JFCR
Journal of Fundamental and Clinical Research
https://jfcr.journals.ekb.eg/
ISSN 2735-023X
Vol. 3, No. 2, 170-189, December 2023

3D Evaluation of Marginal Fit of Interim Crowns Fabricated using Conventional, Virtual and Three-Dimensional Printed Working Dies. (In Vitro Study).

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ABSTRACT

Background: The working die system used in dental prosthesis fabrication impacts the accuracy of dental prosthesis. Conventional, virtual, and 3D-printed dies are used in various clinical scenarios. The accuracy of 3D-printed models for diagnosis has been extensively studied. There needs to be more research on the marginal fit of interim single crowns made with 3D-printed dies compared to conventional and virtual dies. ***Aim of the study:*** to evaluate the marginal fit of interim crowns fabricated using conventional, virtual, and three-dimensional printed working Dies. ***Materials and methods:*** A total of 18 interim crowns were milled and divided into three groups according to the die system on which they were fabricated; group A (fabricated on conventional dies), group B (fabricated on virtual dies), and group C (fabricated on 3D-printed dies). Six physical impressions using polyvinyl siloxane material were taken to create conventional dies (group A) for the maxillary right first molar. Additionally, six optical scans were performed to fabricate virtual dies (group B) and printed dies (group C). Interim crowns were milled, and a triple scan protocol was used to evaluate their marginal fit. ***Results:*** The virtual group demonstrated significantly better marginal fit compared to the other groups ($p<0.001$). However, there was no statistically significant difference between the 3D-printed and conventional groups. ***Conclusion:*** virtual dies yielded the highest marginal fit, while conventional and 3D-printed dies produced comparable results. The marginal fit of all interim crowns fell within the clinically acceptable range of 30 to 141 µm.

Keywords: digital techniques, marginal fit, milling method, three-dimensional printing method, and working dies.

INTRODUCTION

The success of restorations relies on various factors, including the crucial factor of marginal fit. Marginal fit refers to the measurement of the gap between the restoration's margin and the prepared tooth's finish line. For single crowns, achieving

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proper marginal fit is essential for long-term stability, durability, and maintaining healthy periodontal tissues. A good fit prevents issues such as plaque accumulation, cement dissolution and leakage, discoloration, poor aesthetics, tooth sensitivity, cavities, and periodontal diseases. Conversely, a poor fit can lead to these problems.[1–4]

Accurate fitting of the restorations requires precision throughout the fabrication process. Two main techniques, conventional and digital, are used for restoration fabrication. In the conventional technique, maintaining precision in all manufacturing steps is necessary for achieving proper marginal fit. However, the digital method utilizing CAD/CAM technology simplifies the process, as only an accurate optical impression is crucial for fabricating the final restoration. The accuracy of the impression directly impacts the proximity between the restoration and abutment, ultimately influencing the marginal fit of the restorations.[5]

In addition to an accurate impression, the precision of the model is crucial for creating a well-fitting prosthesis. Two impression methods are available for creating working models and dies: conventional impressions using elastomeric materials and optical impressions utilizing intraoral scanners to generate digital replicas of oral tissues. Therefore, precise execution of the impression and model fabrication steps in both conventional and digital methods significantly impact their accuracy and, consequently, the final restoration's fit.[6]

Creating an accurate working model is crucial for minimizing framework misfit, which greatly impacts the prognosis of the final prosthesis. Gypsum casts poured from conventional impressions have long been regarded as the gold standard for constructing dental models. Despite the availability of alternative methods, many dental technicians still rely on the conventional pouring method. However, this workflow is time-consuming, labour-intensive, and prone to errors due to the multiple clinical and laboratory procedures involved.[7–9]

With the advent of CAD/CAM systems, optical impressions have replaced physical ones, developing new fabrication techniques for working models and dies. Nowadays, various digital fabrication methods, including different.[10,11] 3D printing technologies, are available for dental models, moving away from traditional stone casts. 3D printing has gained popularity in the dental field due to its additive layer-by-layer approach, which allows for accurate and precise manufacturing of working models with minimal material waste. It is considered an economical and fast technique, capable of producing fine details, including undercuts and better anatomical replication. Some commonly used 3D printing techniques in dentistry include stereo lithography (SLA), Photopolymer jetting, selective laser sintering (SLS), and fused deposition modeling (FDM).[8,11–15]

Among the most popular technologies is stereo lithography uses a scanning laser to build an object one layer at a time using light-cured photopolymer resin. Each layer is scanned by the laser on the surface of the liquid resin, this creates a 'build platform' that descends, and another layer of resin is added over the surface, and the process is repeated.[13,14]

Supports should be used and are designed by CAD software and printed to resist the wiping action and to resist gravity. At the end, they are removed from the finished product. Post- processing procedures include the removal of excess resin and a hardening process in a UV oven. The process is costly when used for large objects, but this technology is commonly used for the industrial production of 3D-printed implant drill guides.[13]

Mclean and von Fraunhofer[16] reported that the clinically accepted boundary value of the vertical marginal gap is ≤100-120 µm after a 5-year clinical study of 1000 restoration. Christenson[16] suggested a clinical goal of 25 µm to 40 µm for the marginal adaptation of cemented restorations. For CAD/CAM restorations, the generally acceptable marginal gap discrepancies are between 50 and 141 µm.[17]

The use of 3D printing technology in fixed prosthodontics is still being extensively researched, and its clinical superiority over conventional methods for using printed models as working cast and die for dental prostheses has yet to be proven.[5,18–22] Although there are several studies.[18,20,23–26] that focus on the accuracy and reproducibility of 3D-printed models for diagnosis, there is a lack of knowledge regarding the accuracy of 3D-printed models in producing well-fitted fixed prostheses. This study aims to evaluate the marginal fit of interim crowns fabricated using conventional, virtual, and 3D-printed working dies. The null hypothesis of the study states that there will be no difference in marginal fit between interim crowns fabricated using conventional dies, virtual dies, and 3D-printed dies.

MATERIALS AND METHODS

Three die systems conventional, virtual, and 3D-printed dies were generated and compared to each other in term of their accuracy for producing milled interim crowns with appropriate marginal fit. Then, the marginal fit of these crowns was assessed by superimposition using Geomagic software.

Sample size calculation:

According to Jang Y 2018[3], the mean value of marginal gap using conventional technique was 41.6±1.9, in comparison to 42.1±2.1 in virtual group, while the mean gap using 3D printing was 48.2±1.4. A large effect size of approximately 0.88 is expected.

A total sample size of 18, six in each group, will be sufficient to detect an effect size of 0.9 and setting a power (1-β error) of 0.8 Using a two-sided hypothesis test setting a Significance level (α error) 0.05 for the data. Sample size calculation was performed using G*Power Version 3.1.9.2.

Sample grouping:

Eighteen digitally fabricated interim single crowns will be divided into 3 equal groups according to the used die systems:

- Group 1: interim single crowns (n=6) fabricated using conventional stone dies (control group).
- Group 2: interim single crowns (n=6) fabricated using CAD/CAM virtual dies.
- Group 3: interim single crowns (n=6) fabricated using 3D-printed stereo-lithography dies.

Preparation of a typodont:

A typodont model of maxillary right 1st molar was prepared, and PVS silicone putty and light midsagittal and buccal indices were made to calibrate the amount of reduction.

The preparation was performed by using a ceramic preparation kit. The amount of preparation was set following the guidelines of all ceramic preparations to be 1.5 mm occlusally and 1.0 mm axially with a deep chamfer margin all around, guided by the rubber base preparation indices and depth grooves.[27–29] **(Figure1)**

Figure (1): Final preparation.

Fabrication of a reference scan:

The prepared typodont was scanned by using high accuracy (7mm) desktop scanner 3 Shape E3, and the STL data obtained will be the reference used for the measurement of the marginal fit by superimposition. **(Figure 2)**

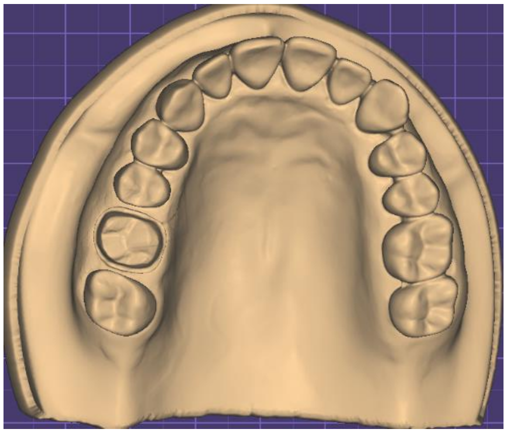

Figure (2): Reference scan model.

Fabrication of different die system:

Fabrication of the conventional stone dies (group 1):

Six dual-viscosity two-step physical final impressions of the prepared typodont were performed using polyvinyl siloxane impression material and size two plastic stock trays. Then the impressions were poured with low expansion stone (0.09%) type IV GC Fuji Rock EP to fabricate six conventional dental models. [3,10,11] **(Figure 3)**

Figure (3): Conventional stone models with removable dies.

These dies will be then scanned by desktop scanner to obtain the dataset required for fabricating the interim crowns of this test group.

Fabrication of the virtual dies (group 2):

For assessment of the accuracy of the whole digital chair-side workflow, six digital impressions were taken by using an intra-oral scanner TRIOS 3 basic for the prepared typodont maxillary right first molar to mimic the clinical situation. Then, these scans were exported as STL files to get a total of six final virtual 3D working dies **(Figure 4).**

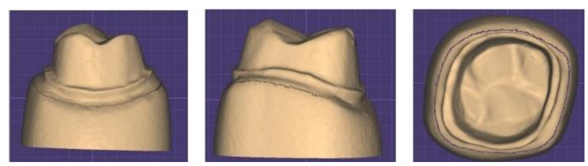

Figure (4): Virtual dies.

Fabrication of the 3D-printed dies (group 3):

To assess the accuracy of 3D-printed dies, six digital impressions were taken of a prepared typodont maxillary right first molar using an intra-oral scanner called TRIOS 3 basic, following the manufacturer's instructions. These impressions were used to print six working dies using a Formlabs SLA 3D printer. The "preform software" was used to select the model material and set a layer thickness of 0.05 mm for accuracy and speed. The solid dies were positioned on the built platform at a 120-degree orientation. Formlabs Dental Model Resin was used as the printing material. After printing, the dies were rinsed with isopropyl alcohol and cleaned using a Form Wash unit. They were then air-dried and post-cured with a Form Cure unit, which exposed them to 405 nm light for 60 minutes at 60°C. Following these steps, the printed dies were ready for use **(Figure 5).**

Figure (5): Printed dies.

Designing the tooth supported provisional dental prosthesis:

On the Exocad software (exocad, Darmstadt, Germany), interim crowns were designed using the data of each STL file of each of the three test groups of the dies; each individually, with the data of the antagonist arch and the buccal scan of the interarch relationship.[30,31] The finish line of the abutment tooth was traced, then, a design of a full anatomic crown was set. The cement space was set up for both abutments; cement gap: 0.04 mm and finish line thickness: 1mm.[32–34] Finally, the occlusal and proximal contacts of the crown were adjusted. Finally, the design was saved **(Figure 6).**

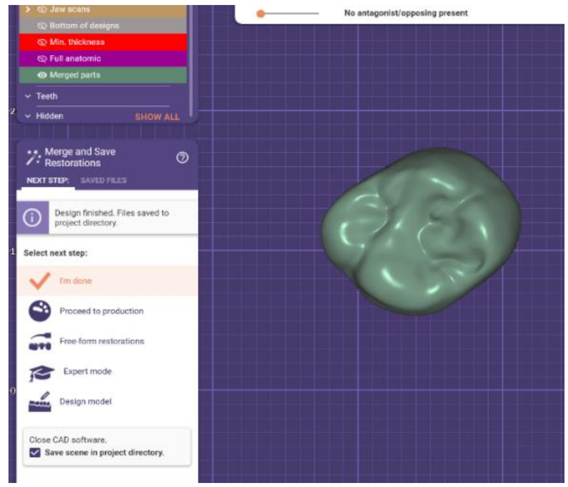

Figure (6): Final design on the Exocad.

Milling the interim crowns:

A total of 18 STL files of designed interim crowns were sent to the milling machine after positioning the interim crown in the desired position in the blank through the CAM 5-S1 impression milling machine software (Vhf, Baden-Württemberg, Germany). The Tempo-CAD PMMA discs (On dent, Bornova, Turkey) was fixed to the machine holder.[35] Then, the order was given to mill and get the final end product of the milled crowns. Finally, the milled crowns were finished and fitted on their corresponding dies **(Figure 7).**

Measurements:

Digitizing the interim crowns of the three test groups:

Figure (7): PMMA milled crowns;
(a) PMMA crowns fabricated on stone dies,
(b) PMMA crowns fabricated on 3D printed dies,
(c) PMMA crowns fabricated on virtual dies.

The inner surface of the milled crowns in each test group was scanned using a high-accuracy desktop scanner called 3 Shape E3. Additionally, each crown was scanned again after being placed on the reference die. The triple scan protocol was employed, utilizing the initial scan of the reference model and accurate alignment through the " Geomagic software´(Artec 3D, Santa Clara, California, USA). Marginal discrepancies were evaluated using a color map that displayed the whole deviation range. Tolerance limits were set between 10 mm to 100 mm. (after alignment by the software, the marginal discrepancies will be evaluated.[10,36]

The RMS (Root Mean Square) formula was used to calculate the differences in measurements between the scanned reference die data and the digitized crown data, following this equation:

$$RMS = \frac{1}{\sqrt{n}} \cdot \sqrt{\sum_{i=1}^{n} D_i^2}$$

Where D_i represents the gap distance of the point (i) of reference and test models, and (n) is the number of all points evaluated of the point cloud of each test model. A higher RMS value indicated a larger error or difference between the reference and measurement data. The color map corresponded to the RMS value, where blue indicated tight contact and red indicated loose contact, providing a qualitative representation of the marginal fit.[37]

Data analysis:

They were explored for normality by checking the data distribution and using Shapiro-Wilk test. Data were found to be normally distributed and were analyzed using one-way ANOVA followed by Tukey’s post hoc test. Correlation analysis was done using Spearman’s correlation coefficient. The significance level was set at $p \leq 0.05$. Statistical analysis was performed with R statistical analysis software version 4.1.3 for Windows.

RESULT

Descriptive statistics:

In **Table (1)** and **Figure (8)**, Descriptive statistics of marginal gap (µm) for different groups were presented.

Table (1): Descriptive statistics of marginal gap (µm) for different groups.

	Mean	95% confidence interval		SD	Min	Max
		Lower	Upper			
3D printed	140	140	150	0.01	130	160
Conventional	130	120	140	0.01	120	150
Virtual	110	100	120	0.02	90	140

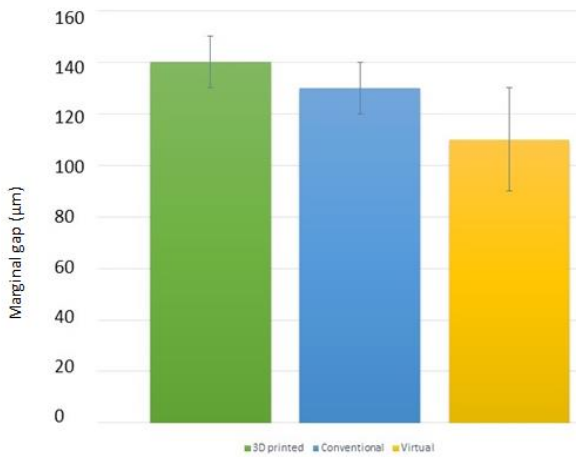

Figure (8): Box plot showing marginal gap values (µm).

Intergroup comparisons:

On the other hand, for the intergroup comparisons, in **Table (2)** and **Figure (9)**, Intergroup comparison, mean and standard deviation values of marginal fit (µm) were presented. There was a significant difference between different groups ($p=0.001$). The highest value was found in 3D-printed (140±10), followed by conventional method (130±10), while the lowest value was found at virtual group (110±20). Post hoc pairwise comparisons showed virtual group to have significantly lower value than other groups ($p<0.001$). The values of the 3D-printed, and conventional groups showed no statistically significant difference.

Table (2): Intergroup comparison, mean and standard deviation values of marginal gap (µm).

Marginal fit (mm) (mean±SD)			p-value
3D printed	**Conventional**	**Virtual**	
$140±10^{A}$	$130±10^{A}$	$110±20^{B}$	0.001*

Means with different superscript letters within the same horizontal row are significantly different
*; significant ($p \le 0.05$).

Color difference map:

The 3D color maps showed a deviation pattern denoting a marginal gap between the tested crowns and control reference die. Areas of yellow and red color indicate positive discrepancy, which means that the crown is larger than master model because of the expansion of the models when compared with the control model. Area of light blue to dark blue indicates negative

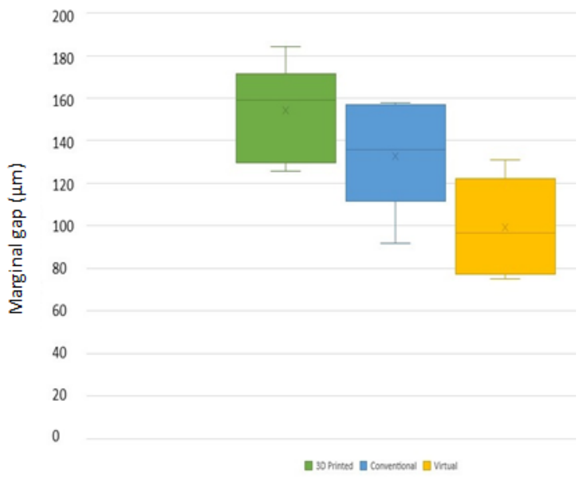

Figure (9): Bar chart showing average marginal gap (µm) for different groups.

discrepancy which means that the crown is smaller than master model because of the shrinkage of the models when compared with the control model. The pattern of deviation was heterogeneous **(Figure 10).**

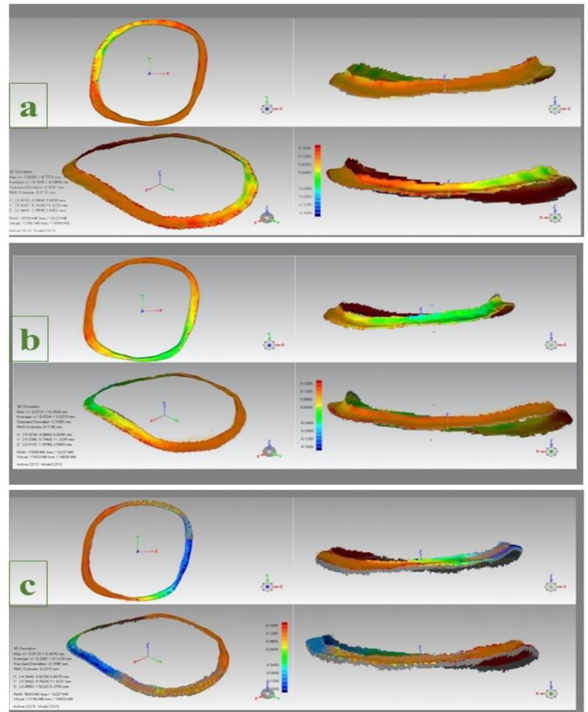

Figure (10): 3D Color map images denoting the marginal gap of milled interim crowns fabricated on different die systems;
a. (conventional die),
b. (virtual die), and
c. (3D printed die).

DISCUSSION

Digital fabrication techniques have become popular and have effectively replaced conventional methods in recent times. These techniques enable the creation of restorations using CAD software on virtual models and dies, eliminating the need for physical models. Subtractive (milling) or additive (3D printing) techniques are then used for digital manufacturing. Provisional restorations are essential for the success of a treatment plan as they allow for the refinement of functional, occlusal, and esthetic aspects before the final restoration is made. In complex cases requiring long-term provisionalization, precise and highly biocompatible restorations are necessary. CAD/CAM fabrication techniques have successfully achieved this by milling from pre-cured blocks, resulting in restorations of superior quality.[38–40]

Marginal fit is one of the most significant criteria in evaluating restorations and in their success. In addition to marginal discrepancy is one of the main causes of failure of indirect restorations.[41]

By reviewing the literature, few studies[11,42,43] compared the accuracy of 3D-printed dies. Most of the studies[3,10,44–46] compared the conventionally fabricated working models and dies to digitally fabricated 3D-printed ones or compared different printing technologies. However, there was decreased evidence on the accuracy of the complete digital workflow on virtual dies compared to printed and conventional systems.

Thus, this study was conducted to assess the marginal fit of interim crowns fabricated using conventional, virtual, and three-dimensional printed working Dies. Consequently, it would help in evaluating their reliability in the production of accurate working dies and provisional restorations during digital workflow.

In the present study, in accordance with standardization, the STL scan file of typodont prepared maxillary right 1st molar was used to assess the marginal fit of the interim crowns fabricated on different die systems.[47]

Furthermore, the material used for the fabrication of the interim crowns was standardized as well for all groups as it was fabricated of resinous materials, Tempo-Ivory PMMA disk used in this study is a pre-processed PMMA block. **Stawarczyk et al**.[35] (2012) reported that these blocks possess better color stability and more precise marginal quality than conventionally processed resin.[48,49]

Teeth preparation of the typodont was performed according to **Rosenstiel et al.**[50] **(**2006) All ceramic teeth preparation criteria were followed because all ceramic crowns after the innovation of high-strength ceramics constitute a promising highly demanded alternative for the porcelain fused to metal restorations with a survival rate of 95.2% in three years according to the retrospective study conducted by **Saarva et al.**[51] in 2017.

The conventional dies were fabricated by performing a PVS final impression for the prepared typodont. Edge PVS Addition silicone material was used as it allows for excellent reproduction of all details due to its hydrophilicity.[52].**Naumovski et al.**[53] (2017), in their systemic review, emphasized the superiority of the addition silicone (PVS) compared to other elastomers in terms of accuracy.

Then, the impressions were poured with GC Fuji rock extra hard dental stone type IV of its high precision, outstanding edge hardness, its excellent flow, and handling properties. Its setting expansion is 0.09% or less after 2 hours[54] which is well within the American Dental Association (ADA) Specification #25 which describes that the expansion of the dental gypsum should be less than. 0.2%.[55]

All the scans utilized to fabricate the virtual and 3D-printed dies in this study were performed by a skilled operator using an intraoral scanner to simulate an actual clinical setting[11]. TRIOS 3 basic IOS was chosen because, according to **Michelinakis**[56] **(**2020), TRIOS 3 was found to be more precise than Medit i500 and Planmeca Emerald. Also, in terms of trueness, TRIOS 3 was determined the most accurate than Medit i500 scanner as well. ADA published a study by **Hack et al.**[57] **(**2015) that evaluated the trueness and precision of six different IOS, and the results showed that TRIOS has the highest trueness (6.9 ± 0.9 mm) and precision (4.5 ± 0.9 mm) among all of them.

Given its higher precision, the 5-axis milling machine, CAM 5-S1 impression milling machine, was used to fabricate the milled crowns. It enables the milling of complex geometries.[58,59]

While Stereolithography printing technology (SLA) was used for the additive manufacturing using Formlabs 2 printer because it is the most popular technique in the dental field. Moreover, according to the systemic review performed by **Etemad-Shahidi et al**.[7] (2020), the different relevant studies assessed SLA printers to produce the most consistently accurate clinically acceptable dies and acceptable results regardless of their layer thickness. A 50-micron layer thickness was adopted for both the printed dies, allowing for a balance between accuracy and printing time.

In the present study, the 3 Shape E3 desktop scanner was used for the digitalization of the tested dies and fitting surface of the crowns. It has an accuracy of 6 μm according to the ISO standard # 12836:2015-11 that seems suitable for the intended purpose. This is in accordance with comparable studies,[15,43] which also used a laboratory scanner as a reference .

A specialized 3D analysis software was used to assess the accuracy of different die systems. This method analyses the accuracy of all point clouds in the X, Y, and Z axes, providing a comprehensive assessment of errors throughout the tested volume. This approach is more accurate than the linear measuring method, which only compares distances between limited reference points. Geomagic Control X software was employed to evaluate errors in the CAM process by comparing digitalized test groups to the reference model's STL file through superimposition. The software calculates the root mean square (RMS) error for each specimen compared to the reference model. To obtain point cloud data, desktop scanners were used, generating fewer errors than intraoral scanners and not dependent on the practitioner's skill level. Geomagic Control X is a commonly used and precise 3D analysis software that allows for 3D comparison, unlike other software that uses surface or mesh distance comparisons. It also provides flexibility in modifying the color map extents, enabling customization based on the object being measured and its clinical significance, a feature lacking in some other software such as Materialise 3-matic color map.[11,37]

In the current study, the null hypothesis was partially accepted as there was no statistical significance between the conventional and printed groups in terms of the marginal fit. However, there was statistical significance between these groups and the virtual group, where the virtual group showed better results.

By reviewing the literature, currently there is no consensus on the clinically acceptable value for marginal fit of CAD/CAM crowns. In this concern, the values of the marginal fit in the current study were between 110 to 140 microns which is in accordance with the systematic review conducted by **Chochlidakis et al.**[60] in 2016 that showed that several studies reported clinically acceptable values for CAD/CAM restorations range from 30 to 141 µm which is well within the results of this study.

The study findings indicate that the crowns fabricated by the virtual group exhibited better marginal fit. This aligns with a previous study by **Chochlidakis et al.**[60] in 2016, which also reported a superior fit of crowns made on virtual dies compared to those made using 3D printing. The improved fit can be attributed to the simplified fabrication process, eliminating potential discrepancies introduced during the printing procedure. Furthermore, traditional techniques involving impression materials and dental stone, which can introduce additional discrepancies, were not factors in this virtual fabrication method. [3,60]

Savencu et al.[61] in 2020 declared that the decreased accuracy of the 3D-printed copings is due to the accumulation of errors at different fabrication stages; the design segmentation by the printing software, processing, and during the printing process itself. Also, the shrinkage during building and post curing procedures are significant factors. Likewise, other studies conducted by **Svanborg et al.[62]** in 2014 and **Su et al.[63]**

in 2015, have demonstrated similar findings regarding the marginal fit of FDPs fabricated on stone and virtual dies. These studies found that virtual dies offer greater precision and significantly better fit for 3-unit FDPs compared to conventional techniques. The triple-scan protocol was identified as a suitable method for assessing the 3D fit of tooth-supported FDPs, except for evaluating the marginal gap, where larger readings were obtained compared to other techniques. The difference between the replica technique and the triple scan protocol can be attributed to the scanner's ability to accurately capture the outermost edge of the restorations. The interval between measurement points plays a role in the precision of the last point in relation to the sharp edge of the restoration. Additionally, variations in the software analysis technique used for measuring the absolute marginal gap may exist among different measurement software. The conventional technique introduces additional errors, such as those caused by material expansion and contraction.

A study by **Corso et al.**[64] revealed that PVS impression material undergoes contraction after storage, which could explain the significant difference in results between digital and conventional techniques.

Contradicting results were found by **Jang et al.**[3] in 2018, who showed no statistically significant difference between the virtual and conventional groups in terms of marginal fit which is contradictory with the results of this study that elaborated significant difference between the virtual and conventional groups. This could be because of some differences in the methodology including the use of reference scanner for the measurements, not using cement gap and also, he should have mentioned the exact methodology of alignment used during superimposition procedure.

The limitation of this study includes failing to fully reproduce clinical situations; saliva, patient movement, and anatomical features (tongue, lips, and cheeks). In addition, the scanner used during digitalization of the tested models was not an industrial “reference scanner.” Also, the present study was limited to the analysis of the fit of single crowns.

The outcome of this study is that During the digital workflow, virtual and 3D-printed dies can replace conventional ones or construction of interim crowns for their satisfactory accuracy, and technique insensitivity, allowing chair side fabrication of the restorations and easier communication with the laboratory.

CONCLUSION

Within the limitations of the present study, the following points could be concluded:

1. Virtual dies showed the highest marginal fit of the fabricated interim crowns.

2. Conventional and 3D-printed dies showed comparable results in terms of the marginal fit of the interim crowns.

3. The marginal fit of interim crowns was within the clinically acceptable range (30 to 141 μm), which is clinically acceptable.

CLINICAL SIGNIFICANCE

During the digital workflow, virtual, and 3D-printed dies can replace conventional ones in the construction of interim crowns for its satisfactory accuracy, technique insensitivity, allowing chair-side fabrication of restorations and easier communication with the laboratory.

FUNDING

This research received no external funding.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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