinic phase ratio is often higher [1, 21]. Furthermore, the cervical margins are the only area in which the zirconia's inner, outer, and edge surfaces are all treated. Some studies suggest that the compressive stresses produced by the transition from the tetragonal phase to the monoclinic phase can improve the material's flexural strength and LTD resistance [22–24]. However, this could compromise the restorations' longevity. Sandblasting and other surface treatments have been found to lower the Weibull modulus of zirconia, which serves as an indicator of clinical reliability [25]. As a result, these changes may negatively affect the marginal fit of restorations over time. Inadequate marginal fit can lead to plaque accumulation, increased caries risk, microleakage, and periodontal issues, all of which can reduce the longevity of the restoration and even result in tooth loss. According to research, marginal gap (MG) values range from 3.7 to 200  $\mu\text{m}$ , with a maximum acceptable MG of 120  $\mu\text{m}$  [26, 27].

The mechanical characteristics of bilayered and MZ are influenced by a number of variables, such as cement gap, veneering procedures, cementation methods, and tooth preparation design [1, 28]. While the effects of thermal aging on zirconia's microstructure and LTD characteristics have been investigated by various researchers [1, 22–25, 29–31], the long-term influence of thermal aging on marginal fit remains unclear. Therefore, the aim of this *in vitro* study was to evaluate the effect of thermal cycling at 10,000, 30,000, and 50,000 cycles on the marginal fit of different zirconia crowns produced with a bilayered and monolithic approach, and to compare the durability of two distinct, clinically alternative zirconia restoration types. The null hypothesis of this study was that there would be no difference in the marginal/internal fit among the different production techniques of zirconia crowns tested within each time interval after thermal cycling.

## 2 | Materials and Methods

A maxillary central incisor tooth with a prepared crown was digitally designed and fabricated with a 3D printer (Anycubic Photon Mono Ultra), using photosensitive resin. The tooth preparation was designed with a 5-mm mesiodistal cervical diameter, 7-mm labiolingual cervical diameter, 6.5-mm height, 2.5-mm cingulum height, and a 1-mm-wide chamfer-type marginal finish line. Then, the printed abutment tooth was placed on a dentate maxillary typodont study model and scanned with the laboratory scanner (E3, 3Shape) with an accuracy of  $\pm 15 \mu\text{m}$ . The acquired standard tessellation language (STL) file was sent to the dental laboratory for designing crowns with a 70- $\mu\text{m}$  cement space for the axial and incisal surfaces of the abutments and zero space at the finish line. The axial wall thickness of the crowns was uniformly set at 0.8 mm, while the incisal thickness was 2.5 mm.

The sample size of the study was determined through power analysis (G\*Power, v3.1.9.7, Germany) using an effect size of 0.8,  $\alpha = 0.05$ , and power = 0.8 for two independent groups, indicating that a minimum of seven specimens per group was needed. Therefore, inclusion of 10 specimens per group ( $n = 10$ ) was considered appropriate and increased the power. The anatomically contoured milled MZ crowns ( $n = 10$ ) were produced from pre-sintered MZ blocks (IPS e.max ZirCAD Prime Esthetic, Ivoclar AG) with a milling machine (PrograMill PM7, Ivoclar AG) according to the manufacturer's instructions. Then, the crowns were sintered at 1500°C for 9 h 50 min. Adjustments of any crowns were avoided and they were manually polished (Luster Zirconia Adjusting and Polishing Kit, Hager & Meisinger GmbH) after sintering procedures. For the second group of the study, the frameworks of the veneered zirconia (VZ) crowns ( $n = 10$ ) were fabricated from pre-sintered Y-TZP zirconia blocks (Everest, KaVo Dental GmbH) with a milling machine and sintered at 1500°C for 9 h 50 min. A silicone index from a MZ crown was used to ensure standardized porcelain layering, achieving an identical axial wall thickness of 0.8 mm and incisal thickness of 2.5 mm for both MZ and VZ crowns. The copings were then veneered with hand-layered porcelain (IPS e.max Ceram, Ivoclar AG) by a dental technician with 30 years of experience. The veneer porcelain was fired in a furnace (Vacumat 4000 Premium T; VITA Zahnfabrik) up to 750°C with a 40°C/min heating rate, according to the manufacturer's instructions.

Among various adaptation assessment techniques, 3D superimposition methods have shown high reliability, precision, and repeatability in evaluating internal and marginal fit [32–38]. The dual scan method by Kane et al. [39], which is a well-described and common technique, was applied to assess the marginal adaptation of the crowns. All measurements were performed without any crown luting procedure, and only a single reference abutment placed on the model was used, allowing for the analysis of the changes in crown adaptation over time within the same sample. A “reference scan” was generated by scanning a 3D printed prepared abutment tooth mounted on the maxillary typodont study model using a laboratory scanner (E3, 3Shape).

Polyvinyl siloxane light body impression material (Aquasil Ultra LV, Dentsply Sirona) with approximately 20- to 25- $\mu\text{m}$  film

thickness [34, 40] was then placed inside the crown, filling it only halfway. The crown was installed on the abutment with finger pressure; excess impression material was cleaned with a wet cotton swab before setting, which lasted 5 min under a 50N load. The crown was delicately removed after the setting was complete, keeping the impression material adhered to the tooth surface (Figure 1). Finally, the same laboratory scanner was used to take a “test scan” of the abutment and impression material. These steps were performed three times for each crown. The average values of the three measurements were recorded as “baseline” measurements (T0). All procedures were performed by a single calibrated operator to ensure consistency and measurement accuracy.

The crowns underwent thermal aging for 10,000, 30,000, and 50,000 cycles, respectively. Thermal cycling parameters were set to a temperature of 5°C and 55°C. MZ and VZ crowns underwent the aging process with a dwell time of 20s and a transfer time of 10s. The reference abutment tooth was not stored in



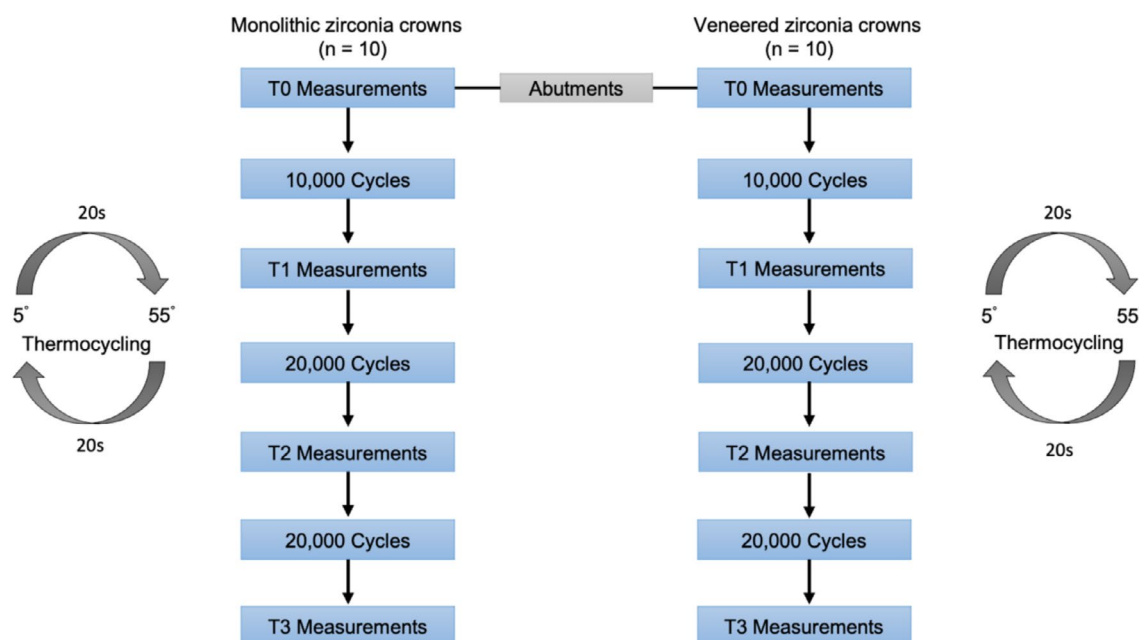
**FIGURE 1** | A silicon-coated abutment tooth before scanning.

the thermal cycling machine. It was stabilized on the maxillary model to enable the repeated repositioning of each crown during measurements. At the end of each interval, the measuring procedure was repeated on this reference abutment tooth for each sample. Three scans were taken for each crown, representing the completion of 10,000, 30,000, and 50,000 cycles. These measurements were recorded as T1 (10,000 cycles), T2 (30,000 cycles), and T3 (50,000 cycles) measurements (Figure 2).

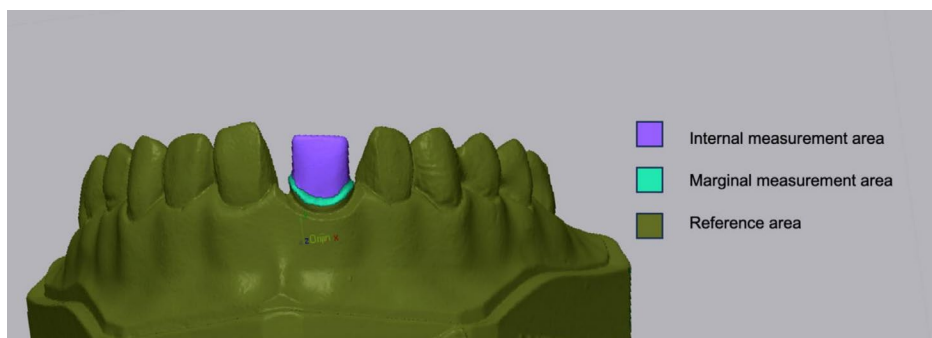
The four sets of STL files for each crown were imported into the Geomagic Design X software (3D Systems, Rock Hill) in order to superimpose the images taken before and after 10,000, 30,000, and 50,000 thermal aging cycles, as well as those taken with and without the silicone impression material. This procedure was used to evaluate changes in both marginal and internal adaptation by comparing differences in the cervical gap and internal space between the crown and the abutment tooth. Stable surfaces on adjacent teeth, located outside the region of interest, were selected as reference areas (Figure 3). Superimposition between the reference and test scans was performed using a best-fit alignment based on these unaltered reference surfaces. The marginal and internal areas were manually defined on the reference scan and analyzed as whole regions rather than through discrete measurement points. After alignment, the reference and silicone-applied scans were superimposed, and deviations within the selected marginal area were calculated (Figure 4). A similar analysis was performed for the internal surfaces, particularly along the axial walls, to evaluate the internal fit of the crowns (Figure 5). The RMS values calculated within the selected marginal and internal regions reflected the thickness of the silicone material by quantifying the deviation between the reference scan (without silicone) and the test scan (with silicone) after superimposition. This value served as a numerical representation of the marginal fit in the analyzed area.

$$RMS = \sqrt{\frac{\sum_{i=1}^n (X_{1,i} - X_{2,i})^2}{\sqrt{n}}}$$

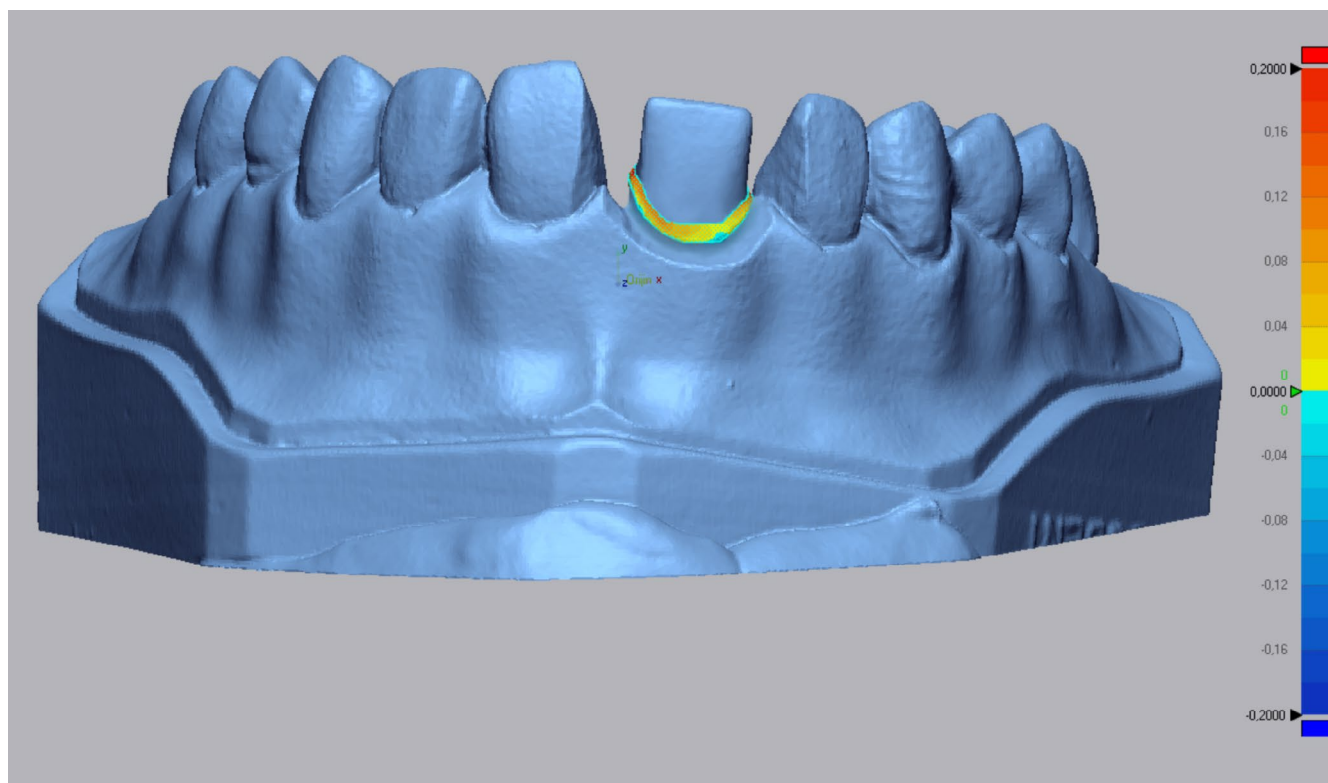
where  $X_{1,i}$  is the measuring



**FIGURE 2** | Schematic presentation of the study design.



**FIGURE 3** | Defined reference and measurement areas for marginal analysis. The reference area was selected from the entire model surface, excluding the defined marginal measurement area. After best-fit alignment of the reference and test scans based on these stable regions, the marginal region of interest was manually defined. RMS values were calculated from the deviations within this selected marginal zone to assess the thickness of the silicone layer and the marginal fit.



**FIGURE 4** | Marginal fit analysis on the maxillary incisor. A color-coded deviation map was generated using Geomagic Design X to visualize the marginal discrepancies representing the superimposition of the reference scan and the silicone-applied test scan.

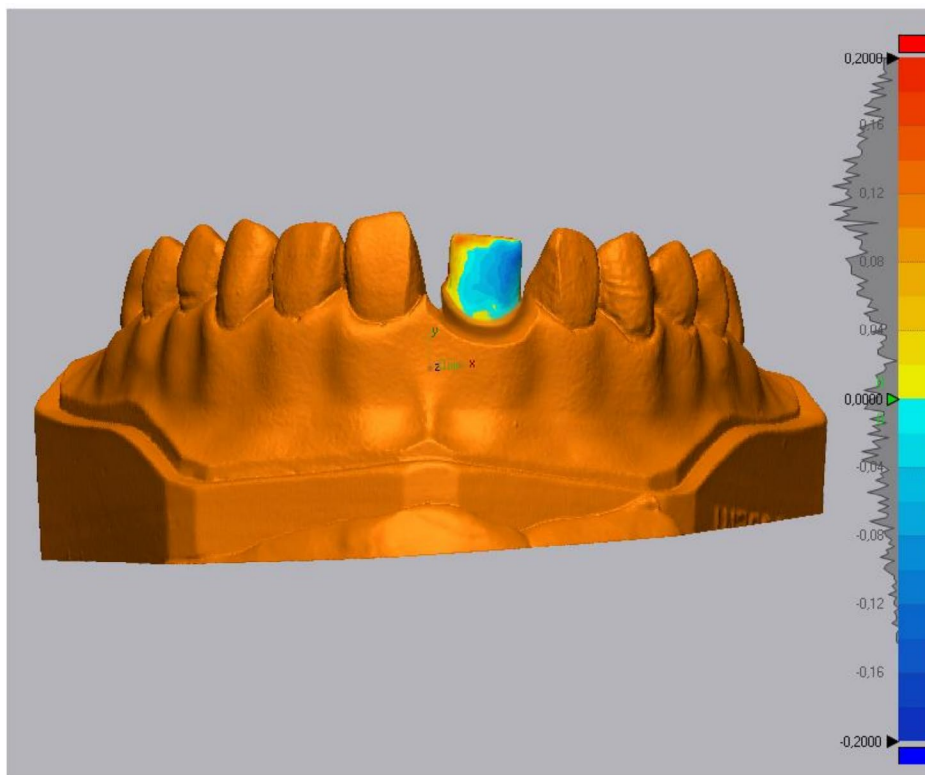
point in the abutment,  $X_{2,i}$  is the measuring point in the abutment with the attached silicone, and  $n$  is the total number of measuring points. The mean value of each crown was recorded as a millimeter (mm) and then converted to a micrometer ( $\mu\text{m}$ ). All scans and analyses were performed by a single calibrated operator to ensure consistency.

The study data were analyzed and shown using the SPSS 28 software package. The normality of the data distribution was determined using the Shapiro–Wilk test. Due to the non-normal distribution of the data, nonparametric tests were applied. Comparisons between groups were conducted using the Mann–Whitney  $U$  test. In addition, the comparison of thermal cycle

treatments was evaluated using the Friedman test and post hoc Wilcoxon signed-rank test. A  $p < 0.05$  was considered statistically significant.

### 3 | Results

The means and the standard deviations of the measurements for each group are presented in Table 1. When the internal gap change of the MZ crowns by aging was analyzed, a statistically significant difference was observed between the groups ( $p < 0.05$ ). The highest to lowest change was observed as  $T3 > T2 > T0 = T1$ , respectively. About the MG of the MZ crowns,



**FIGURE 5** | Internal fit analysis on the maxillary incisor. A color-coded deviation map was generated in Geomagic Design X to evaluate internal fit by visualizing discrepancies between the reference scan and the silicone-loaded test scan.

**TABLE 1** | RMS values ( $\mu\text{m}$ ) of the MZ and VZ crowns in internal and marginal areas at different time intervals.

Thermal cycle times		T0 (baseline)	T1 (10,000)	T2 (30,000)	T3 (50,000)	$p^+$
Crown	Area	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	
Monolithic	Internal	122 $\pm$ 30 <sup>A,a</sup>	119 $\pm$ 15 <sup>A,a</sup>	130 $\pm$ 11 <sup>B,a</sup>	146 $\pm$ 27 <sup>C,a</sup>	*
Veneered	Internal	136 $\pm$ 19 <sup>A,b</sup>	134 $\pm$ 10 <sup>A,b</sup>	172 $\pm$ 13 <sup>B,b</sup>	204 $\pm$ 30 <sup>C,b</sup>	*
	$p^{++}$	*	*	*	*	
Monolithic	Marginal	104 $\pm$ 11 <sup>A,a</sup>	100 $\pm$ 11 <sup>A,a</sup>	112 $\pm$ 11 <sup>B,a</sup>	115 $\pm$ 10 <sup>B,a</sup>	*
Veneered	Marginal	82 $\pm$ 6 <sup>A,b</sup>	87 $\pm$ 6 <sup>A,b</sup>	125 $\pm$ 11 <sup>B,b</sup>	128 $\pm$ 13 <sup>B,b</sup>	*
	$p^{++}$	*	*	*	*	

Note: Lowercase letters in-group (vertical), capital letters (horizontal) indicate statistical difference between groups.

<sup>+</sup>Friedman test–Wilcoxon test.

<sup>++</sup>Mann–Whitney *U* test.

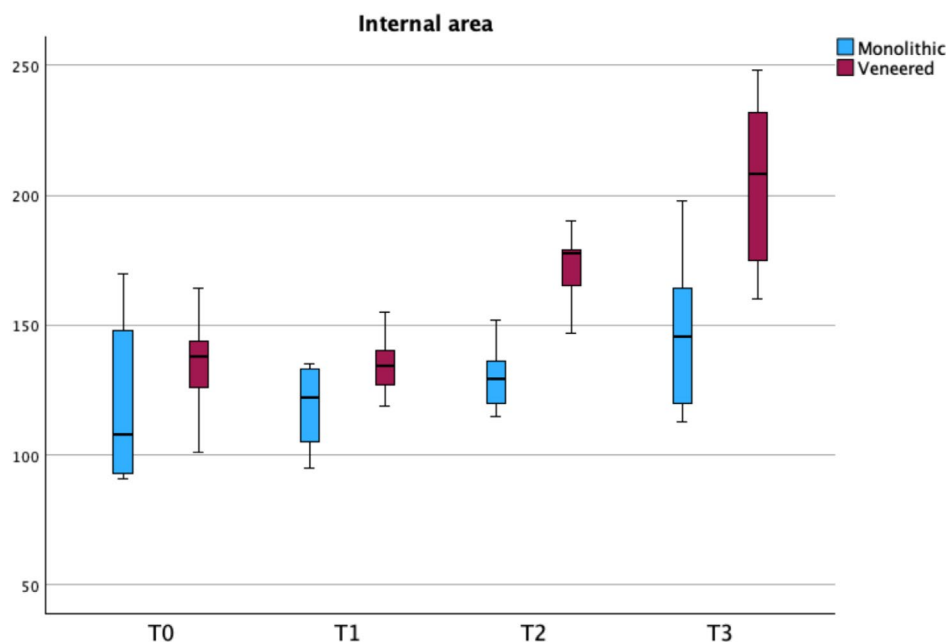
\* $p < 0.05$ .

a statistically significant difference was observed between the groups ( $p < 0.05$ ). Statistically, the highest and the lowest changes were shown as  $T3 = T2 > T0 = T1$ .

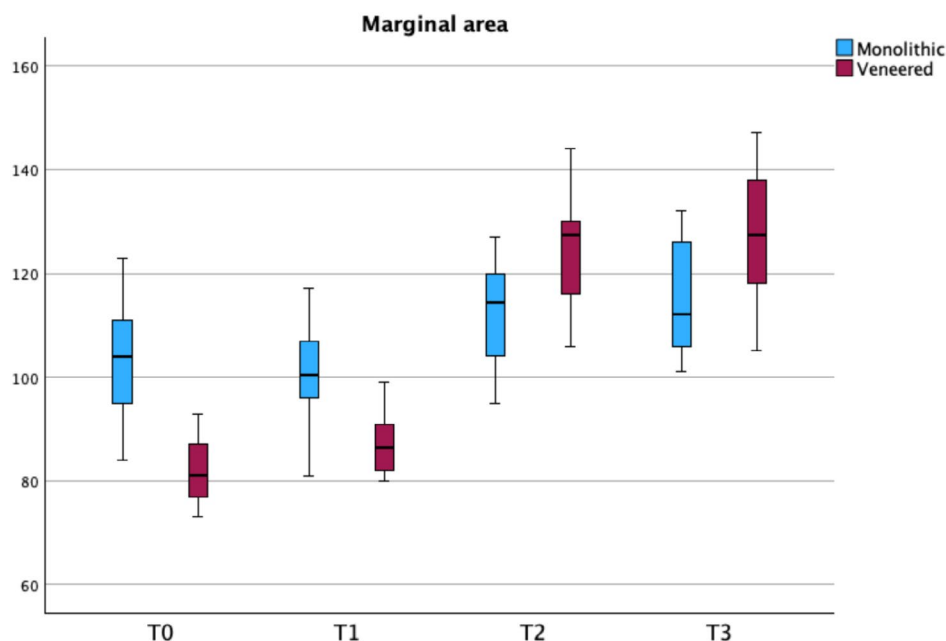
There were statistically significant differences between the mean values of the different thermal aging groups for internal gap values of the VZ crowns ( $p < 0.05$ ). The highest to lowest dimensional change values were observed as  $T3 > T2 > T0 = T1$ , respectively. Likewise, a statistically significant change was shown in MG distance within the VZ crowns ( $p < 0.05$ ). The

highest to lowest dimensional change values were observed as  $T3 = T2 > T0 = T1$ .

When the internal gap changes of the MZ and VZ groups were compared with each other, there was a statistically significant difference between the groups in all time periods ( $p < 0.05$ ). VZ crowns showed higher internal dimensional change than MZ crowns (Figure 6). Similar results were obtained with the marginal dimensional changes of the MZ and VZ groups. There was a statistically significant difference between the



**FIGURE 6** | Illustration of internal gap values ( $\mu\text{m}$ ) among groups tested (T0: baseline, T1: 10,000 cycles, T2: 30,000 cycles, T3: 50,000 cycles).



**FIGURE 7** | Illustration of marginal gap values ( $\mu\text{m}$ ) among groups tested (T0: baseline, T1: 10,000 cycles, T2: 30,000 cycles, T3: 50,000 cycles).

groups in all time periods ( $p < 0.05$ ). Although the MZ group showed a higher mean MG value at T0 and T1 cycle time, the VZ group showed higher mean values at T2 and T3 cycle time (Figure 7).

#### 4 | Discussion

This in vitro study investigated the marginal/internal gap changes of monolithic and VZ crowns after thermal aging with 10,000, 30,000, and 50,000 cycles. According to the results, the null hypothesis that there would be no difference in the marginal/internal fit among the different production techniques

of zirconia crowns tested at each thermal cycling interval was rejected.

There is still no consensus in the literature about the clinically acceptable MG size of a crown restoration, although less than  $120\mu\text{m}$  is the generally accepted value, which was reported by McLean and Fraunhofer [27]. According to the present study, the MG values of VZ and MZ crowns at baseline (T0) were within the clinically acceptable limits of 82 and  $104\mu\text{m}$ , respectively. The difference in these initial MG values can be attributed to the different zirconia materials and milling machines used. After 10,000 cycles, there were no significant differences between the marginal discrepancies of VZ and MZ crowns ( $p > 0.05$ ).

However, MG values of VZ crowns were significantly increased, slightly exceeding acceptable limits after 30,000 (125  $\mu\text{m}$ ) and 50,000 (128  $\mu\text{m}$ ) cycles ( $p < 0.05$ ). For MZ crowns, these values were increased to 112 and 115  $\mu\text{m}$ , after 30,000 and 50,000 cycles ( $p < 0.05$ ). The highest MG values were observed after 50,000 cycles for both types of crowns.

It is important to note that VZ crowns exhibited a much greater change (56%) in marginal discrepancy compared to MZ crowns (10%) between the baseline and 50,000 cycles. Similarly, the internal gap of VZ crowns increased by 50% from the baseline, representing a greater change than the 19% increase observed in MZ crowns after 50,000 cycles. This result may be due to differences in the processing techniques of the crowns. Within VZ, the procedures of layering and firing porcelain onto the zirconia substructure necessitate extra heat treatments, which in turn might lead to structural changes within the zirconia itself [8]. Transient and residual thermal stresses also arise in the crowns due to the mismatch in thermal expansions between zirconia and porcelain during heating and cooling [9]. Veneering porcelain layers have low fracture toughness and are more prone to cracking or marginal failure due to thermal expansion differences [10]. Unlike VZ, monolithic crowns do not utilize a veneer-core system involving high-temperature firing during their manufacturing process [13]. In this study, the copings were veneered with hand-layered porcelain and fired in the furnace up to 750°C with a 40°C/min heating rate. MZ crowns were only manually polished after sintering in the furnace according to the manufacturer's instructions (9 h 50 min, 1500°C).

Another possible explanation for this difference may be the structural differences between the materials. It was stated that the mechanical and optical properties of zirconia are influenced by the mol concentration of yttria [15–17]. In the 1st generation zirconia, 3 mol% yttria is added, creating stabilized tetragonal zirconia polycrystals (3Y-TZP). The alumina content is reduced and sintering temperatures are increased in the second generation. The third-generation zirconia is stabilized by increasing its cubic phase content through the addition of extra stabilizing oxides, specifically resulting in a composition with 5 mol% yttria [16, 17]. However, the inability of the cubic grains to undergo phase transformation under stress causes a reduction in the material's strength and fracture toughness, even with the improvement in translucency [14]. Fourth-generation zirconia is designed to improve the mechanical and optical qualities of MZ with 4 mol% yttria (4Y-TZP) [16, 17]. In the current study, IPS e.max ZirCAD Prime Esthetic with a layered composition, featuring 4 mol% yttria-stabilized zirconia (4Y-TZP) in the dentin area for enhanced strength and 5 mol% yttria-stabilized zirconia (5Y-TZP) in the incisal region for improved translucency, was selected for MZ crowns. The copings of the VZ crowns were fabricated from pre-sintered 3Y-TZP zirconia blocks (Everest, KaVo). Variations in yttria concentration may lead to differing reactions to thermal stress during thermal aging, impacting material properties. Besides, the increase of the cubic phase in MZ, which is stable at room temperature, causes the tetragonal phase to decrease and offers improved resistance to the phase transformations that cause LTD [19].

It was reported that the marginal stability of MZ is better preserved after thermal aging and thermal cycling than that of VZ

[10]. Pereira's findings suggest that lower density and higher porosity promote water diffusion, thereby accelerating aging by facilitating the access of water molecules to the material's internal structure [7]. The increased density and reduced porosity of MZ ceramics contribute to their improved resistance to hydrothermal degradation (aging). Therefore, this risk is lessened in MZ ceramics [7, 13]. The varying thickness of the MZ and VZ crowns, in addition to other factors, should be considered as a potential factor influencing the study's findings. In MZ crowns, the marginal area and the axial walls were uniformly adjusted to 0.8 mm in thickness, while the zirconia substructure was set at 0.4 mm in VZ crowns. The decreased thickness of the zirconia material may be more susceptible to thermal changes and the accelerated access of water after 50,000 cycles.

Existing literature details the impact of thermal aging on zirconia's microstructure and LTD characteristics [1, 22–25, 29, 30]; however, a clear understanding of the marginal or internal adaptation of zirconia crowns fabricated using different techniques remains limited [1, 29]. In their study, Del Pinal et al. [1] reported no significant differences between MG values among VZ and MZ posterior crowns after 20 h of hydrothermal aging at 131°C. Elsayed et al. [29] evaluated the marginal adaptation of printed and milled MZ posterior crowns before and after 5000 cycles of thermal aging, and the least discrepancy was observed in the milled crowns. The absence of standardized methodologies presents a challenge for comparing limited research outcomes with the current study. Although MZ crowns and the copings of VZ crowns were produced with a fully digital workflow in the present study, there are various systems using devices with different working principles, production technologies, and kinds of materials. Such differences may affect the quality of the crowns produced, and this may be an explanation for the different values reported in the literature. In addition, the numerous thermal cycles in the current study (10,000, 30,000, and 50,000) may have caused different results to be obtained. It was stated that 10,000 cycles corresponded to approximately 1 year of in vivo function. Therefore, 30,000 and 50,000 cycles simulate 3 and 5 years of thermal aging in the oral cavity in this study [31].

An ideal cement space for achieving optimal adaptation of CAD/CAM restorations is not yet established, according to a recent review article [20]. It was reported that cement space values ranged from 50 to 80  $\mu\text{m}$  in conventionally milled zirconia crowns [28]. Therefore, a 70- $\mu\text{m}$  cement space was created for the axial and incisal surfaces of the abutments and zero space at the finish line during the design of the crowns in the current study. According to ADA Specification No. 96 [40], luting cements must have a film thickness under 25  $\mu\text{m}$ . Thus, a polyvinyl siloxane light body impression material was used to represent the cement space, which had 20–25  $\mu\text{m}$  film thickness [34].

Conducting thermal aging after cementation represents the clinically ideal scenario. However, the primary and fundamental objective of this study was to investigate the isolated, direct effect of thermal stress on the inherent structure and geometry of the zirconia restoration itself. Testing without cementation allowed evaluation of the direct impact of thermal cycling on the material's intrinsic stability and the crown's microgeometry—particularly its marginal integrity. This approach may provide crucial

data on the material's inherent performance, independent of any potential protective or stress-distributing effects of the cement. The degradation of the cement interface is often accelerated following the initiation of marginal discrepancies [41] or microcracks within the crown itself [42]. These defects provide a pathway for oral fluids to infiltrate the interface, leading to hydrolytic degradation of the luting cement [43]. Therefore, understanding the crown's resistance to thermal stress is a critical prerequisite for predicting the long-term success of the cemented system. While thermal aging in the literature is predominantly studied post-cementation, the present study provides preliminary data by isolating the aging effect on the restoration itself, excluding the cement factor. This may establish a reference point for future investigations involving cemented assemblies.

Destructive and nondestructive techniques were employed to measure the marginal and internal fit of the crowns [33–37]. Among nondestructive techniques, 3D-superimposition was reported as repeatable, reliable, standardized, and more effective in evaluating crown adaptation [32, 33]. In this study, the dual scan method, in which scanning of the abutment, silicone-attached abutment, and analysis with superimposition were performed. A laboratory scanner was selected for this study to scan the reference and test models due to its reported superior accuracy [33, 38].

The present study has some limitations. A single-brand zirconia for each production technique (monolithic and veneered) was selected and one type of tooth (incisor) was tested. The two groups of the study involve materials produced with different milling machines. The light body polyvinyl siloxane application may be within the clinical variability. A noninvasive technique (dual scan) was employed for measurements of the adaptation of the crowns. There was no mechanical loading, although the aging of ceramics is a complex process that includes time, temperature, moisture, and mechanical loading. Only the influence of thermal degradation was investigated. Another limitation of this study is that all measurements were performed before cementation, which may not accurately reflect the clinical setting, as the cement can influence the observed gap distance between abutments and crowns. The authors suggest that future studies explore alternative production methods such as 3D printing, different zirconia brands, restorations involving posterior teeth with crowns or bridges, thermomechanical aging, and various fit evaluation techniques such as the triple scan method, without any additional silicone impression material.

## 5 | Conclusion

In vitro studies that simulate long-term intraoral conditions are essential for the development of durable dental restorations and for predicting their clinical performance over time. Within the limitations of the study, it can be concluded that thermal aging had a significant effect on the marginal/internal fit of incisor monolithic and VZ crowns. The results specifically confirm that thermal aging after 30,000 and 50,000 thermocycles increased the marginal and internal gap of VZ crowns in maxillary central incisors. MZ crowns had a better marginal fit than traditional bilayered zirconia crowns after 30,000–50,000 thermocycling.

These findings suggest that monolithic designs may offer improved dimensional stability under thermal stress.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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