Comparative Evaluation of Fit Accuracy of Milled Versus 3D-Printed Provisional Crowns over Endodontically Treated Abutments

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ABSTRACT:

Background: Provisional crowns placed over endodontically treated abutments must provide a precise marginal fit to preserve the coronal seal, prevent bacterial microleakage into the obturated canal system, and protect the structurally weakened tooth during the interim period. Computer-aided design and computer-aided manufacturing (CAD/CAM) milling and additive manufacturing (three dimensional (3D) printing) are now the two principal digital workflows used for fabricating these restorations, but comparative data on their fit performance specifically over endodontically treated abutments remain limited.

Objective: To compare the marginal and internal fit accuracy of provisional crowns fabricated by subtractive milling (CAD/CAM) and additive manufacturing (digital light processing (DLP) 3D printing) over endodontically treated abutments using the silicone replica technique.

Methods: Sixty extracted, single-rooted human premolars that had received standardized orthograde root canal treatment were randomly allocated into two groups of 30 specimens each. Group I

received milled polymethylmethacrylate (PMMA) provisional crowns from pre-polymerised CAD/CAM blocks, while Group II received 3D-printed crowns fabricated from a DLP printable resin. A standardized tooth preparation with a 1 mm chamfer finish line, 6 degree taper, and a 2 mm ferrule was completed. All crowns were designed from a single STL file with a 50 μm cement spacer. The marginal gap, axial gap, occlusal gap, and absolute marginal discrepancy were measured at 16 reference points per specimen using the silicone replica technique under a digital microscope at ×100 magnification. Data were analysed using independent t-tests with significance set at $p < 0.05$.

Results: The mean marginal gap was 58.4 ± 9.7 μm in the milled group and 76.2 ± 12.3 μm in the 3D-printed group, a difference that was statistically significant ($p < 0.001$). The mean axial and occlusal gaps were also significantly smaller in the milled group (axial: 71.5 ± 10.8 μm vs 89.6 ± 13.4 μm; occlusal: 112.4 ± 18.6 μm vs 138.9 ± 22.1 μm; $p < 0.001$ for both). All values, however, fell within the clinically acceptable threshold of 120 μm for the marginal interface. Inter-examiner reliability for replica measurements was high (intraclass correlation coefficient (ICC) = 0.92).

Conclusion: Milled provisional crowns demonstrated superior marginal and internal fit compared with their 3D-printed counterparts when seated on endodontically treated abutments, although both fabrication methods produced restorations within the clinically acceptable range. The choice of fabrication technique should consider the duration of provisionalization, restorative complexity, and chairside efficiency, with milling preferred where prolonged interim service over a structurally compromised tooth is anticipated.

Keywords: CAD/CAM, 3D printing, Endodontically treated teeth, Marginal fit, Provisional crowns, Silicone replica technique, Subtractive milling

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Introduction

Provisional restorations are an indispensable element of fixed prosthodontic therapy, fulfilling protective, diagnostic, and biological functions during the interval between tooth preparation and the cementation of the definitive prosthesis. They preserve pulpal vitality where applicable, maintain the position of the prepared abutment and adjacent teeth, support periodontal health, and provide the patient with acceptable function and esthetics during a sometimes prolonged interim period [1]. The mechanical and biological adequacy of these restorations therefore exerts a direct influence on the success of the definitive prosthesis [2].

Marginal and internal fit are widely accepted as the principal indicators of clinical performance for any indirect restoration, including provisional crowns. A poorly adapted margin permits cement dissolution, plaque accumulation, microleakage,

and recurrent caries, while excessive internal discrepancies impair seating, retention, and load distribution [3]. The clinical acceptability threshold for the marginal gap, originally proposed by McLean and von Fraunhofer and subsequently corroborated by multiple investigators, lies between 50 and 120 μm, although values closer to 50 μm are increasingly considered the gold standard for digitally fabricated restorations [4].

The fit requirements become even more critical when the abutment has undergone endodontic therapy. Endodontically treated teeth are structurally weakened by access cavity preparation, dehydration of dentin, and the loss of pulpal proprioception, all of which predispose them to fracture and biological failure if the coronal seal is compromised [5]. Bacterial recontamination of the obturated canal system through a leaking provisional restoration is a well-documented cause of post-treatment endodontic failure, particularly when the interim phase exceeds a few weeks. A precisely fitting provisional crown therefore performs a dual role on an endodontically treated abutment: protecting the residual tooth structure from masticatory load, and acting as a barrier against coronal microleakage.

The two principal digital workflows now used to fabricate provisional crowns are subtractive manufacturing (computer-aided design and computer-aided manufacturing, CAD/CAM milling) and additive manufacturing (three-dimensional (3D) printing). CAD/CAM milling produces restorations from pre-polymerised polymethyl methacrylate (PMMA) blocks, offering predictable mechanical properties, dimensional stability, and freedom from polymerisation shrinkage [6].

3D printing, particularly digital light processing (DLP) and stereolithography (SLA), builds restorations layer-by-layer from photopolymerisable resins, allowing complex geometries, minimal material waste, and the parallel production of multiple units [7,8].

3D printing has become a defining technology of contemporary digital dentistry, with established applications across prosthodontics, endodontics, surgical guidance, and implantology [9]. Its accuracy, however, is influenced by build direction, layer thickness, post-curing protocol, and resin chemistry, all of which may affect the marginal adaptation of the final restoration [10]. Comparative evidence on the fit of milled versus printed provisional crowns has accumulated over the past five years, but findings remain inconsistent, with some studies favouring milled restorations [11], others favouring printed restorations [12,13], and others reporting no statistically significant difference [14]. Crucially, almost all of the available investigations have used vital, unmodified abutments rather than endodontically treated teeth with restored access cavities, leaving a clear evidence gap relevant to everyday clinical practice.

The present study was therefore designed to compare the marginal and internal fit accuracy of milled and 3D-printed provisional crowns over endodontically treated single-rooted abutments using the silicone replica technique. The findings are intended to inform the selection of fabrication workflow when an endodontically treated tooth requires extended provisionalization prior to definitive restoration.

Methodology

This in vitro comparative study was conducted in the Department of Prosthodontics and Crown & Bridge in collaboration with the Department of Conservative Dentistry and Endodontics, over a period of 12 months. Ethical approval was obtained from the Institutional Ethics Committee, and the use of extracted human teeth was consented to in accordance with the Declaration of Helsinki.

Specimen selection and grouping

A total of 60 freshly extracted, caries-free, single-rooted human maxillary premolars with comparable crown height and root anatomy were collected. Teeth with cracks, restorations, resorption, or open apices were excluded. The specimens were cleaned of debris, stored in 0.9% normal saline at 4 °C, and used within three months of extraction. Specimens were randomly allocated into two equal groups of 30 each using a

computer-generated randomisation list. Group I received milled provisional crowns and Group II received 3D-printed provisional crowns.

Endodontic preparation of abutments

Each specimen underwent standardized orthograde non-surgical root canal treatment to simulate the clinical scenario of an endodontically treated abutment. A conventional access cavity was prepared, working length was established 1 mm short of the apical foramen, and biomechanical preparation was carried out using rotary nickel-titanium files up to size 30/0.04. Irrigation was performed using 3% sodium hypochlorite and 17% ethylenediaminetetraacetic acid (EDTA), followed by a final saline rinse. Canals were obturated using gutta-percha and a calcium silicate-based bioceramic sealer with the single-cone technique. The access cavity was sealed with a flowable composite resin orifice barrier and a layer of light-cured composite to reproduce the standard post-endodontic coronal seal.

Tooth preparation

All specimens received a standardized full-coverage crown preparation by a single calibrated operator using a milling-platform-mounted parallelometer to ensure reproducibility. The preparation parameters were a 1 mm circumferential chamfer finish line placed 1 mm coronal to the cementoenamel junction, a 6° total occlusal convergence, an occlusal reduction of 2 mm, a minimum of 2 mm ferrule height, and rounding of all internal line angles. Each prepared specimen was then mounted in autopolymerising acrylic resin within a standardised cylindrical mould to facilitate handling and seating during evaluation.

Digital workflow and crown design

All prepared specimens were scanned with an intraoral-equivalent laboratory scanner (meditT710, Medit Corp., Seoul, South Korea) at a stated accuracy of <7 μm. The resulting STL files were imported into exocad Dental CAD software (exocad GmbH, Darmstadt, Germany), and a single representative crown design was generated for each preparation. A virtual cement gap of 50 μm was set, beginning 1 mm above the finish line, with a relief gap of 30 μm at the marginal area. The same STL file was used to fabricate both the milled and 3D-printed crowns to eliminate design-related variability.

Crown fabrication

In Group I, milled provisional crowns were produced from pre-polymerised PMMA blocks (Telio CAD, Ivoclar Vivadent, Schaan, Liechtenstein) using a five-axis dental milling unit (Progra Mill PM7, Ivoclar Vivadent) following the manufacturer's recommended parameters. In Group II, crowns were printed from a Class IIa, CE-certified PMMA-based resin specifically indicated for long-term provisional restorations (NextDent C & B MFH, NextDent B.V., Soesterberg, Netherlands) on a DLP-based 3D printer (NextDent 5100, NextDent B.V.) at a layer thickness of 50 μm and a build orientation of 135°. Printed crowns were ultrasonically washed in isopropyl alcohol and post-cured for 30 minutes following the manufacturer's protocol.

Fit evaluation by the silicone replica technique

The marginal and internal fit of all 60 crowns was assessed using the silicone replica technique, which has been previously validated against 3D superimposition analysis. A light-body polyvinyl siloxane impression material (Elite HD+ Light Body, Zhermack, Rovigo, Italy) was applied to the inner surface of each crown, which was then seated onto its corresponding prepared abutment under a constant 5 kg static load until the silicone fully set. After removal of the crown, a heavy-body silicone (Elite HD+ Putty Soft) was applied over the light-body film to provide structural support to the thin replica. The composite replica was then sectioned in the buccolingual and mesiodistal directions using a sharp scalpel blade, producing four quarter-segments. Sixteen reference points per specimen were defined: four marginal, four cervical, four axial, and four occlusal. Each point was measured under a digital microscope (KH-7700, Hirox, Tokyo, Japan) at ×100 magnification by two calibrated examiners blinded to specimen group.

Statistical analysis

Data were tabulated and analysed using SPSS version 26 (IBM Corp., Armonk, NY, USA). Normality was assessed with the Shapiro-Wilk test. Independent samples t-tests were used to compare the mean marginal, axial, and occlusal gaps between the two groups. Inter-examiner reliability was assessed using the intraclass correlation coefficient (ICC). A p-value of less than 0.05 was considered statistically significant.

Results

All 60 specimens completed fit evaluation, with no specimens lost during fabrication, seating, or replica sectioning. Inter-examiner reliability for the silicone replica measurements was high, with an ICC of 0.92 (95% CI: 0.88-0.95). Baseline characteristics of the abutments were comparable between groups, including mean abutment height, taper, and finish line dimensions, as summarised in Table 1.

Table 1: Baseline characteristics of the prepared endodontically treated abutments

Parameter	Milled Group (n=30)	3D-Printed Group (n=30)
Mean abutment height (mm)	5.84 ± 0.32	5.79 ± 0.29
Mean total occlusal convergence (°)	6.1 ± 0.4	6.0 ± 0.5
Mean chamfer width (mm)	1.02 ± 0.08	1.01 ± 0.07
Mean ferrule height (mm)	2.08 ± 0.18	2.05 ± 0.16

The marginal gap, defined as the perpendicular distance between the crown margin and the finish line of the abutment, differed significantly between the two fabrication methods. Milled crowns produced a smaller mean marginal gap than 3D-printed crowns at every measurement point. The pooled marginal gap values are presented in Table 2.

Table 2: Mean marginal gap values (μm) at four reference positions

Position	Milled Group	3D-Printed Group	p-value
Buccal	57.8 ± 9.4	75.6 ± 11.9	<0.001
Lingual	59.1 ± 10.2	77.4 ± 12.6	<0.001
Mesial	58.0 ± 9.6	75.9 ± 12.1	<0.001
Distal	58.7 ± 9.8	76.0 ± 12.5	<0.001
Overall mean	58.4 ± 9.7	76.2 ± 12.3	<0.001

Internal fit parameters, comprising the cervical, axial, and occlusal gaps, also favoured the milled group. The largest discrepancy in both groups occurred at the occlusal region, consistent with previous reports relating to the geometric complexity of the occlusal surface. The detailed values are summarized in Table 3.

Table 3: Mean internal gap values (μm) at three internal regions

Region	Milled Group	3D-Printed Group	p-value
Cervical	65.2 ± 11.0	82.8 ± 13.1	<0.001
Axial	71.5 ± 10.8	89.6 ± 13.4	<0.001
Occlusal	112.4 ± 18.6	138.9 ± 22.1	<0.001

The proportion of specimens producing a marginal gap within the strict 50 μm clinical-excellence threshold was higher in the milled group, while the proportion within the broader 120 μm clinically acceptable threshold was high in both groups. These distributions are summarised in Table 4.

Table 4: Distribution of specimens by clinical acceptability of marginal gap

Marginal gap range	Milled Group (n)	3D-Printed Group (n)
≤ 50 μm (excellent)	11	3
51-120 μm (acceptable)	19	27
> 120 μm (unacceptable)	0	0

Variability of measurements within each group, expressed as the standard deviation of the marginal gap, was lower in the milled group (9.7 μm) than in the 3D-printed group (12.3 μm), indicating greater fit uniformity in milled restorations. No specimens in either group exceeded the 120 μm threshold for clinical unacceptability. Summary outcomes are presented in Table 5.

Table 5: Summary of fit accuracy outcomes between the two groups

Outcome	Milled Group	3D-Printed Group
Overall mean marginal gap (μm)	58.4 ± 9.7	76.2 ± 12.3
Overall mean internal gap (μm)	83.0 ± 13.5	103.8 ± 16.2
Specimens within 120 μm marginal threshold (%)	100.0	100.0
Coefficient of variation, marginal gap	16.6%	16.1%

Overall, the in vitro fit performance of milled provisional crowns over endodontically treated abutments was statistically superior to that of 3D-printed crowns at every measured location, although both fabrication techniques produced clinically acceptable restorations.

Discussion

The present in vitro investigation compared the marginal and internal fit accuracy of milled and 3D-printed provisional crowns seated over endodontically treated single-rooted abutments. The principal finding is that, while both digital workflows produced restorations within the clinically acceptable marginal threshold of 120 μm, milled provisional crowns demonstrated significantly smaller marginal and internal gaps and greater fit uniformity than 3D-printed crowns at every measured reference point.

The mean marginal gap of 58.4 μm observed in the milled group is consistent with values previously reported for CAD/CAM milled PMMA provisional restorations, which have ranged from approximately 46 to 80 μm in comparable in vitro studies. The mean marginal gap of 76.2 μm in the 3D-printed group falls within the upper end of values reported for DLP-based interim crowns, which typically range from 60 to 110 μm depending on resin chemistry, layer thickness, and build orientation [15, 16].

The superior performance of milled restorations is generally attributed to the use of pre-polymerised PMMA blocks that are essentially free from polymerisation shrinkage, in contrast to additively manufactured restorations that polymerise during printing and post-cure and therefore exhibit a small but measurable dimensional change [17].

Sidhom et al. (2022) [14] reported that milled and 3D-printed PMMA provisional restorations exhibited statistically comparable vertical marginal fit on conventional vital abutments, a finding that contrasts with the present results. The discrepancy may be explained by the use of endodontically treated abutments in the present work, where the residual coronal architecture, the access cavity restoration, and the resulting micro-irregularities of the prepared surface present a more demanding seating environment than an intact vital tooth.

Several mechanistic factors may explain the observed superiority of milling over printing in the present setup. First, the layer-by-layer photopolymerization that defines additive manufacturing can produce a stair-step effect at curved internal surfaces, particularly along the chamfer finish line, which translates into a marginally larger gap. Second, post-curing of printed resins induces residual polymerisation shrinkage that is not encountered with pre-polymerised milled blocks [15]. Third, the build direction influences both the smoothness of the intaglio surface and the positional accuracy of the marginal area; in the present study, a 135° build orientation was used because it has been associated with the best compromise between fit and mechanical strength in the published literature [16]. Even with this optimised orientation, milled restorations retained a measurable advantage.

The clinical implications of these findings are particularly relevant when the abutment is an endodontically treated tooth. The work of Mittal et al. (2024) [4] in their narrative review on 3D printing in dentistry highlighted the rapid evolution of additive manufacturing for prosthetic restorations and emphasized the need for standardization of build parameters and post-curing protocols to optimize clinical outcomes. The present study supports this perspective; in clinical scenarios where an endodontically treated tooth must remain in provisional service for several weeks or months, for example during full-mouth rehabilitation, periodontal stabilization, or staged occlusal therapy, the smaller marginal gap and greater fit uniformity offered by milled restorations may better preserve the coronal seal and reduce the risk of bacterial recontamination of the obturated canal system. The pivotal role of an intact coronal seal for endodontic success has been reaffirmed by multiple investigators and is the rationale for placing a definitive restoration as early as feasible [17].

It is, however, important to recognize that the additive workflow offers practical advantages that may favour its use in selected clinical situations. 3D printing produces multiple restorations in parallel with minimal material waste, supports complex geometries, and enables chairside production with limited operator intervention. Recent surveys of digital adoption in dental practice, including the work of Kashwani et al. (2025) [13] on emerging digital technologies, have

noted the increasing penetration of 3D printing into routine dental workflows, particularly for short-term provisional restorations and surgical guides. Our findings should not be interpreted as discouraging the use of 3D-printed provisional crowns; rather, they suggest that the choice of fabrication route should be guided by the duration of provisionalization, the structural status of the abutment, and the operator's quality control over print parameters.

The marginal threshold of 120 μm, originally derived from in vivo studies of cement dissolution and plaque accumulation [18], remains the most widely cited benchmark for clinical acceptability. Both fabrication techniques in the present study produced 100% of specimens within this threshold, confirming that DLP-based 3D printing, when used with an appropriate build orientation and post-curing protocol, is clinically viable. However, the proportion of specimens achieving the stricter <50 μm 'excellence' threshold was substantially higher in the milled group (37%) than in the 3D-printed group (10%), and this distinction may become clinically important in extended interim service or where esthetic margins are critical [19,20].

Internal fit, particularly at the occlusal region, was poorer in both groups than at the cervical or axial regions. This pattern is well-documented and reflects both the geometric complexity of the occlusal surface and the cumulative effect of cement spacer settings during digital design [21,22]. The occlusal gap of 112.4 μm in the milled group and 138.9 μm in the 3D-printed group is consistent with prior reports and is not expected to compromise crown seating or load distribution under interim function. The greater dispersion of values in the 3D-printed group (occlusal SD 22.1 μm vs 18.6 μm) again reflects the inherent variability introduced by additive manufacturing [23-25].

Limitations

Our study has several limitations. First, the in vitro setting precludes direct extrapolation to the clinical environment, where saliva, occlusal forces, thermal cycling, and patient-related variability may influence the long-term marginal seal. Second, only a single milling system, a single 3D printer, and one resin per technique were investigated; results may differ with other equipment, materials, or print parameters. Third, the silicone replica technique, although validated and widely used, is a two-dimensional method that may underestimate three-dimensional discrepancies; future work should incorporate micro-computed tomography or three-dimensional superimposition analysis. Fourth, the specimens were single-rooted premolars, and the findings may not transfer directly to molars with more complex preparation geometries. Fifth, only one cement spacer setting (50 μm) and one build orientation (135°) were tested; both parameters can influence fit and warrant systematic evaluation in future studies.

Despite these limitations, the present study contributes useful comparative evidence to a previously sparse literature on the fit performance of milled and 3D-printed provisional crowns over endodontically treated abutments. The findings reinforce the importance of marginal accuracy in this specific clinical scenario and support the development of evidence-based recommendations for selecting digital fabrication workflows.

Conclusion

Within the limitations of this in vitro study, milled provisional crowns produced significantly smaller marginal and internal gaps than 3D-printed provisional crowns when seated over endodontically treated single-rooted abutments. Both fabrication techniques nevertheless produced restorations within the clinically acceptable marginal threshold of 120 μm. Milling demonstrated greater fit uniformity and a higher proportion of restorations within the stricter <50 μm threshold, suggesting that it remains the preferable digital workflow when extended provisionalization over a structurally compromised, endodontically treated abutment is anticipated. 3D printing remains a clinically viable alternative, particularly where production speed, parallel fabrication, and material efficiency are priorities, and its performance is expected to continue improving with advances in resin

chemistry, printer accuracy, and post-curing protocols.

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