Journal of Dental Sciences 20 (2025) 2135–2142

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Original Article

Accuracy and fitness of digital light processing-fabricated resin-based permanent crowns after thermal aging

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Received 4 June 2025; Final revision received 7 July 2025
Available online 30 July 2025

KEYWORDS
Digital light processing;
Resin-based permanent crowns;
Thermal aging;
Accuracy;
Marginal and internal fitness

Abstract *Background/purpose:* Resin-based materials fabricated using digital light processing (DLP) have received increasing attention for use in permanent dental restorations. This study investigated the accuracy and fit of DLP-fabricated resin-based permanent crowns before and after thermal aging.
Materials and methods: A maxillary right first premolar resin tooth was scanned and digitally designed as a reference computer-aided design (CAD) model. Twenty DLP-fabricated permanent resin crowns were produced. Half of the specimens remained unaged, while the others underwent thermal aging through 10,000 cycles between 5 °C and 55 °C. To evaluate crown accuracy, trueness was assessed by comparing virtual models of the fabricated crowns to the design reference model. Precision was evaluated through inter-sample comparisons among the virtual models of the fabricated crowns. Color difference maps were generated for four distinct crown regions, and root mean square (RMS) values were calculated for each. Crown fitness was evaluated using the silicone replica method by measuring silicone thickness at four intaglio areas with a digital microscope. Data differences before and after thermal aging were analyzed using paired *t*-tests ($\alpha = 0.05$).

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https://doi.org/10.1016/j.jds.2025.07.007

Results: Thermal aging significantly increased RMS values for external surface trueness ($P < 0.001$). Marginal and internal gaps remained within the clinically acceptable discrepancy threshold of 120 μm. Significant differences were observed in the marginal and occlusal gaps in both the coronal and sagittal planes after aging.
Conclusion: DLP-fabricated resin permanent crowns demonstrated acceptable trueness and clinically acceptable marginal and internal fitness. However, thermal aging reduced both the accuracy and fitness of these crowns.

Introduction

Digital technologies have profoundly transformed clinical workflows in dentistry, particularly within the realm of restorative dentistry.[1–4] Intraoral scanners facilitate the acquisition of digital oral data, which subsequently enables the design of restorations using computer-aided design (CAD) systems. These digitally designed restorations are then realized through computer-aided manufacturing (CAM) systems, employing either subtractive or additive manufacturing techniques.[5]

In recent years, additive manufacturing has garnered increasing attention for fabricating various removable appliances due to its inherent flexibility and rapid production capabilities for intricate geometries.[6,7] Among the diverse additive manufacturing modalities, digital light processing (DLP), a type of vat photopolymerization, stands out as a prevalent technique for fabricating resin-based restorations due to its efficient processing times and cost-effectiveness.[8–10] The application of additive manufacturing for provisional restorations using a variety of resin-based materials has been validated and is gaining widespread adoption.[9,11,12] Concurrent advancements in materials science have led to the introduction of photosensitive resin materials that manufacturers claim are suitable for permanent restorations. However, there is still a paucity of information in the literature regarding utilization of additive manufacturing for fabricating permanently fixed restorations.[13,14]

DLP-fabricated permanent restorations are intended for long-term intraoral service, which entails repetitive masticatory loading and continuous exposure to the aqueous oral environment.[15,16] For fixed prostheses to exhibit satisfactory long-term clinical performance, they must possess adequate mechanical properties and also high manufacturing accuracy, coupled with optimal marginal and internal fitness.[17,18] An inadequate marginal fitness can predispose the restoration to increased plaque accumulation and subsequent compromise of gingival health, whereas internal misfitnesss can negatively impact the restoration's long-term durability and retention.[19–21] Various methodologies have been proposed and employed to assess the accuracy and fitness of dental restorations.[22,23] One such quantitative method involves three-dimensional (3D) virtual inspection, which analyzes root mean square (RMS) deviations between the CAD reference design model and the virtual model of a DLP-fabricated restoration.[24] This comprehensive inspection can be further segmented into evaluations of the external and intaglio surfaces to gain a more-granular understanding of the manufacturing process accuracy.[25–28] Another established technique, the silicone replica method, simulates the cementation process using an impression material to evaluate internal and marginal discrepancies, providing a reliable and non-destructive assessment.[6,29,30]

Given the current limited body of knowledge concerning the long-term performance of DLP-fabricated resin-based materials in permanent restorations, the geometric accuracy and fitness characteristics of DLP-fabricated permanent crowns remain largely undefined. Therefore, in this study, we aimed to confirm (1) that the accuracy of DLP printing technology is sufficient for fabricating permanent crowns suitable for clinical application, and (2) how thermal aging affects the accuracy as well as the marginal and internal fit of DLP-printed permanent crowns made from resin-based materials.

Materials and methods

In the present study, we evaluated the geometric accuracy and fitness of permanent crowns fabricated using DLP technology; the experimental workflow is illustrated in Fig. 1. A desktop scanner (3Shape D900; 3Shape A/S, Copenhagen, Denmark) was employed to obtain a digital impression of a maxillary right first premolar resin tooth (A5AN-500; Nissin Dental Products, Tokyo, Japan). Based on this digital impression, resin abutments were fabricated using model resin (Aqua Gray 4K; Phrozen Technology, Hsinchu, Taiwan) and printed with a liquid-crystal display (LCD) 3D printer (Sonic Mini 4K; Phrozen Technology, Hsinchu, Taiwan). In total, 20 resin abutments were fabricated. The same digital impression served as the basis for designing a single crown using CAD software (3Shape Dental Designer; 3Shape A/S, Copenhagen, Denmark). The crown design incorporated a uniform thickness of 1.5 mm and a cement space of 50 μm. The resulting design was exported in standard tessellation language (STL) format and served as the reference CAD model for subsequent analyses.

Permanent crown specimens were fabricated using a light-curing resin (A2 shade, FREEPRINT crown; DETAX, Ettlingen, Germany) with a DLP-based printing system (DMG 3Demax; DMG Dental Material, Hamburg, Germany)

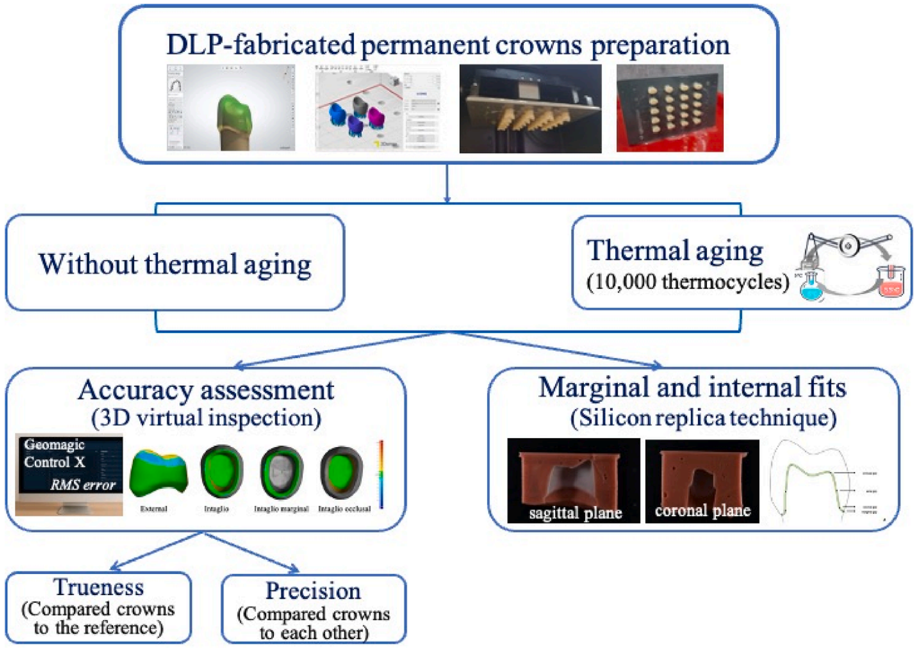

Figure 1 Schematic diagram of the study flow.

utilizing a 385-nm light source at a build angle of 0°. Post-processing procedures included washing the printed crowns in 95 % isopropyl alcohol for 180 s using an automated cleaning unit (3Dewash; DMG Dental Material, Hamburg, Germany), followed by thorough air-drying with compressed air. Polymerization was then performed for 30 min in a light-curing unit (3Decure; DMG Dental Material, Hamburg, Germany). After completing the curing process, the support structures were carefully removed. In total, 20 permanent crowns were fabricated, with half assigned to the without-thermal-aging group and the other half to the thermal-aged group.

Half-fabricated crowns were subjected to thermal aging for 10,000 cycles using a thermocycler (TBN-1100805; TEN Billion Technology, New Taipei City, Taiwan). Each cycle consisted of 30 s of immersion in a water bath at 5 °C, followed by 30 s at 55 °C, simulating one year of intraoral use.[31] After completing the thermocycling protocol, the accuracy and fitness of the crowns were re-evaluated using the above-described procedures. Subsequently, half of the accuracy and fitness evaluations were conducted before thermal aging, and the remaining half were performed after aging.

In this study, a 3D virtual inspection method was employed to evaluate the accuracy of the fabricated crowns. A DLP-fabricated crown was scanned using the same desktop scanner (3Shape D900; 3Shape A/S), and the resulting virtual model, saved in STL format, was analyzed using 3D inspection software (Geomagic Control X 2017; 3D Systems, Rock Hill, SC, USA). For trueness evaluation, the virtual model of each crown was initially aligned with the reference CAD file using a three-point pre-matching protocol, followed by a best-fitness alignment algorithm. For precision evaluation, the virtual model of the fabricated crown was superimposed onto one another specimen for direct inter-sample comparison. Color difference maps were generated, and RMS values were automatically calculated by the software to evaluate volumetric surface discrepancies between the two datasets based on deviation errors.[28] For a comprehensive accuracy analysis, the crown contour was segmented into four regions: the external surface (Fig. 2A) and the intaglio surface. The intaglio surface was further subdivided into three distinct areas—marginal, axial, and occlusal—based on established anatomical definitions and methodologies established in previous studies (Fig. 2B–D).

The marginal and internal fitness were assessed using the silicone replica technique, as previously described.[6] Each crown was internally coated with a thin layer of silicone fitness checking material (Fit Checker; GC Corporation, Tokyo, Japan) and seated onto the corresponding resin abutment under consistent finger pressure applied for 5 min. Following crown removal, a vinyl polysiloxane impression material (Exadenture; GC Corporation, Tokyo, Japan) was applied over the Fit Checker-covered abutment. Two silicone replicas were obtained for each crown and subsequently sectioned in either the sagittal or coronal plane. Eighteen reference points were meticulously established on each section to quantitatively assess the marginal and internal fitness using a digital microscope (SZX16; Olympus, Tokyo, Japan) at 50 × magnification (Fig. 3). The marginal gap (MG) was defined and measured as the perpendicular thickness of the Fit Checker at the crown margin. The cervical gap (CG) was determined as the perpendicular distance at the finish line (chamfer line). The axial gap (AG) was recorded as the perpendicular distance at the midpoint of the axial wall, and the occlusal gap (OG) was calculated as the average perpendicular thickness at three predefined reference points within the occlusal region.

Statistical analyses were performed using SPSS software (vers. 19.0; IBM, Armonk, NY, USA), and mean values and standard deviations of the collected data were calculated.

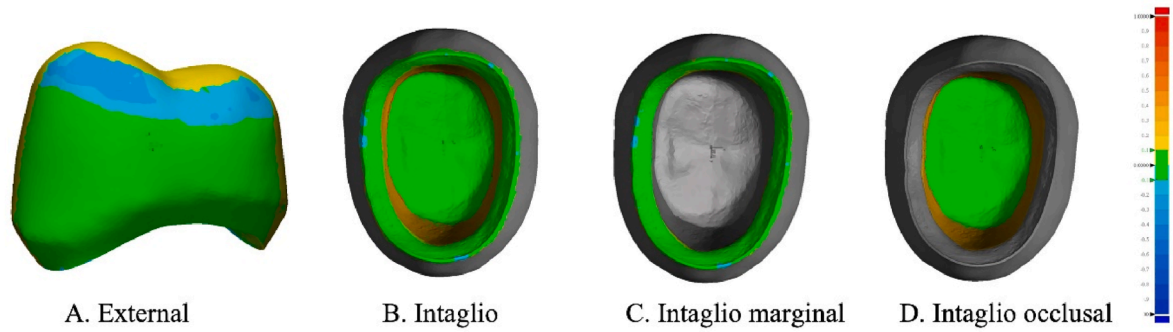

Figure 2 Accuracy assessment. (A) External surface. (B) Intaglio surface. (C) Intaglio marginal area. (D) Intaglio occlusal area.

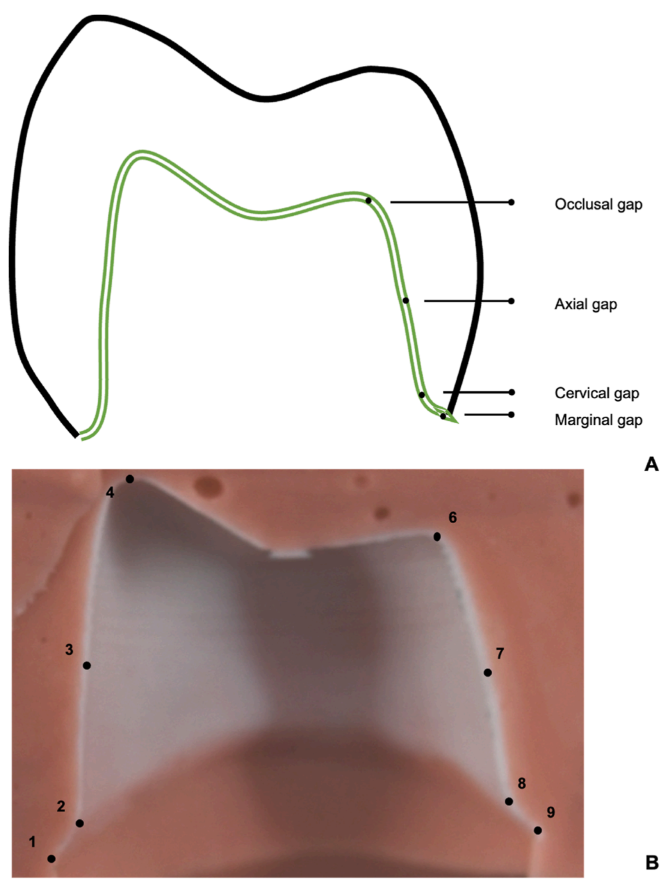

Figure 3 Fitness evaluation using cross-sections of silicone replicas. (A) Schematic illustration of the silicone replica cross-section, indicating the marginal and internal regions analyzed. (B) Microscopic image of a sectioned silicone replica showing the cement space between the crown and tooth structure.

The normality and homogeneity of the variance of the obtained measurements were assessed using the Shapiro–Wilk test and Levene's test. Paired *t*-tests were employed to compare the crown accuracy and fitness measurements obtained before and after thermal aging. Discrepancies among the three distinct areas of the intaglio surface were analyzed using a one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test for pairwise comparisons.

Results

Figure 4 illustrates the accuracy analysis of DLP-fabricated crowns before and after thermal aging. Regarding trueness (Fig. 4A), the highest RMS value was observed on the external surface, which significantly increased from 60.8 ± 6.6 to 84.4 ± 4.6 μm following thermal aging ($P < 0.001$). For the intaglio surface, significant differences in trueness were detected among the different locations

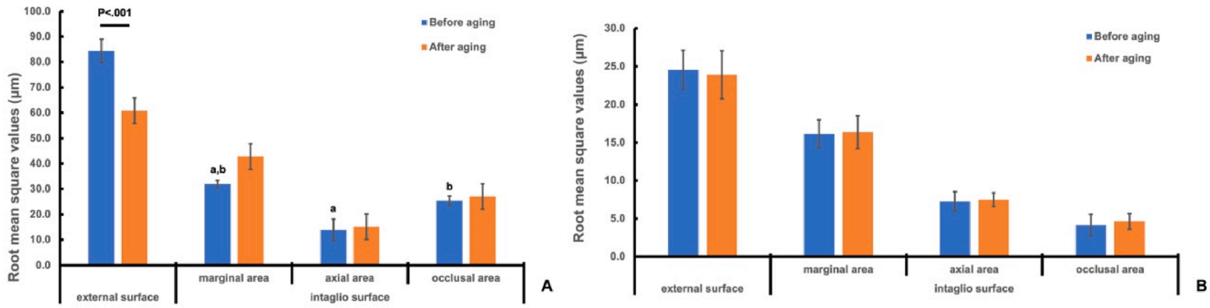

Figure 4 Mean values and standard deviations of root mean square values of digital light processing (DLP)-fabricated crowns in four locations. (A) Trueness evaluation. (B) Precision evaluation.

prior to thermal aging ($P < 0.001$). Specifically, the marginal area exhibited the highest RMS value, which was significantly greater than those of the axial area ($P < 0.001$) and occlusal area ($P = 0.023$). Following thermal aging, no significant differences were observed in RMS values across intaglio surface locations ($P = 0.493$), although a numerical increase in RMS values was evident for all locations. Regarding precision (Fig. 4B), a similar trend in RMS values across the specific analyzed areas was noted. Thermal aging did not significantly affect the precision of the fabricated crowns (all $P > 0.05$).

Figures 5 and 6 present color difference maps respectively comparing the DLP-fabricated crown and the reference CAD file before and after thermal aging. Green areas on the maps indicate minimal deviation (good fit). Blue areas represent negative deviations, signifying that the dimensions of the DLP-fabricated crown were smaller than those of the designed CAD model. Conversely, red areas indicate positive deviations, where the fabricated crown exhibited larger dimensions. Before thermal aging (Fig. 5), positive deviations were primarily observed in the occlusal grooves of the external surface and at the junction between the axial and occlusal surfaces of the intaglio surface. After thermal aging (Fig. 6), an increase in yellow to red areas, indicative of positive deviations, was noted.

Figure 7 presents the fitness analysis of DLP-fabricated permanent crowns before and after thermal aging in both the sagittal and coronal planes, demonstrating that all measured gaps were within the clinically acceptable discrepancy threshold of 120 μm. From the coronal plane perspective (Fig. 7A), the marginal gap significantly decreased from 70.8 ± 5.1 to 46.9 ± 6.9 μm after thermal aging. For the internal fitness in the coronal plane, the gaps ranged 54.9–115.4 μm before thermal aging, with no statistically significant differences observed among these measurements ($P = 0.089$). Following thermal aging, reductions in the cervical and occlusal gaps were observed, while the axial gap showed an increase. However, a statistically significant reduction was only noted in the occlusal gap. Similar trends were observed from the sagittal plane perspective (Fig. 7B), with significant reductions in the marginal, cervical, and occlusal gaps after thermal aging.

Discussion

Various factors, including printing parameters, post-polymerization procedures, and the aging process, are known to significantly influence the mechanical properties and surface characteristics of DLP-fabricated resin-based specimens, ultimately impacting the clinical performance of fixed restorations.[1] In our preliminary investigations, a build angle of 0° and a post-cleaning duration of 180 s yielded specimens with optimal mechanical properties (data not presented herein). Consequently, these specific parameters were employed in the present study to fabricate permanent crowns.

In this study, the accuracy (trueness and precision) and fitness (marginal and internal) of permanent crowns fabricated using DLP technology for clinical application were assessed. The trueness of the DLP-fabricated crowns was evaluated across four distinct areas by comparing virtual models obtained from a desktop scanner to the reference design model.[8,9] The external surface exhibited significantly lower trueness, characterized by higher RMS values compared to the intaglio surface. This observation can likely be attributed to the removal of the printing support structures that were attached during the fabrication process. Within the intaglio surface, the axial area demonstrated the smallest RMS values. This finding may be explained by the surface-stepping effect inherent to additive manufacturing processes, wherein surfaces with pronounced curvature at the axial–occlusal transition area are more susceptible to inaccuracies than relatively vertical surfaces.[28] This observation is consistent with the findings of a previous study that evaluated the trueness of DLP-fabricated zirconia crowns.[2] The generally recommended intaglio surface trueness for fixed dental prostheses is below 100 μm, and various studies have reported trueness values for crowns ranging 24.91–44.8 μm, despite variations in materials and manufacturing technologies.[25–27] Therefore, the resin-based material utilized for the permanent crowns in this study can be considered clinically acceptable with respect to trueness.

The silicone replica technique was employed to evaluate the marginal and internal fitness of the fabricated crowns, with 18 measuring points selected in both the sagittal and coronal planes.[19] While a universally accepted range for clinically acceptable marginal discrepancies remains a subject of ongoing debate, a range of 100–120 μm is commonly considered permissible in clinical practice.[19–21] Results of the present study indicated that the marginal and internal gaps of the DLP-fabricated crowns were within this clinically acceptable range. The smallest gap in both planes was consistently observed at the marginal site, ranging

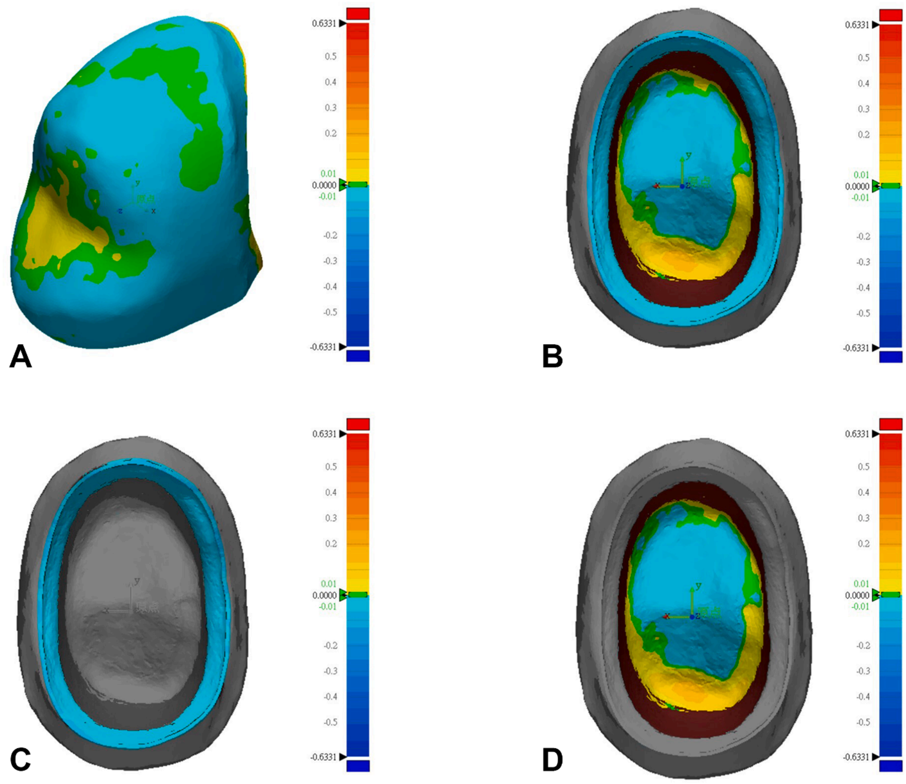

Figure 5 Color difference maps of digital light processing (DLP)-fabricated crowns in four locations in the sagittal plane before thermal aging. (A) External surface. (B) Intaglio surface. (C) Intaglio marginal area. (D) Intaglio occlusal area.

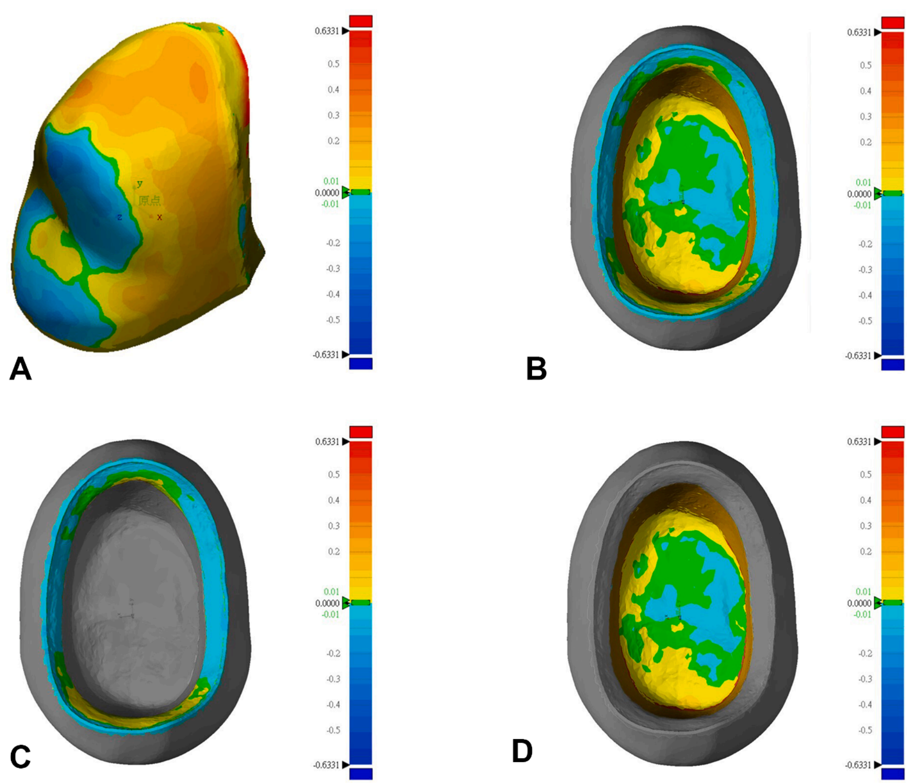

Figure 6 Color difference maps of digital light processing (DLP)-fabricated crowns in four locations in the sagittal plane after thermal aging. (A) External surface. (B) Intaglio surface. (C) Intaglio marginal area. (D) Intaglio occlusal area.

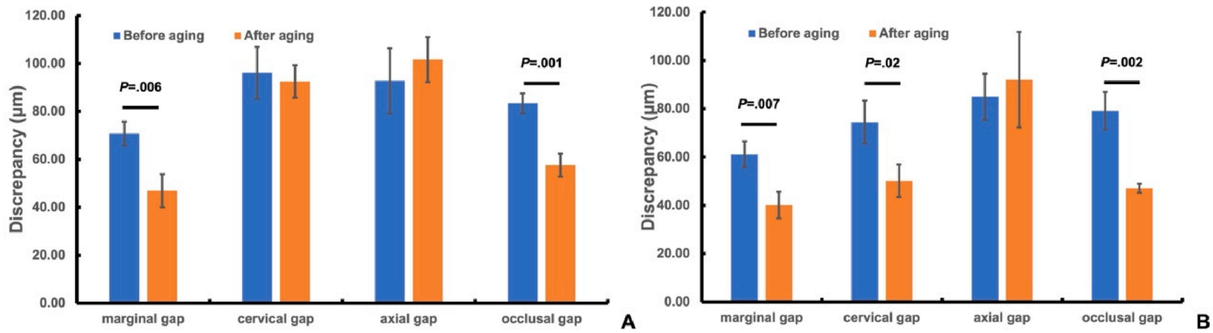

Figure 7 Mean values and standard deviations of marginal and internal fitness of digital light processing (DLP)-fabricated crowns at the marginal, cervical, axial, and occlusal gaps. (A) Coronal plane. (B) Sagittal plane.

54.09–79.43 μm, closely approximating the predetermined cement space of 50 μm. The other three measurement locations on the intaglio surface did not exhibit statistically significant differences in gap values, suggesting a relatively uniform cement space. However, the numerically lower value observed for the occlusal gap did not directly correlate with the RMS results for intaglio occlusal trueness. This apparent discrepancy might be attributable to the finger pressure applied during the seating of the crowns with the Fitness Checker material on the intaglio surface, a factor that warrants further investigation in future studies.

The present study revealed statistically significant alterations in the accuracy, marginal fitness, and internal fitness of DLP-fabricated permanent crowns following thermal aging. Marginal misfit or discrepancies in dental restorations may lead to plaque accumulation around the restoration and negatively affect its long-term survival.[5,30] Thermal aging is a widely used in vitro method to simulate the effects of the dynamic oral environment on dental materials by subjecting specimens to repeated cycles of temperature fluctuations, thereby mimicking intraoral conditions.[15] During the thermal aging process, water molecules can penetrate the resin matrix, potentially leading to expansion and degradation of the polymeric network. Additionally, alternating cycles of heating and cooling can induce shrinkage within the polymeric matrix.[16] In the present study, a statistically significant increase in RMS values was observed in the intaglio marginal area following thermal aging. After thermal aging, water sorption and subsequent swelling may have affected the dimensional stability, thereby influencing precision. However, the lack of significant differences in trueness among the specimens indicates that the DLP fabrication process is a reliable and consistent method for producing accurate restorations. Regarding crown fitness, statistically significant decreases in all measured discrepancies were noted after thermal aging. These findings suggest that water sorption and subsequent swelling of the resin material primarily affected the intaglio surface, consequently reducing the marginal and internal gaps.[5]

This study focused specifically on the trueness, fitness, and dimensional stability of DLP-fabricated permanent crowns after thermal aging and did not include a comparative analysis of these parameters with those of crowns fabricated using milling or other additive manufacturing technologies. Future research endeavors should encompass a broader range of manufacturing methods to provide a more-comprehensive evaluation of fabrication trueness across different techniques. Additionally, mechanical fatigue testing and long-term clinical studies are necessary to further validate the clinical applicability of the material.

In summary, the DLP-fabricated permanent resin-based crowns evaluated in this study met the established trueness requirements and demonstrated acceptable precision. Furthermore, these crowns exhibited clinically acceptable marginal and internal fitness prior to thermal aging. However, thermal aging significantly influenced both the trueness and marginal and internal fitness of the DLP-fabricated permanent resin-based crowns. Specifically, a significant increase in RMS values was observed on the external surface after thermal aging in the trueness evaluation. The observed swelling effects likely contributed to reductions in gaps in the marginal and occlusal regions following thermal aging.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

Acknowledgments

This work was supported by Shin Kong Wu Ho-Su Memorial Hospital, Taiwan, under grant no. 2024SKHADR029.

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