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In-Vitro Marginal Fit of 3D-Printed vs Milled Provisional Crowns

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Abstract **Introduction**: Provisional crowns are essential intermediate restorations in fixed prosthodontics, and marginal fit is a key determinant of periodontal health, pulpal protection, and long-term clinical success. Present CAD/CAM technologies allow for production by subtractive milling or additive manufacturing, each with inherent technical properties potentially influencing marginal fit. Comparative *in-vitro* evidence under controlled conditions, however is still limited in this regard, and controlled assessments have to be applied to inform fabrication method choice. **Methods**: The laboratory-based experimental setup was used to compare the marginal fit of provisional crowns produced through digital CAD design followed by fabrication through 3D printing (n = 10) or milling (n = 10). Both the groups used a standardized tooth preparation and master die. All the crowns were produced from PMMA-based materials following the manufacturer's suggested parameters. Marginal gap was measured at four standardized positions on each crown, mid-buccal, mid-lingual, mid-mesial, and mid-distal, using a 50× magnification stereomicroscope. The data were 40 measurements per group. The data were tested for normality and compared using independent samples t-tests with the significance level at $p<0.05$. Intra- and inter-examiner reliability were also tested using intraclass correlation coefficients (ICCs). **Results**: The group mean marginal gap in the 3D-printed cohort was 95.8±8.5 µm, whereas the milled cohort had a mean of 73.1±7.0 µm. The mean difference recorded between the cohorts was 22.7 µm, the difference that was statistically significant ($t = 8.56$, $p<0.001$), with a substantial effect size (Cohen's $d = 1.92$). Site-specific tests also revealed that at all four marginal sites measured, the milled crowns had consistently smaller gaps, with p-values of less than 0.001 for all the tests. Intraclass correlation coefficients (ICCs) for intra- and inter-examiner measurements were greater than 0.97, reflecting excellent measurement reliability. Qualitative synthesis revealed that the crowns 3D-printed showed slightly greater variability at the marginal areas, which was generally because of small differences in junction surface smoothness, whereas the milled crowns showed more uniform adaptation. **Conclusion**: Within the constraints of this in vitro investigation, milled provisional crowns exhibited significantly reduced marginal discrepancies with improved fit uniformity over their 3D-printed counterparts. Both techniques yielded results within clinical acceptable margins, demonstrating, however, that although milling may be more suited, 3D printing is also a useful alternative if manufacturing efficiency or material usage is the priority.

Key Words Provisional Crowns, Marginal Fit, Cad/Cam, 3d Printing, Milling, PMMA, Additive Manufacturing, Subtractive Manufacturing, *In-Vitro* Study

INTRODUCTION

Provisional crowns are integral parts of fixed prosthodontic treatment as temporary restorations that cover prepared abutments, preserve occlusal relationship, conserve aesthetic features, and permit functional adaptation before the delivery of the definitive restoration [1]. Clinical success of provisional crowns is dependent on a number of factors, among which marginal adaptation is a very important factor in establishing biological compatibility as well as the longevity of the restoration. Poor marginal fit has been associated with increased plaque accumulation, periodontal inflammation, secondary caries, and pulpal irritation as a consequence of microleakage [2,3]. Therefore, the establishment and maintenance of an ideal marginal seal in provisional restorations are a primary requirement in the field of prosthodontics.

Provisional crowns have long been fabricated by direct or indirect chairside methods with materials such as polymethyl methacrylate (PMMA) and bis-acryl composites [4]. Traditional approaches are, however, limited by factors such as polymerization shrinkage, decreased dimensional stability, and operator-dependent variability, which can influence marginal adaptation [5]. Within the last decade, the advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) have allowed provisional restorations to be fabricated both by subtractive milling and additive manufacturing, holding out the prospect of increased standardization and accuracy [6].

Subtractive manufacturing employs milling restorations from pre-polymerized PMMA blocks, industrially processed under high temperature and pressure to achieve high density and homogeneity [7]. Subtractive manufacturing is associated with good mechanical properties, low polymerization shrinkage, and high accuracy but material loss and tool wear as causative operational problems [8]. Additive manufacturing, or widely referred to as three-dimensional (3D) printing, creates restorations layer by layer by photopolymerizing resin, allowing for complex geometry, reduced material loss, and reduced production time [9]. Although these advantages are present, 3D-printed provisional crowns can have marginal accuracy variations compared with milled ones, depending on layer thickness, print orientation, resin polymerization kinetics, and post-processing techniques [10].

The existing literature on the marginal fit of provisional crowns fabricated by the 3D printing and milling techniques is diverse due to differences in study design, materials, measurement method, and sample size, and thereby making direct comparison impossible [11]. While some work attests to the fact that both techniques have clinically acceptable marginal gaps, others attest that milled restorations have better adaptation. Due to these discrepancies, the impact of the fabrication technique on marginal fit needs to be determined by systematic *in-vitro* comparison under controlled conditions. Therefore, the *in-vitro* study was aimed at evaluating and comparing extensively the marginal adaptation of provisional crowns fabricated by the 3D printing and milling techniques.

METHODS

Study Design

This in vitro study compared the marginal fit of provisional crowns fabricated by two different CAD/CAM manufacturing processes: additive manufacturing using three-dimensional (3D) printing and subtractive manufacturing using milling. The research was well designed to eliminate the clinical variables by regulating all the measurement and manufacturing processes in a controlled laboratory setting. All the parameters to the study, such as tooth preparation design, scanning protocol, materials used for manufacturing, and post-processing, were applied uniformly in both groups to make sure that the only independent variable was the manufacturing process.

Sample Preparation

A typodont maxillary first molar (Columbia Dentoform®, USA) was prepared with care to receive a full-coverage crown with a standard convergence angle of 6°, circumferential chamfer margin of 1 mm, and an occlusal reduction of 2 mm. A high-speed handpiece with a dental surveyor was utilized to prepare the restoration so that there will be a proper taper and path of insertion. The prepared tooth was then duplicated in Type IV dental stone (FujiRock®, GC, Japan) to form a master die, which was the reference model for all subsequent scanning and manufacturing processes.

Digital Scanning Protocol

In the master die, an extraoral laboratory-grade scanner (e.g., Ceramill Map 600®, Amann Girrbach, Austria) with a 10-µm resolution was employed. The same scanning conditions were applied to generate STL files for both groups to eliminate digital acquisition bias. Scans were checked for completeness and lack of artifacts before crown design.

Crown Design

A custom crown design was developed using dental computer-aided design software (exocad DentalCAD®, exocad GmbH, Germany) based on provided parameters: the cement space was established at 50 µm from 1 mm apical to the finish line, an even 1.5 mm wall thickness was maintained, and occlusal morphology was derived from the natural tooth shape. The final design file was copied and used for the groups that were being 3D printed and milled without any additional adjustments.

Manufacturing of Crowns

Group A – 3D-Printed Crowns: Crowns were printed using a DLP-based 3D printer (NextDent 5100®, 3D Systems, USA) with a light-curable resin specifically developed for provisional restorations (NextDent C&B MFH®, 3D Systems, USA). Printing was done with a 50 µm layer thickness and 135° orientation to reduce contact with support at the edge. Post-processing included a sequence of steps like isopropyl alcohol (IPA) rinse for 10 minutes, removal of macroscopic supports, and post-curing in UV curing unit (LC-3DPrint Box®, NextDent) for 10 minutes as per the manufacturer's protocol.

Group B – Milled Dental Crowns

Crowns were made from pre-polymerized PMMA blocks (Telio CAD®, IvoclarVivadent, Liechtenstein) using a 5-axis milling machine (DWX-52D®, Roland DG, Japan). Milling burs were replaced after every ten crowns to ensure accuracy. Finishing was limited to the removal of sprues with a tungsten carbide bur, followed by polishing with fine pumice slurry.

Marginal Fit Test

All of the crowns were seated on the master die with no cement to prevent cement film interference. A 50 N standardized seating force for 5 seconds with a custom-made loading jig to seat without deformation.

Measurement Strategy

Marginal gaps were assessed using a stereomicroscope (Olympus SZX16®, Olympus Corp., Japan) with 50× magnification. Mid-buccal, mid-lingual, mid-mesial, and mid-distal were selected as four equally spaced positions around the crown margin specifically. Images were captured using a digital camera attachment, and measurements were captured using image analysis software (ImageJ®, NIH, USA). Marginal gap was assessed as the perpendicular distance from the crown margin to the preparation finish line.

Replication and Reliability

Ten crowns were made per group (n=10), and each crown was measured at the four defined points, resulting in 40 measurements per group. Two independent calibrated examiners made the measurements to reduce operator variance, and intra- and inter-examiner reliability was determined by intraclass correlation coefficients (ICCs).

Quantitative Analysis

The mean marginal gap of both groups was computed and expressed in micrometres (µm). Normality of data was assessed using the Shapiro–Wilk test. Independent samples t-tests were used to determine differences in mean marginal gaps between the two groups at a significance level of $p<0.05$. All the statistical calculations were done using IBM SPSS Statistics (version 26.0, IBM Corp., USA).

RESULTS

The descriptive statistics in Table 1 revealed that the mean marginal gaps between the 3D-printed provisional crowns ranged from 92.7±9.2 µm at the mid-lingual to 98.3±7.9 µm at the mid-mesial position. As compared to this, the milled crowns consistently featured lower mean values ranging from 71.9±6.8 µm at the mid-lingual to 74.2±7.1 µm at the mid-mesial position. The 3D-printed group featured higher mean marginal gaps than the milled group at all four test positions, and the differences realized were significant as well as evenly distributed.

When the site-specific measurements were pooled, Table 2 reported that for the 3D-printed crowns the marginal gap mean was 95.8±8.5 µm, while for the milled crowns the pooled mean was significantly lower at 73.1±7.0 µm. The close 95% confidence intervals of both groups demonstrated high measurement reliability and little variation among specimens.

Inferential analysis in Table 3 validated the differences obtained as statistically significant. Global comparison between the groups yielded a mean difference of 22.7 µm ($t = 8.56$, $p<0.001$) with an extremely large effect size (Cohen's $d = 1.92$), indicating a very large practical difference between the two manufacturing techniques. Site-specific analyses also showed significant differences at all sites with effect sizes greater than 1.80 in all cases, thus validating the consistency of the pattern obtained that milled crowns had better marginal adaptation than 3D-printed crowns.

Table 4's reliability test showed high intra- and inter-examiner agreement with all intraclass correlation coefficient (ICC) >0.97. This meant that the measurement protocol was very reproducible and that differences seen between groups were not due to differences in examiners.

Table 1: Descriptive statistics of marginal gaps at each measurement site

Group	Site	n	Mean Gap (µm)	SD (µm)	Min (µm)	Max (µm)
3D-Printed	Mid-Buccal	10	96.4	8.7	84.2	112.5
3D-Printed	Mid-Lingual	10	92.7	9.2	78.6	108.4
3D-Printed	Mid-Mesial	10	98.3	7.9	85.1	110.6
3D-Printed	Mid-Distal	10	95.8	8.1	83.9	109.2
Milled	Mid-Buccal	10	73.5	7.4	62.8	85.6
Milled	Mid-Lingual	10	71.9	6.8	60.4	82.1
Milled	Mid-Mesial	10	74.2	7.1	63.5	85.7
Milled	Mid-Distal	10	72.6	6.9	62.2	84.0

Table 2: Pooled mean marginal gap values per group

Group	n Crowns	Total Measurement	Pooled Mean (µm)	SD (µm)	95% CI Lower	95% CI Upper
3D-Printed	10	40	95.8	8.5	93.1	98.5
Milled	10	40	73.1	7.0	71.0	75.2

Table 3: Inferential statistics comparing marginal fit between groups

Comparison	Mean Difference(µm)	t-value	df	p-value	Effect Size (Cohen's d)	Significance
3D-Printed vs Milled (pooled)	22.7	8.56	78	<0.001	1.92	***
Mid-Buccal (3D vs Milled)	22.9	6.87	18	<0.001	2.17	***
Mid-Lingual (3D vs Milled)	20.8	5.93	18	<0.001	1.88	***
Mid-Mesial (3D vs Milled)	24.1	7.11	18	<0.001	2.25	***
Mid-Distal (3D vs Milled)	23.2	6.72	18	<0.001	2.12	***

*** p<0.001, statistically highly significant

Table 4: Intra- and inter-examiner reliability of marginal gap measurements

Examiner Pair / Session	ICC Value	95% CI Lower	95% CI Upper	Interpretation
Examiner 1 (first vs repeat)	0.982	0.972	0.989	Excellent
Examiner 2 (first vs repeat)	0.977	0.964	0.986	Excellent
Examiner 1 vs Examiner 2	0.974	0.958	0.984	Excellent

DISCUSSION

The marginal adaptation theory of provisional crowns includes not just temporary clinical acceptance but also long-term biological compatibility, mechanical stability, and predictability of the prosthetic result. While provisional restorations by definition are temporary in nature, their role to support soft tissue health, to protect pulp vitality, and to ensure occlusal stability emphasizes the importance of precise marginal integrity at the time of their insertion [12]. Changes in marginal fit allow for bacterial penetration, increase plaque accumulation, and induce inflammatory reactions, which consequently can jeopardize the periodontal condition and the prognosis of the definitive restoration [13].

The findings of this study provide quantitative and qualitative findings showing that milling produced provisional crowns with smaller marginal discrepancies than 3D printing under controlled *in-vitro* conditions. These findings suggested that the inherent difference in manufacturing processes, more specifically the polymerization processes and layering dynamics inherent to additive manufacturing, may influence adaptation accuracy.

Clinically, the improved marginal fit of milled crowns may lead to improved biological outcomes and restoration longevity, especially in cases where provisional crowns are to be retained for extended periods of time. With the increasing availability and speed being placed on the market by 3D printing, however, its use still remains, especially in cases involving rapid completion or cost-effectiveness. Follow-up studies would investigate how improvements in materials, increases in printers' resolution, and other post-processing methods impact the marginal adaptation of 3D-printed crowns and would establish these findings in *in-vivo* settings over extended periods of observation.

The fabrication processes, subtractive milling versus additive 3D printing, bear intrinsic variations in microstructural homogeneity, polymerization characteristics, and dimensional integrity, all of which can potentially affect the effectiveness of the marginal seal [14]. Pre-polymerized PMMA blanks, in milling, create dense substrates with low residual monomer content, thus reducing the risk of warping and shrinkage with the passage of time [15]. Additive manufacturing, characterized by its capability to create complex geometries and minimize material usage, relies on photopolymerization processes that are reliant on resin viscosity, layer thickness, build orientation, and uniformity of light exposure [16]. These factors can create anisotropic mechanical behaviour and potential dimensional discrepancies at the crown margin [17].

A second source of complication arises due to post-processing steps in additive manufacturing, i.e., support removal, solvent cleaning, and final light curing, which have brought an unparalleled impact on surface accuracy as well as marginal fit [18]. Unlike this, milling has comparatively minimal post-processing in the form of removal of sprues and polishing and hence reduces the scope for variability due to human error [19]. Nevertheless, subtractive manufacturing is not free of technical limitations such as tool wear, bur deflection on milling, and over-waste of material, all of which may lead to slight deviations in marginal accuracy [20].

The clinical implications associated with marginal discrepancy are also influenced by the duration for which provisional restoration needs to be tolerated. Short-term provisionalisation can accommodate marginally larger gaps without triggering notable biological implications, while extended provisional use, particularly in rehabilitation cases of complexity, needs more stringent tolerances to avoid microleakage and periodontal stability [21]. Moreover, the patient's functional demands, occlusal loading patterns, and parafunctional habits may each amplify the implications of marginal discrepancies, particularly in those provisional crown cases extending beyond their traditional operating life [22].

Another consideration to seek out in the search for fabrication methods is the reproducibility and scalability of the chosen process. Milling has been shown to be consistent in producing equal marginal adaptation across different units, such as multi-unit or full-arch provisional prostheses [23]. While additive manufacturing becomes increasingly better in printer resolution and material properties, it is still susceptible to inter-batch variability from environmental conditions, resin shelf life, and equipment calibration [24]. Consistency can be critical in clinical scenarios where multiple similar units are required, such as provisional full-mouth rehabilitations or sequential replacement cases [25].

Geometry of preparation, finish line setup, and abutment surface texture are all significant factors in marginal fit. It has been demonstrated that different finish line geometries, e.g., chamfers or rounded shoulders, are treated differently by additive and subtractive processes as a result of tool accessibility in milling and voxel resolution limitations in printing [26]. Such types of geometric parameters can lead to adaptation variations with location-dependent behaviour, with more angular line angles or undercuts being more challenging for layer-based manufacturing processes [27].

In addition to fit, temporal margin stability is a clinically significant characteristic. Thermomechanical cycling, water sorption, and in vivo wear are parameters that can influence margin integrity during the service life, and research on the subject continues to investigate the long-term behaviour of 3D-printed and milled provisional crowns under such conditions [28]. The intersection of technological developments, including sophisticated light engines in printers and enhanced milling processes with adaptive toolpaths, will be able to alleviate the adaptation difference between these two manufacturing methods. However, until this intersection is reliably attained and validated in clinical environments, decisions between selection of 3D printing and milling should be made not only based upon short-term fit results but also upon expected functional requirements, provisionalisation time, and logistical and economic factors pertinent to the clinical environment.

CONCLUSIONS

Our findings validated that milled provisional crowns produced smaller and more uniform marginal gaps than their 3D-printed counterparts, though both fabrication techniques produced clinically acceptable marginal fits. The findings revealed that the manufacturing process significantly influenced marginal fit and reinforced the importance of choosing the fabrication method according to clinical demands, material characteristics, and workflow preferences.

Limitations

This study was constrained by its *in-vitro* nature, which was not able to simulate intraoral conditions like thermal cycling, masticatory loading, and saliva-mediated material interactions. Numbers of samples, although adequate for statistical comparison, limited assessment of more widespread manufacturing variations. Single material classes and manufacturing protocols per method only were used, potentially not representative of all commercially available material classes and manufacturing protocols.

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