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# Marginal Adaptation of Autopolymerized, Heat-Cured, Milled Polymethyl Methacrylate, and Three-dimensional Printed Methacrylate-Based Resin Provisional Crowns using Triple Scan Technique: An *in vitro* Study

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***Research Article***

## Abstract

**Objective:** To compare the marginal adaptation of provisional crowns fabricated by four different fabrication methods using three-dimensional analysis.

**Materials and Methods:** Forty standardized resin dies simulating a prepared tooth were randomly assigned to four experimental groups (n=10/group). Provisional crowns were fabricated using autopolymerized polymethyl methacrylate (Unifast TRAD), heat-cured polymethyl methacrylate (SR Ivocron), milled polymethyl methacrylate (DD provi P HI), and three-dimensional printed methacrylate-based resin (Temp C&B UV 2.0). After temporary cementation with Temp-Bond NE under a standardized load, the marginal gap was assessed using a triple-scan protocol and three-dimensional inspection software (Geomagic Control X). Eight circumferential reference sites were evaluated for each specimen. Data were analyzed using one-way analysis of variance and Tamhane T2 post hoc tests ($\alpha$=0.05).

**Results:** Fabrication method significantly affected the marginal gap ($F=56.256$, $p<0.001$). The milled group showed the smallest mean marginal gap (69.45±15.20 µm), followed by the three-dimensional printed group (72.43±9.29 µm), heat-cured group (108.33±5.57 µm), and autopolymerized group (113.24±5.65 µm). The digitally fabricated groups demonstrated significantly smaller marginal gaps than the conventionally fabricated groups ($p<0.001$).

**Conclusion**: Within the limitations of this *in vitro* study, fabrication method significantly influenced marginal adaptation. Milled and three-dimensional printed provisional crowns showed smaller marginal gaps than conventionally fabricated autopolymerized and heat-cured provisional crowns. However, no significant difference was found between the two digital fabrication methods or between the two conventional fabrication methods. For provisional restorations in which marginal accuracy is particularly important, clinicians may consider either milling or three-dimensional printing instead of conventional fabrication methods.

**Keywords:** Marginal Adaptation/ Provisional Crowns/ Polymethyl Methacrylate/ CAD-CAM/ 3D analysis

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## Introduction

Provisional restorations protect prepared teeth, maintain function and esthetics, and support periodontal health during fixed prosthodontic treatment. Accurate marginal adaptation is essential because marginal discrepancy may promote plaque retention, cement dissolution, sensitivity, periodontal inflammation, and recurrent caries.[1-4]

Polymethyl methacrylate (PMMA) remains widely used because it is esthetic, easy to manipulate, inexpensive, and clinically familiar. Autopolymerized PMMA is convenient for chairside use, whereas heat-cured PMMA may provide improved conversion and mechanical properties. However, both conventional techniques involve operator-dependent procedures that may affect dimensional accuracy.[2,5-7] Digital fabrication methods have been introduced to improve the reproducibility of provisional restorations. CAD/CAM milling uses pre-polymerized PMMA blanks, which may reduce polymerization-related dimensional change during fabrication. Three-dimensional printing builds methacrylate-based resin through layer-by-layer polymerization. These four material groups were selected because they represent the principal conventional, subtractive, and additive fabrication methods currently used for provisional crowns. Previous studies have compared the fit of provisional restorations fabricated using these workflows, but their findings have not been consistent. Wu et al. compared manually fabricated, CAD/CAM-milled, and three-dimensional printed provisional crowns and reported better internal fit and smaller absolute marginal discrepancies for the conventionally fabricated group.[8] In contrast, Mai et al. compared compression-molded, milled, and photopolymer-jetting printed interim crowns and found that three-dimensional printing provided favorable fit, particularly at the occlusal surface.[9] Lee et al. compared only milled and three-dimensional printed interim crowns and reported smaller marginal and internal discrepancies for the printed groups. Differences in the tested materials, restoration designs, manufacturing systems, cement-space settings, and measurement protocols may account for these conflicting findings.[10]

Several methods have been used to evaluate marginal gap, including direct microscopy, silicone replica techniques, sectioning, micro-computed tomography, and three-dimensional analysis. Although the silicone replica technique has been widely used, it is technique-sensitive, and requires additional impression materials that may distort during sectioning or measurement. Lee et al.[10] used silicone replicas to evaluate milled and printed interim crowns, whereas Wu et al.[8] combined a polyvinyl siloxane replica method with optical coherence tomography. The triple-scan protocol introduced by Holst et al. provides a non-destructive alternative by superimposing scans of the seated restoration, abutment, and restoration intaglio surface. This approach enables cross-sectional and three-dimensional assessment of fit without limiting the number or direction of measurement sites.[11]

Although previous studies have compared selected conventional and digital workflows, direct comparison of autopolymerized PMMA, heat-cured PMMA, milled PMMA, and three-dimensional printed methacrylate-based resin crowns under the same crown design, cement-space setting, cementation procedure, and digital three-dimensional measurement protocol remains limited. Therefore, this *in vitro* study aimed to compare the marginal gap of provisional crowns fabricated by these four methods. The null hypothesis was that the fabrication method would not significantly affect the marginal adaptation of provisional crowns.

## Materials and Methods

### Study design

This *in vitro* study compared marginal adaptation of four provisional crown fabrication methods. Forty standardized resin dies were randomly allocated into autopolymerized PMMA, heat-cured PMMA, milled PMMA, and three-dimensional printed resin groups. Marginal gap was measured after temporary cementation. The methodological flowchart of the study is shown in Figure 1.

### Sample size estimation

Sample size calculation was performed using G*Power software (version 3.1.9.4, Heinrich-Heine-Universität, Düsseldorf, Germany) based on pilot data from five specimens per group. The effect size was calculated from the pilot data as Cohen's f = 0.712, corresponding to an eta squared value of 0.336. For a one-way ANOVA with four groups, $\alpha$ = 0.05, and 95% power, the required sample size was 10 specimens per group. Therefore, 40 specimens were included in the present study. The achieved power with the final sample size was approximately 96.0%.

### Materials and instruments

The tested materials were autopolymerized PMMA (Unifast TRAD; GC Corporation, Tokyo, Japan), heat-cured PMMA (SR Ivocron; Ivoclar Vivadent AG, Schaan, Liechtenstein), milled PMMA (DD provi P HI; Dental Direkt GmbH, Spenge, Germany), and three-dimensional printed methacrylate-based resin (Temp C&B UV 2.0; Guangzhou HeyGears IMC Inc., Guangzhou, China). Main materials and instruments are listed in Table 1.

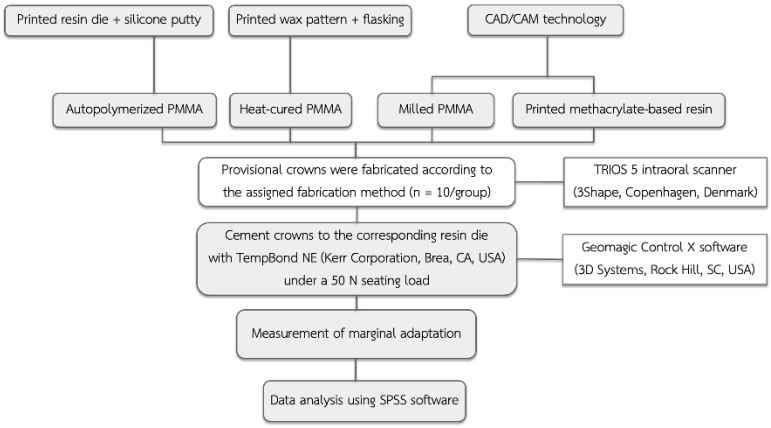



**Figure 1** Methodological flowchart of specimen preparation, provisional crown fabrication, temporary cementation, three-dimensional scanning, and marginal gap analysis.

**Table 1** Materials used for provisional crown fabrication.

| Material | Brand | Manufacturer | Composition |
|---|---|---|---|
| Autopolymerized PMMA | Unifast TRAD | GC Corporation, Tokyo, Japan | Powder: PMMA, benzoyl peroxide, pigment; liquid: MMA ≥90%, tertiary amine.[12,13] |
| Heat-cured PMMA | SR Ivocron | Ivoclar Vivadent AG, Schaan, Liechtenstein | PMMA, dibenzoyl peroxide; liquid: MMA with EGDMA/TEGDMA.[14] |
| Milled PMMA | DD provi P HI | Dental Direkt GmbH, Spenge, Germany | Pre-polymerized PMMA milling blank with dyes/pigments.[15] |
| Three-dimensional printed methacrylate-based resin | Temp C&B UV 2.0 | Guangzhou HeyGears IMC Inc., Guangzhou, China | Acrylated aliphatic urethane, acrylate monomers, acryloyl morpholine, and urethane dimethacrylate.[16] |

**Abbreviations:** EGDMA, ethylene glycol dimethacrylate; MMA, methyl methacrylate; PMMA, polymethyl methacrylate; TEGDMA, triethylene glycol dimethacrylate. Composition data were obtained from the manufacturers' safety data sheets and product information documents.[12-16]

**Die preparation**

A standardized resin die simulating a prepared mandibular first molar was designed using exocad software (exocad GmbH, Darmstadt, Germany) and Blender software (Blender Foundation, Amsterdam, Netherlands). The preparation design consisted of a 1.5-mm occlusal reduction, a 1.0-mm deep chamfer finish line, and a 6-degree total convergence angle. The die was designed with eight equally distributed external planes to provide reproducible reference landmarks for marginal gap measurement. The same die design was used for all specimens to standardize the experimental conditions. The resin dies were printed using Model HP UV 2.0 resin and an UltraCraft A2D printer (Guangzhou HeyGears IMC Inc., Guangzhou, China). Forty defect-free resin dies were produced and randomly assigned to groups. The digital die design and a representative fabricated resin die are shown in Figures 2 and 3, respectively.

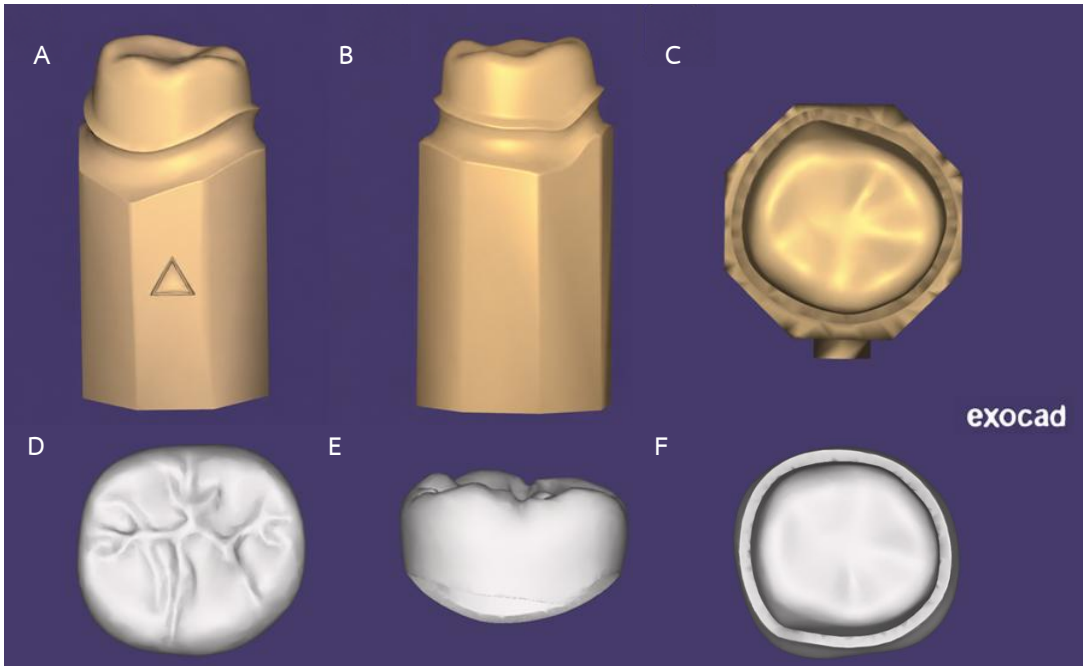



**Figure 2** Digital design of the standardized resin die and full-contour crown. The resin die simulated a prepared mandibular first molar with a 1.5-mm occlusal reduction, a 1.0-mm deep chamfer finish line, a 6-degree total convergence angle, and eight external reference planes: (A) Buccal view of the die, (B) Lingual view of the die, (C) Occlusal view of the die, (D) Occlusal view of the full-contour crown, (E) Lingual view of the full-contour crown, (F) Intaglio view of the full-contour crown.

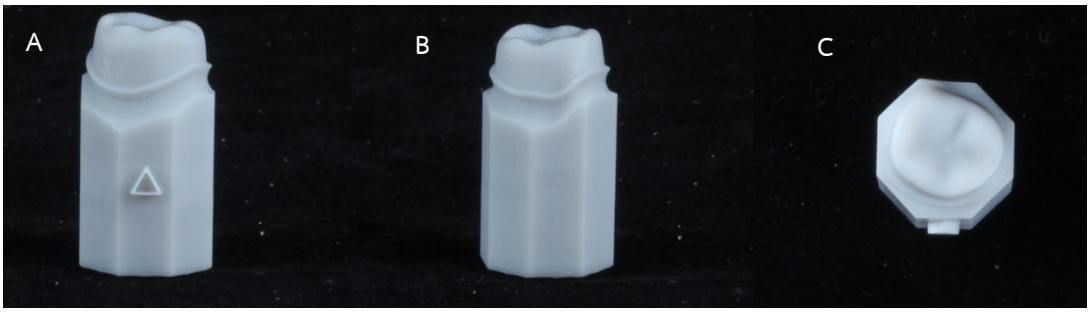



**Figure 3** Representative standardized resin die used for marginal gap measurement: (A) Buccal view, (B) Lingual view, and (C) Occlusal view.

**Provisional crown fabrication**

A full-contour provisional crown simulating a mandibular first molar was designed using exocad software (Figure 2). The same external crown morphology was used for all groups. A 50-μm cement space was digitally specified for the heat-cured, printed, and milled workflows. The specimens were then fabricated according to the assigned fabrication method: autopolymerized PMMA, heat-cured PMMA, milled PMMA, and three-dimensional printed methacrylate-based resin.

For the autopolymerized PMMA group, a silicone mold (Silagum Putty Soft, DMG, Hamburg, Germany) was made from the full-contour crown design and used as the external surface form. Five layers of gold die spacer (Bredent GmbH & Co. KG, Senden, Germany) were applied to the resin die to provide the intended nominal cement space.[17] Unifast TRAD (GC Corporation, Tokyo, Japan) was mixed according to the manufacturer's instructions, placed into the silicone mold, and seated on the corresponding resin die. Immediately after seating, the mold–die assembly was placed in a pressure polymerization unit (Vertex MultiCure; Vertex-Dental B.V., Soesterberg, the Netherlands) at 50°C under a pressure of 2.5 bar for 5 minutes during polymerization to reduce internal porosity and minimize polymerization-related dimensional changes of the provisional crown.

For the heat-cured PMMA group, printed wax patterns from the same crown design were invested and eliminated using the lost-wax technique. SR Ivocron (Ivoclar Vivadent AG, Schaan, Liechtenstein) was then packed into the mold and polymerized in a heat-curing unit under controlled temperature conditions at 70°C for approximately 30 minutes according to the manufacturer's instructions. After polymerization, the specimens were allowed to cool and deflasked.

For the milled PMMA group, crowns were fabricated from the same crown design and milled from DD provi P HI discs using a five-axis milling machine (CORiTEC 250i; imes-icore GmbH, Eiterfeld, Germany).

For the three-dimensional printed group, crowns were fabricated from the same crown design using Temp C&B UV 2.0 resin (Guangzhou HeyGears IMC Inc., Guangzhou, China) and an UltraCraft A2D printer (Guangzhou HeyGears IMC Inc., Guangzhou, China). The crowns were printed at a layer thickness of 50 μm. The printed crowns were fabricated at a 0-degree build orientation, with the occlusal surface positioned parallel to and facing the build platform, while the intaglio surface was oriented upward. After printing, the crowns were post-cured using a post-curing unit (UltraCraft AirCure; Guangzhou HeyGears IMC Inc., Guangzhou, China) with 400–410 nm light for 3 minutes according to the manufacturer's instructions.

After fabrication, the crown margins were minimally finished without internal surface adjustment and inspected under 2.5× magnification before cementation. Representative provisional crowns fabricated by the four methods are shown in Figure 4: (A) autopolymerized PMMA, (B) heat-cured PMMA, (C) milled PMMA, and (D) three-dimensional printed methacrylate-based resin.

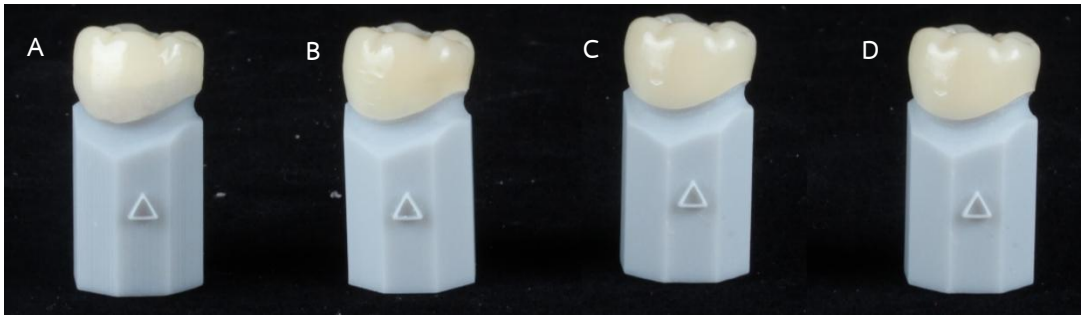



**Figure 4** Representative provisional crowns seated on standardized resin dies after fabrication: (A) Autopolymerized PMMA, (B) Heat-cured PMMA, (C) Milled PMMA, and (D) Three-dimensional printed methacrylate-based resin.

**Cementation and digital measurement of marginal gap**

Each crown was cemented to its corresponding die with Temp-Bond NE (Kerr Corporation, Brea, CA, USA). A constant 50 N seating load was applied with a loading device for 5 minutes to standardize cement thickness and seating pressure across specimens (Figure 5).[8] Excess cement was removed, and marginal adaptation was evaluated. The triple-scan protocol was used to evaluate the spatial relationship between the restoration and abutment without sectioning. Three datasets were obtained for each specimen: the master die, the crown intaglio surface, and the cemented crown seated on the die (Figure 6). All scans were obtained with a TRIOS 5 intraoral scanner (3Shape, Copenhagen, Denmark) and saved as standard tessellation language files.[11]

The scan files were imported into Geomagic Control X software (3D Systems, Rock Hill, SC, USA). The crown intaglio and die files were aligned using the seated-crown adaptation file as a reference. After initial and best-fit alignment, the adaptation file was removed, leaving the die and crown intaglio files as the reference and measurement data, respectively. Four cross-sectional planes were generated using the predefined external edges of the standardized die as reference landmarks. These edges were incorporated into the die design before fabrication as reproducible landmarks, allowing the same circumferential measurement sites to be identified consistently across all specimens and thereby improving the reproducibility and accuracy of marginal gap assessment.

The marginal gap was then measured at eight locations: buccal, distobuccal, distal, distolingual, lingual, mesiolingual, mesial, and mesiobuccal. According to Holmes et al., the marginal gap was defined as the perpendicular distance from the preparation finish line to the restoration margin.[18] The gap at each site was measured three times using the Linear Dimension tool on sectioned views, and the average of the three measurements was recorded for that site. The mean value of the eight sites was then calculated for each specimen and used for statistical analysis (Figure 7).

**Statistical analysis**

SPSS Statistics version 28 (IBM Corp., Armonk, NY, USA) was used for analysis. Descriptive statistics included minimum, maximum, mean, standard deviation, and 95% confidence interval. Data normality was assessed using the Shapiro–Wilk test, and homogeneity of variance was evaluated using Levene's test. One-way analysis of variance was used to test the effect of fabrication method on marginal gap. Since the assumption of homogeneity of variances was violated, Tamhane's T2 post hoc test was used for multiple comparisons. An independent samples t-test was used to compare conventional and digital workflows. Effect sizes were reported as eta squared, partial eta squared, and Cohen's d. Alpha was set at 0.05. Intra-examiner reliability was assessed using a two-way mixed-effects intraclass correlation coefficient model with absolute agreement and 95% confidence intervals, based on the three repeated measurements.

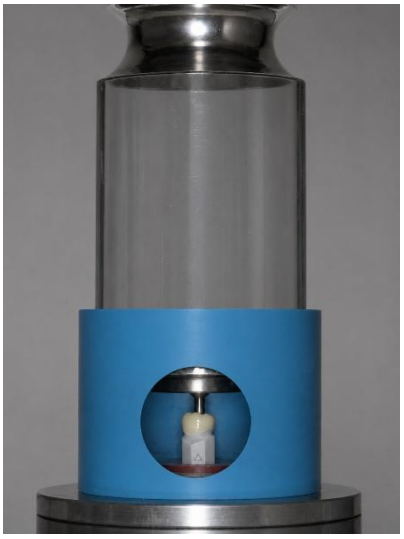


**Figure 5** Standardized temporary cementation using a constant 50 N seating load applied for 5 minutes with a loading device.

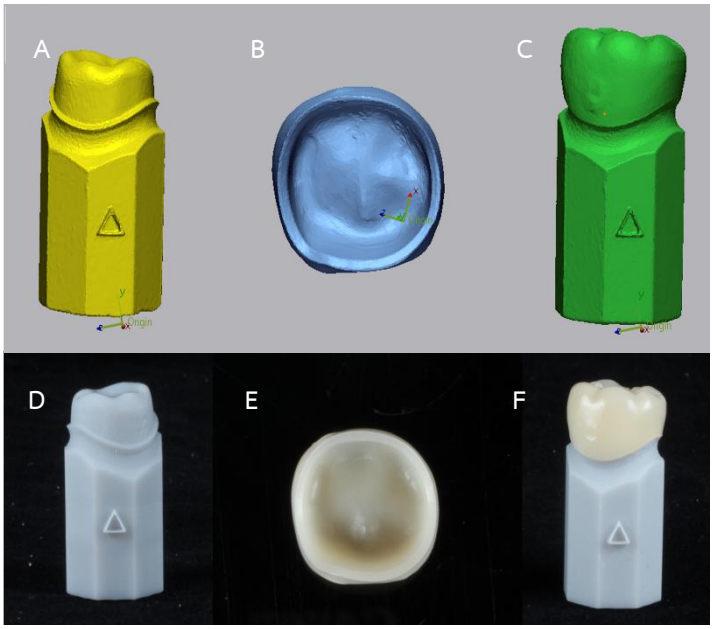



**Figure 6** Triple-scan protocol and corresponding datasets. The upper row shows the digital scan datasets: (A) Die, (B) Crown intaglio surface, and (C) Cemented crown seated on the die. The lower row shows the corresponding physical specimens used to obtain each dataset: (D) Standardized resin die, (E) Provisional crown showing the intaglio surface, and (F) Cemented provisional crown seated on the standardized resin die.

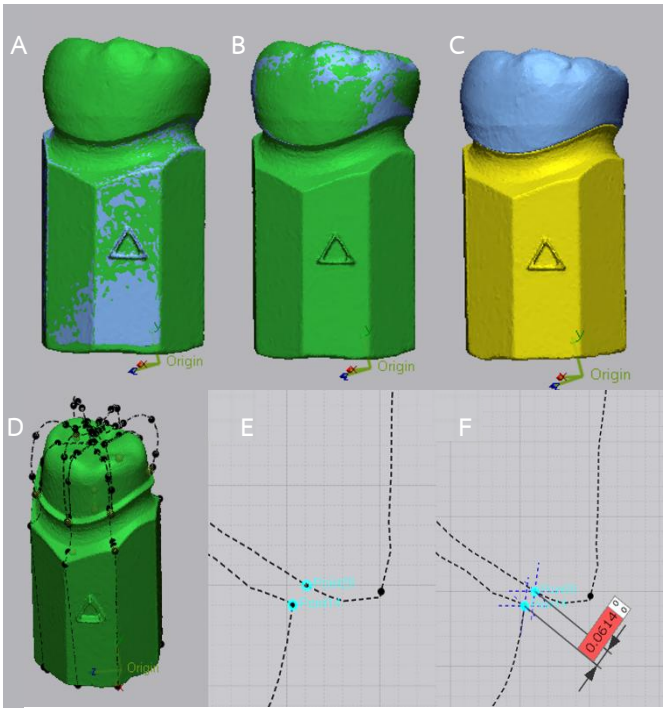



**Figure 7** Digital alignment and marginal gap measurement workflow in Geomagic Control X software. (A) Die scan aligned with the seated-crown adaptation file, (B) Crown intaglio scan aligned with the same seated-crown adaptation file. (C) Final alignment of the die and crown intaglio datasets after removal of the adaptation file; the die and crown intaglio datasets were subsequently used for marginal gap measurement. (D) Four cross-sectional planes defining eight circumferential measurement sites, (E) Identification of the preparation finish line and restoration margin according to the definition proposed by Holmes et al., and (F) Measurement of the perpendicular distance between the two reference points using the Linear Dimension tool.

## Results

Mean marginal gaps differed among groups. The milled group showed the smallest gap (69.45±15.20 μm), followed by the three-dimensional printed (72.43±9.29 μm), heat-cured (108.33±5.57 μm), and autopolymerized groups (113.24±5.65 μm) (Table 2, Figure 8). Shapiro–Wilk tests showed no significant departures from normality in the autopolymerized (W=0.897, p=0.203), heat-cured (W=0.924, p=0.391), three-dimensional printed (W=0.951, p=0.680), or milled groups (W=0.968, p=0.874). Levene's test indicated unequal variances, F (3, 36)=5.005, p=0.005; therefore, Tamhane's T2 test was used for post hoc comparisons. One-way analysis of variance showed a significant effect of fabrication methods on marginal gap, F (3, 36)=56.256, p<0.001, partial $\eta^2$=0.824 (Table 3). Tamhane T2 comparisons showed no significant difference between autopolymerized and heat-cured PMMA (p=0.336) or between the milled and three-dimensional printed groups (p=0.996) (Table 4). When grouped by fabrication workflow, digitally fabricated crowns showed significantly smaller marginal gaps than conventionally fabricated crowns (70.94±12.35 μm versus 110.79±6.01 μm), Welch's t (27.52)=12.969, p<0.001, Cohen's d=4.101 (Table 5). Intra-examiner reliability was excellent. The single-measure ICC was 0.996 (95% CI, 0.976–1.000) and the average-measure ICC was 0.999 (95% CI, 0.992–1.000), indicating high agreement among the three repeated measurements.

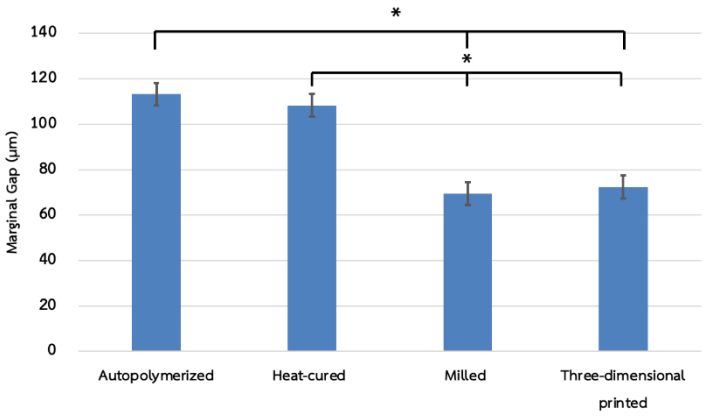



**Figure 8** Mean marginal gap of provisional crowns according to fabrication method. Error bars indicate standard deviations. Horizontal brackets with asterisks indicate statistically significant pairwise differences according to the Tamhane T2 post hoc test (p<0.05).

**Table 2** Marginal gap of provisional crowns according to fabrication method.

| Group | Abbrev. | n | Min (μm) | Max (μm) | Mean ± SD (μm) | 95% CI (μm) |
|---|---|---|---|---|---|---|
| Autopolymerized PMMA | S | 10 | 103.50 | 120.10 | 113.24 ± 5.65 | 109.20, 117.28 |
| Heat-cured PMMA | H | 10 | 102.00 | 118.40 | 108.33 ± 5.57 | 104.35, 112.31 |
| Milled PMMA | M | 10 | 42.10 | 90.80 | 69.45 ± 15.20 | 58.58, 80.32 |
| Printed methacrylate-based resin | P | 10 | 60.90 | 89.60 | 72.43 ± 9.29 | 65.79, 79.07 |

Note: CI, confidence interval; PMMA, polymethyl methacrylate; SD, standard deviation.

**Table 3** One-way analysis of variance for the effect of provisional fabrication methods on marginal gap.

| Source | SS | df | MS | F | p-value | $\eta^2$ | Partial $\eta^2$ |
|---|---|---|---|---|---|---|---|
| Between groups | 16,000 | 3 | 5,333.33 | 56.256 | <0.001 | 0.824 | 0.824 |
| Within groups | 3,413 | 36 | 94.81 | | | | |
| Total | 19,413 | 39 | | | | | |

Note: SS, sum of squares; MS, mean square.

**Table 4** Tamhane T2 post hoc pairwise comparisons of marginal gap among provisional restoration fabrication methods.

| | Autopolymerized | Heat-cured | Milled | Printed |
|---|---|---|---|---|
| Autopolymerized | - | 0.336 | <0.001 | <0.001 |
| Heat-cured | - | - | <0.001 | <0.001 |
| Milled | - | - | - | 0.996 |
| Printed | - | - | - | - |

**Table 5** Independent samples t-test comparing marginal gap between conventional and digital fabrication methods.

| Method | n | Mean ± SD (μm) | t | df | p-value | Cohen's d |
|---|---|---|---|---|---|---|
| Conventional | 20 | 110.79 ± 6.01 | 12.969 | 27.52 | <0.001 | 4.101 |
| Digital | 20 | 70.94 ± 12.35 | | | | |

Note: Conventional fabrication included autopolymerized and heat-cured groups. Digital fabrication included printed and milled groups.

## Discussion

This study evaluated the effect of four provisional crown fabrication methods on marginal adaptation: autopolymerized PMMA, heat-cured PMMA, milled PMMA, and three-dimensional printed methacrylate-based resin. Fabrication method significantly affected marginal adaptation; therefore, the null hypothesis was rejected. Milled and printed crowns showed significantly smaller marginal gaps than autopolymerized and heat-cured PMMA crowns. Although the milled group had the lowest mean gap, it did not differ significantly from the printed group.

The smaller marginal gaps of the digitally fabricated groups may be explained by differences in fabrication workflow. Conventional fabrication involves several operator-dependent procedures, including wax-up, investing, packing, polymerization, deflasking, finishing, and polishing, introducing cumulative errors. By contrast, milling and three-dimensional printing use digital design data and standardized manufacturing procedures, improving reproducibility.[9,19] In the present study, printed crowns were fabricated directly from the digital design, whereas milled crowns were produced from pre-polymerized PMMA blanks, avoiding manual processing steps. This agrees with Angwarawong et al., who reported smaller marginal gaps in digitally than conventionally fabricated interim restorations.[20]

Material-related factors may also have contributed to group differences. Berghaus et al. reported that fabrication method influenced the degree of conversion and residual monomer release, even in materials with similar monomer matrices. Self-curing materials showed the greatest monomer release, whereas milled blanks showed minimal release. Industrial polymerization under controlled temperature and pressure may produce a more homogeneous polymer structure with a higher degree of conversion, thereby improving dimensional stability and partly explaining the smaller marginal gaps of the milled group.[21]

The milled and printed groups showed comparable initial marginal adaptation, possibly because the same crown design, cement space, and standardized fabrication protocol were used. This finding is partly consistent with Sidhom et al., who found no significant difference in three-dimensional accuracy between milled and printed PMMA working models, although printed models showed fewer deviations.[22] The milled group had greater variability, possibly related to bur diameter and tool wear. Sidhom et al. noted that the smallest milling bur was approximately 1 mm, limiting fine-detail reproduction. Smaller burs may generate excessive heat during PMMA milling, causing resin melting, accumulation within the bur flutes, and possible bur fracture. In

contrast, three-dimensional printing builds restorations layer by layer through localized polymerization and is not limited by bur diameter. These factors may explain the greater standard deviation in the milled group. The larger marginal gaps of the autopolymerized and heat-cured PMMA groups may reflect technique sensitivity and dimensional changes during conventional resin processing. Hiramatsu et al. reported that porosity is affected by monomer evaporation, nonuniform mixing, inadequate polymerization pressure, and the stage of resin insertion, indicating that manual manipulation and polymerization conditions influence consistency.[23] Lamb et al. showed that residual monomer levels in autopolymerizing acrylic resin vary with powder/liquid ratio, curing and storage temperatures, and oxygen exposure, and also documented polymerization shrinkage.[24] A higher liquid monomer content reduces the proportion of dimensionally stable pre-polymerized particles and increases the amount undergoing polymerization. Similarly, Balkenhol et al. attributed differences in shrinkage among methacrylate-based provisional materials to composition variations, with a greater liquid component producing greater shrinkage.[25] Although heat-cured PMMA is processed under more controlled thermal conditions, both conventional methods involve several manual procedures and remain susceptible to shrinkage and processing variability. These factors may explain their larger marginal gaps compared with the digital groups.

The favorable marginal adaptation of the printed group may be related to the combined effects of printing parameters and post-curing conditions. Abdelhady et al. reported that both layer thickness and build orientation significantly influence the marginal and internal fit of three-dimensional printed fixed dental prostheses. Layer thicknesses of 20–50 μm, particularly 50 μm, generally produced better adaptation than approximately 100 μm. They also reported that intermediate build orientations of 45°–60° were generally favorable, whereas 0° and 90° orientations could increase stair-stepping artifacts and marginal discrepancies, particularly along curved margins.[26] In the present study, Temp C&B UV 2.0 crowns were fabricated with an UltraCraft-series printer at a 50-μm layer thickness and a 0-degree build orientation. Although this orientation may be less favorable than the intermediate orientations reported in previous studies, the use of a relatively fine 50-μm layer thickness may have helped reduce marginal discrepancies in the printed group. In addition, Reymus et al. demonstrated that layer thickness and post-curing method affect the degree of conversion of three-dimensional printed temporary crown-and-bridge resin.[27] Therefore, the manufacturer-recommended printing and post-curing protocol used in the present study may have contributed to adequate polymer conversion and favorable marginal adaptation. These findings suggest that the marginal accuracy of the printed crowns should be interpreted in relation to the combined effects of layer thickness, build orientation, and post-curing protocol.

The mean marginal gap of the conventional workflow was approximately 40 μm greater than that of the digital workflow, which may be clinically relevant. Marginal discrepancies are associated with plaque accumulation, pulpal irritation, cement dissolution, and periodontal inflammation. Although marginal-gap ranges of 50–120 μm are frequently cited for permanent fixed restorations, no universally accepted marginal-gap threshold has been established specifically for provisional crowns.[4,28,29] Therefore, the values observed in the present study should be interpreted primarily as comparative differences among fabrication methods rather than classified as clinically acceptable or unacceptable solely on the basis of thresholds derived from definitive restorations.[30]

A strength of this study was the digital measurement protocol, which avoided destructive sectioning and allowed circumferential assessment by superimposing the seated crown, master die, and crown intaglio scan files.[11] The triple-scan protocol enables three-dimensional evaluation of the restoration-abutment relationship. Svanborg et al. reported that both the triple-scan protocol and the impression replica techniques could measure the fit of tooth-supported restorations. However, accurate assessment of the absolute marginal gap depends on the scanner's ability to capture the restoration's outermost edge.[31] Thus, although digital measurement was a methodological strength, the findings should be interpreted in relation to scanner accuracy, software alignment, and operator-defined reference points. A recent *in vitro* full-arch implant study reported TRIOS 5 precision and trueness deviations of 37.8±4.53 µm and 54.9±11 µm, respectively.[32] Although these values cannot be directly transferred to the present single-crown triple-scan workflow, they suggest that scanner-related uncertainty may be substantial relative to the approximately 69–72 µm marginal gaps measured in the digital groups. Therefore, measurement uncertainty associated with scanning and software alignment may have limited the ability to detect small differences between the milled and printed groups and should be considered when interpreting their statistically comparable results.

Several aspects of the study design should be considered. In the autopolymerized group, five layers of gold die spacer were applied. According to the manufacturer, each layer provides an approximate thickness of 10 µm; therefore, five layers were intended to produce a nominal cement space of approximately 50 µm, comparable to the digitally specified cement space used in the other groups. However, because the die spacer was applied manually and its actual thickness was not directly measured, minor variation from the digitally specified cement space may have affected the between-group comparisons. This *in vitro* study used resin dies, a single crown design, and one commercial product from each material category. The findings therefore reflect the tested conditions and may not represent all provisional restorative materials. A standardized 50 N seating load was used to minimize operator-dependent variation in crown seating and cement thickness. However, this load should be regarded as a controlled *in vitro* condition rather than an exact simulation of clinical cementation. Future studies should investigate additional materials, preparation designs, cement-space settings, build orientations, and clinically relevant outcomes to further clarify the effects of fabrication method and material composition on marginal adaptation.

## Conclusion

Within the limitations of this *in vitro* study, fabrication method significantly influenced the marginal adaptation of provisional crowns. Milled PMMA and three-dimensional printed methacrylate-based resin crowns fabricated using digital methods showed smaller marginal gaps than conventionally fabricated autopolymerized and heat-cured PMMA crowns. However, no significant difference was found between the two digital fabrication methods or between the two conventional fabrication methods. For provisional restorations in which marginal accuracy is particularly important, clinicians may consider either milling or three-dimensional printing instead of conventional fabrication methods.

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## Ethics statement

This *in vitro* study did not involve human participants, extracted human teeth, animals, or identifiable personal data.

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## Conflict of interest

The authors declare no conflict of interest.

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KDJ Khon Kaen University Dental Journal

# ความแนบสนิทบริเวณขอบของครอบฟันชั่วคราวพอลิเมทิลเมทาไครเลตชนิดบ่มตัวเอง บ่มด้วยความร้อน กลึง และเรซินเมทาคริเลตเบสชนิดพิมพ์สามมิติด้วยเทคนิคทริปเปิ้ลสแกน: การศึกษาในห้องปฏิบัติการ

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***บทความวิจัย***

## บทคัดย่อ

**วัตถุประสงค์:** เพื่อเปรียบเทียบความแนบสนิทบริเวณขอบของครอบฟันชั่วคราวที่ผลิตด้วยวิธีการผลิต 4 วิธี โดยใช้การวิเคราะห์สามมิติ
**วัสดุอุปกรณ์และวิธีการ:** เตรียมฟันหลักเรซินมาตรฐานจำนวน 40 ชิ้น และสุ่มแบ่งเป็น 4 กลุ่ม กลุ่มละ 10 ชิ้น ตามวิธีการผลิตครอบฟันชั่วคราว ได้แก่ พอลิเมทิลเมทาคริเลตชนิดบ่มตัวเอง (ยูนิฟาสต์ แทรด) พอลิเมทิลเมทาคริเลตชนิดบ่มด้วยความร้อน (เอสอาร์ ไอโวครอน) พอลิเมทิลเมทาคริเลตชนิดกลึง (ดีดี โพรวี พี เอชไอ) และเรซินเมทาคริเลตเบสชนิดพิมพ์สามมิติ (เทมป์ ซีแอนด์บี ยูวี 2.0) จากนั้นยึดด้วยซีเมนต์ชั่วคราว (เทมป์บอนด์ เอ็นอี) ภายใต้แรงกดมาตรฐาน แล้วประเมินช่องว่างบริเวณขอบด้วยโปรโตคอลทริปเปิลสแกนและซอฟต์แวร์วิเคราะห์สามมิติ โดยวัดที่ตำแหน่งอ้างอิงรอบขอบครอบฟัน 8 ตำแหน่งต่อชิ้นงาน วิเคราะห์ข้อมูลด้วยการวิเคราะห์ความแปรปรวนทางเดียวและการทดสอบเปรียบเทียบพหุคูณแบบแทมเฮน ทีทู ที่ระดับนัยสำคัญ 0.05
**ผล:** วิธีการผลิตมีผลต่อช่องว่างบริเวณขอบอย่างมีนัยสำคัญทางสถิติ ($p<0.001$) กลุ่มที่ผลิตด้วยการกลึงมีค่าเฉลี่ยช่องว่างบริเวณขอบน้อยที่สุด (69.45±15.20 ไมโครเมตร) ตามด้วยกลุ่มพิมพ์สามมิติ (72.43±9.29 ไมโครเมตร) กลุ่มบ่มด้วยความร้อน (108.33±5.57 ไมโครเมตร) และกลุ่มบ่มตัวเอง (113.24±5.65 ไมโครเมตร) กลุ่มที่ผลิตด้วยระบบดิจิทัลมีช่องว่างบริเวณขอบน้อยกว่ากลุ่มที่ผลิตด้วยวิธีดั้งเดิมอย่างมีนัยสำคัญทางสถิติ ($p<0.001$)
**บทสรุป:** ภายใต้ข้อจำกัดของการศึกษาในห้องปฏิบัติการนี้ วิธีการผลิตมีผลต่อความแนบสนิทบริเวณขอบอย่างมีนัยสำคัญ ครอบฟันชั่วคราวที่ผลิตด้วยการกลึงและพิมพ์มีช่องว่างบริเวณขอบน้อยกว่าครอบฟันชั่วคราวชนิดบ่มตัวเองและชนิดบ่มด้วยความร้อน อย่างไรก็ตาม ไม่พบความแตกต่างอย่างมีนัยสำคัญทางสถิติระหว่างวิธีการผลิตด้วยระบบดิจิทัลทั้งสองวิธี หรือระหว่างวิธีการผลิตแบบดั้งเดิมทั้งสองวิธี สำหรับครอบฟันชั่วคราวที่ต้องการควบคุมความแม่นยำบริเวณขอบ ทันตแพทย์อาจพิจารณาเลือกใช้วิธีการผลิตด้วยการกลึงหรือการพิมพ์สามมิติแทนวิธีการผลิตแบบดั้งเดิม

**คำไขรหัส:** ความแนบสนิทบริเวณขอบ/ ครอบฟันชั่วคราว/ พอลิเมทิลเมทาไครเลต/ แคด-แคม/ การวิเคราะห์สามมิติ

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