Marginal Fit Of Lithium Disilicate Crowns: A Three-Dimensional Analysis

by

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Abstract

Objectives: To compare the marginal fit of lithium disilicate (LDS) crowns fabricated with digital impression and manufacturing (termed "DD"), digital impression and traditional pressed manufacturing (termed "DP"), and traditional impression and manufacturing (termed "TP").

Methods: Tooth #15 was prepared for all-ceramic crowns on an ivorine typodont. There were 45 LDS crowns fabricated using three techniques: DD, DP, and TP. Micro-computed tomography (micro-CT) was utilized to assess the 2D and 3D marginal fit of crowns in all three groups. The 2D vertical marginal gap (MG) measurements were done at 20 systematically selected points/crown while the 3D measurements represented the 3D volume of the gap measured circumferentially at the crown margin. Incidences of different marginal discrepancies were also recorded, including over-extension (OE), under-extension (UE), and porcelain chipping. Crowns with vertical MG>120 μm at more than five points were considered unacceptable and were rejected. The results were analyzed by one-way ANOVA with Scheffe post hoc test (α=0.05).

Results: DD crowns demonstrated significantly smaller mean vertical MG (33.3±19.99 μm) compared to DP (54.08±32.34 μm) and TP (51.88±35.34 μm) crowns. Similarly, MG volume was significantly lower in DD group (3.32±0.58 mm^3) compared to TP group (4.16±0.59 mm^3). Interestingly, the mean MG volume for the DP group (3.55±0.78 mm^3) was not significantly different from the other groups (DD and TP). The incidence of under-extension was higher in DP (6.25%) and TP (5.4%) than in DD (0.33%) group, while over-extension was more frequent in DD (37.67%) than in TP (28.85%) and DP (18.75%) groups. Overall, 4 out of 45 crowns

fabricated were deemed unacceptable based on the vertical MG measurements (three in TP group and one in DP group) while all crowns in DD group were deemed acceptable.

Conclusion: Digital impression and CAD/CAM manufacturing resulted in consistently better marginal fit and was associated with less manufacturing errors.

Preface

This research project was done under the direct supervision of Dr. Christopher Wyatt. The committee members included Dr. Dorin Ruse, Dr. Nancy Ford, and Dr. Rick Carvalho.

This project was a continuation of a previous Master of Science project at UBC Prosthodontics (Students: Dr. Jonathan Ng and Dr. David Alfaro; Supervisor: Dr. Christopher Wyatt). Dental impressions for both the digital and conventional groups were made by Dr. Jonathan Ng and Dr. David Alfaro. Aurum Ceramic Dental Laboratories of Calgary, Alberta, Canada fabricated the standardized zirconia master model and 45 crowns using three methods of fabrications as outlined in the thesis.

Centre for High Throughput Phenogenomics scanned the crowns using micro-computed tomography (micro-CT). I did all subsequent measurements, analysis, and data collection independently.

This study did not require approval from the UBC Research Ethics Board as it did not involve the use of any human subjects, animals or bio-hazardous materials.

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List of Abbreviations

ADA	American Dental Association
ANOVA	Analysis of variance
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CDA	California Dental Association
CT	Computed tomography
DD	Digital impressions and manufacturing
DP	Digital impression and traditional pressed manufacturing
FDP	Fixed dental prosthesis
LDS	Lithium disilicate
MG	Marginal gap
mm	Millimeter
OE	Over-extension
SC	Secondary Caries
SEM	Scanning electron microscopy
STD	Standard deviation
TP	Traditional impression and manufacturing
UE	Under-extension
USPHS	United States Public Health Service
µm	Micro-meter

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I offer my enduring gratitude to the faculty, staff and my fellow students at UBC, who have inspired me to continue my work in this field. I owe particular thanks to:

- **Dr. Christopher Wyatt** for giving me the scientific knowledge and training. The learning experience under his supervision included an emphasis on developing collaborative relationships with peers, and the ability to work both independently as well as part of a team.
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Special thanks are owed to my family, who have supported me throughout my years of education, both morally and financially.

Dedication

I would like to dedicate this thesis to

My dear husband, Mostafa, and my lovely children, Logean and Mohamed, who joined me during the whole process and helped me in every way with their love, support and patience

My beloved parents (A. Mostafa and F. El-Sayed), my dear sister Nermine and my dear brothers (Sameh and Hany), who gave me hope and strength throughout my entire life

Chapter 1: Introduction

Indirectly fabricated full coverage restorations are frequently needed to restore function and esthetics of lost tooth structure due to caries and trauma. Indirect restorations can be made of metal, metal ceramic and all-ceramic materials. All-ceramic restorations have become more popular over the last few decades due to increased esthetic demands.[1] All-ceramic restorations must have adequate biomechanical properties and provide longevity similar to metal–ceramic restorations together with enhanced aesthetics. However, the clinical success of these indirect restorations is mainly based on marginal integrity, anatomic form, and mechanical properties of the material used.[2]

The marginal fit of the crown is an important determinant of the long-term success. Inadequate marginal adaptation results in plaque accumulation, which increases the risk of caries and periodontal disease.[3-5] Marginal discrepancies also expose cement to the oral environment, which could contribute to its dissolution.[6]

1.1 Acceptable Marginal Gap (MG)

It is difficult to identify an acceptable marginal gap clinically for indirect restorations in the literature. The ideal cement thickness for indirect restorations should be 25 μm for type I luting agent (glass ionomer, zinc phosphate, and polycarboxylate cements) or 40 μm for type II luting agent (glass ionomer-resinous hybrid and resin cements).[7] Although MGs in this range have been considered a clinical goal, they are difficult to achieve.[8] McLean et al.[9] assessed the marginal fit of 1000 fixed restorations over a 5-year period and suggested that a marginal gap less than 80 μm is challenging to detect clinically. Moreover, Fransson et al.[10] and McLean et al.[9] stated that the clinically acceptable marginal gap after cementation should be less than 150 μm and 120 μm, respectively. It is important to mention that all these studies measured marginal fit for cast restoration. However, a recent systematic review that included 183 studies reported that the fit of ceramic restorations varies widely from (7.5 to 206.3) μm.[7] Such discrepancy could be attributed to lack of coherence about the marginal gap definition, different methods employed to evaluate the gap, different fabrication methods (conventional vs. CAD/CAM), stage at which the measurements were performed (before/after cementation), and ceramic systems ulilized.[7] Based on the available evidence, several *in vitro* studies considered MG up to 120 μm to be clinically acceptable for cast and ceramic restorations.[11-14]

Toward this end, the aim of this chapter is to summarize the current evidence on marginal fit of crowns and fixed dental prosthesis (FDPs) and to discuss different variables that could influence treatment outcomes.

1.2 Terminology

Holmes et al.[15] proposed a precise terminology to describe the fit of dental restorations.

- **Internal gap** is the perpendicular measurement from the internal surface of the casting to the axial wall of the preparation, while the same measurement at the margin is called the **marginal gap**.

- **Overextended margin** is the perpendicular distance from MG to the crown margin. U**nderextended margin** is the perpendicular distance from MG to the cavosurface angle of the tooth.
- **Absolute marginal discrepancy** can be defined as the angular combination of MG and the extension error (over-extension or under-extension), which represents the distance from the preparation finish line to the restoration margin. It is considered the best alternative measurement, since it reflects the total crown misfit at that point (vertically and horizontally).

1.3 Clinical Methods for Measuring Marginal Gap

Clinically, the marginal fit can be examined directly with a mirror and a probe. Clinical studies mostly utilize standardized criteria to evaluate marginal discrepancy of fixed dental prosthesis, such as United States Public Health Service (USPHS) criteria[16] or California Dental Association rating criteria (CDA).[17]

USPHS criteria provide a standardized system for clinical evaluation of dental restorations based on surface, color, anatomic form, and marginal integrity. In this system, two categories are described as clinically acceptable alpha and bravo. Alpha indicates that the restoration is excellent and meets all clinical standards, while, bravo indicates that the restoration is clinically acceptable with minor errors. The other two categories are considered unacceptable: “charlie”, which indicates replacement to minimize future complication, and “delta”, which indicates immediate removal and replacement (Table 1-1).[16] The CDA system characterizes the restoration as clinically acceptable and clinically unacceptable. The categories used to evaluate the crown margins are summarized in Table 1-2.[17]

Table 1-1: United States Public Health Service (USPHS) criteria for marginal integrity and marginal discoloration [16]

Marginal integrity	
Alpha (A)	No visible evidence of crevice along the margins; no catch or penetration of the explorer
Bravo (B)	Visible evidence of crevice and/or catch of the explorer; no penetration of the explorer
Charlie (C)	Visible evidence of crevice and penetration of the explorer
Delta (D)	Mobile or fractured restoration OR caries contiguous with the margin or the restoration OR tooth structure fractured
Marginal discoloration	
Alpha (A)	No discoloration at the margins
Bravo (B)	Superficial discoloration not penetrating in pulpal direction
Charlie (C)	Discoloration penetrating in pulpal direction

Table 1-2: California Dental Association rating criteria (CDA) criteria for marginal integrity[17]

Score	Acceptable
Excellent	No visible evidence of gap along the margin in which an explorer could get stuck. No evidence of ditching along margin
SCR	Visible evidence of slight marginal discrepancy with no evidence of decay. Repair is possible, but perhaps unnecessary. Explorer gets stuck in one direction
Score	Un**acceptable**
TFAM	Faulty margins that cannot be adequately repaired
TPEN	Penetrating discoloration along the margin of restoration in pulpal direction
TCEM	Retained excess cement
VMO	Mobile restoration
VFR	Fractured restoration
VCAR	Caries continuous with the restoration margin
VTF	Fractured tooth structure

1.4 Marginal Gap and Secondary Caries

Secondary or marginal caries occur around the margins of existing restorations. Caries is a common biological complication in FDPs.[18] However, it is difficult to diagnosis secondary caries around the crown margin. These carious lesions might be active or arrested or could be residual lesions that continued to progress over time.

Although USPHS and CDA criteria rate clinically acceptable or unacceptable margins, they do not consider the presence of secondary caries in their criteria. Therefore, Zoellner et al.[19] proposed a clinical diagnostic index for secondary caries (SC) around crown margin (Table 1-3). Differentiation between the different grades may be beneficial for selecting the appropriate treatment based on the location of severity of carious lesions.

Table 1-3: Grades for Secondary Caries Index (SC)

Grade	Clinical Findings
SC 1	Discoloration at the crown margin because of carious, erosive, or abrasive reasons; no cavitation
SC 2	Cavitation; superficial dentin softening; localized to one site; includes maximum of 25% of the margin
SC 3	Cavitation; 2 or more sites; tendency toward circumferential lesion
SC 4	Cavitation; deep caries lesion; likely to penetrate the pulp chamber

Carious lesions could be detected radiographically. Hence, Zoellner et al.[20] utilized CDA criteria and the radiographic score presented in Table 1-4 to evaluate interproximal carious lesions. The study included a total of 100 patients with high caries risk and concluded that clinical examination was more reliable than radiographic examination for diagnosing caries around crown margins. Moreover, they reported a mean annual increase in marginal caries of 2.3%, which is higher compared with the annual rate (0.36-0.99%) described by the systematic review done by Sailer et al.[18] The latter was based on six studies on 227 all-ceramic FDPs and 5 studies on 2871 conventional metal ceramic FDPs. It is important to mention that Zoellner's study[20] only included patients with high carious risk, while most of the studies that were included in Sailer's review[18] included patients provided with oral hygiene instruction and professional dental hygiene care. This could explain the differences in the annual rate of marginal caries between the two studies.

Table 1-4: Scores for radiographic extension of carious lesions

Score	Radiographic Findings
0	No radiolucency
1	Radiolucency limited to outer half of enamel
2	Radiolucency extending into inner half of enamel but not crossing the enamel/dentin junction
3	Radiolucency limited to outer half of dentin
4	Radiolucency extending into inner half of dentin

Some authors argue that restorative margins, which are not perfectly adapted to the prepared tooth with no evidence of recurrent caries, are not a reason for replacement of the restoration.[20] Moreover, there are factors of greater clinical significance for the longevity of FPDs including proper oral hygiene.[21] From a clinical point of view, an open restorative margin can be considered as plaque retention site and may be considered as an additional risk factor for the development of secondary caries. Sailer et al.[22] conducted a study on 3- 5-unit zirconia based FDPs (n=33) over five years and reported a survival rate of 73.9%. This study reported a statistically significant association between MGs and secondary caries. A major issue with the FDPs in this study was the presence of clinically detectable MGs in 58.7% and subsequent secondary caries in 21.7% of the FDPs after five years. But, it is also known that microbial factors play a major role in caries development. Kholer and Hager[23] reported immediate adherence of streptococcus mutans to restorations margins following cementation in patients with elevated caries risk. This is also consistent with Zoellner et al.,[20] who reported a significant correlation between the frequency of secondary caries and unacceptable margins in patients with high caries risk. Taken all together, marginal fit of dental restorations is an important consideration especially in patients with high caries risk.

Therefore, assigning a patient to caries risk level is an important consideration during treatment planning of dental restorations. To minimize secondary caries around crown margins, it is important to reduce marginal discrepancies and to decrease the cariogenic activity. Caries management may include behavioral modification, chemical alteration of the biofilm, and/or supplements to support re-mineralization using fluorides. Successful management of the patient's caries will improve the long-term success of dental restorations.[24]

1.5 *In Vitro* Methods for Measuring Marginal Gap

Clinically, several confounding factors can make *in vivo* testing challenging including tooth preparation, sulcus bleeding during impression making, impression technique, cementation process, saliva flow rate, and patient compliance.[25] *In vitro* studies, meanwhile, allow for standardization of the experimental setup, allowing ideal testing environment, which may not be easy to achieve *in vivo*. Several *in vitro* techniques are available for measuring the MG, which can be categorized into non-destructive (direct viewing technique, impression replica, profilometry and micro-computed tomography (micro-CT)) and destructive methods (cross-sectioning technique).

Direct view technique is the most widely used non-destructive and reproducible method that measures MG between the crown and the die under magnification using optical or electron microscope. This approach is cheap and less time-consuming than other methods.[26, 27] However, the limitations of this technique include difficulty identifying reference measurement points and repeating measurements from an identical angle. Projection error is another limitation, where vertical or horizontal marginal discrepancy or an absolute marginal discrepancy may have been measured based on the angulation of the specimen during measurement.[26, 27]

Impression replica technique is another non-destructive method that provides an indirect measurement for the MG. In this method, light body silicone is injected to fill the cement space to mimic the cementation process. Then, the replica is sectioned and measured at different sites.[28, 29] This method is easy and cheap, but has the following disadvantages: tearing of the elastomeric film upon removal from the crown and difficulty identifying the crown margins and finishing lines.[7] It also provides a limited number of measurements in one plane that might not be representative of the overall marginal adapation.[30]

Profilometry is a non-destructive method that displays crowns on their respective die in the same focal plane on a monitor resulting in a well-defined focus.[31] But, the cement thickness of the cement layer at the marginal areas can only be measured indirectly and, in the case of sequential analysis, extreme care should be taken in repositioning the samples, otherwise re-profiling inconsistencies can occur.[32]

Cross-sectioning technique is a destructive method where crowns are sectioned and marginal and/or internal gaps are assessed in horizontal and vertical directions under microscope.[7] But, it does not allow repeated assessment of the same specimens before and after cementation or prior to clinical placement. Moreover, sectioning plane limits the number of measurements that might not provide adequate representation of the overall fit of the restoration.[7]

Micro-CT was introduced as a non-destructive method that allows a thorough evaluation of the marginal and internal gaps at multiples planes and locations.[33] It produces 3D data sets that can be used for quantitative analysis and for visualization by specifying cement thickness.[34] It also allows longitudinal assessment of the marginal and internal fit of the same sample before and after employing different testing variables.

1.6 Factors Affecting Marginal Fit

A recent systematic review[7] identified 183 studies that investigated marginal adaptation of different all-ceramic systems by various methods. They found that direct view technique was used by 47.5% of the articles, followed by cross-sectioning (23.5%) and impression replica (20.2%) techniques. Moreover, validating MG measurements among these methods generated great variation even within the same ceramic system. This was attributed to different experimental setups of the included studies. Direct comparisons between included studies were not possible as there is a lack of coherence in the definition of “fit”. Holmes et al.[15] proposed a clear terminology describing “fit” of dental restorations, as previously discussed. Some studies employed this terminology, with either MG or the absolute marginal discrepancy being the evaluated. Other studies, however, do not use the same definitions for the marginal discrepancies, hence, direct comparisons between studies are/were difficult.[26]

Additionally, studies varied in their experimental setups, sample size and number of measurements per specimen, method of fabrication (conventional vs. CAD/CAM), and when the gap was measured (before/after cementation).

1.6.1 Impact of Number of Measurements/ Sample Size

The number of measurements needed for the assessment of marginal fit is controversial. Successful experimental setup requires adequate sample size, as well as adequate number of measurements per specimen. All these factors could potentially influence the strength of statistical analysis and conclusions.[14]

Several studies based their results on 2 to 12 measurements per sample.[28, 35, 36] However, Groten et. al.,[37] indicated that 50 systematically or randomly selected measurement points are needed per crown to precisely measure the marginal gap (i.e. within ±5 μm variability for arithmetic means). Groten et. al.[37] concluded that at least 20 measurements per sample could be accepted based on the required precision level. This study was based on 10 all-ceramic crowns fabricated on a master steel die (i.e. experimental crowns) without sample size calculation, hence the sample size was considered to be small. Gassino et. al.[27] claimed that Groten et. al.[37] results were flawed. Gassino et. al.[27] employed a more sophisticated methodology of running 360 gap measurements at 360° and determined that 18 measurements were needed to assess experimental crowns that are fabricated from abutments prepared in the laboratory and 90 measurements for clinical crowns fabricated from abutments prepared intraorally to generate a sample mean within ±5 μm of the true mean, with 4 μm standard error. But, some conclusions in this study were based on the analysis of only two crowns, which might not be representative of everyday practice. In conclusion, both studies had small sample size and compensated this with a large number of measurements per sample to achieve a more consistent distribution of data with small standard deviations. Although increasing the number of gap measurements per specimen enhances the precision of the analysis, the longer time required for recording the measurements and the complexity of the measurement method makes the approach impractical to perform on a regular basis. Toward this end, more studies involving three-dimensional analysis of MG using micro-CT could provide a more realistic perception of MG within the range of a few micrometers at multiples sites and directions. The resulting 3D data sets could be used for both quantitative analysis and for visualization by specifying cement thickness. Moreover, the volume and geometry of MGs can be assessed from 3D reconstructions.

1.6.2 Influence of Method of Fabrication

Ural et. al.[13] conducted an *in vitro* study based on 50 standardized dies that were divided into five groups based on the method of fabrication (n=10 per group), including two different CAD/CAM (Cerec-3 and Cercon), heat-press (IPS Empress), glass-infiltration (In- Ceram), and conventional lost wax (metal ceramic). Vertical MG was measured using scanning electron microscope (SEM; 30 measurements per sample). Cerec-3 group (29.26±4.08 µm) had the smallest MG, which significantly differed from all other groups ($P < 0.001$). The highest MG values were reported with the metal ceramic group (120.63±7.52 µm). This result could be explained by the difference between the fabrication techniques. CAD/CAM eliminates the need for multiple steps, each with potential errors, required with the traditional lost wax technique employed in the fabrication of metal ceramic restorations.

Yeo et. al.[14] evaluated the marginal adaptation of three all-ceramic restorations (Celay In-Ceram, conventional In-Ceram, and IPS Empress 2) and utilized metal ceramic restorations as a control (n=30 per group). MG measurements were determined at 50 points spaced approximately 400 µm along the crown margin using the optical microscope. Mean marginal opening for the fabricated crowns was 87±34 µm for control, 83±33 µm for Celay In-Ceram, 112±55 µm for conventional In-Ceram, and 46±16 µm for IPS Empress 2. The marginal discrepancies for all the groups were within the clinically acceptable standard (<120 µm). IPS Empress 2 crowns demonstrated the best marginal fit as compared to the other groups. The conventional In-Ceram group exhibited significantly greater marginal discrepancies as compared to control group, but there was no significant difference between the Celay In-Ceram and control group. This study is well designed with large sample size and large number of measurements per specimen.

1.6.3 Effect of Cementation

Creating a space for the cement layer between the die and the crown/FDP is a critical step during the fabrication of indirect restorations. Hence, a spacer varnish is used to coat the die, but not the finish line. However, the cement space is set digitally using CAD software for FDPs and crowns fabricated using CAM technology.[26] Studies claimed that cement space is more critical than margin design for producing adequately fitting restorations.[35] A small cement space could result in internal interferences at the intaglio surface of the crown preventing complete seating of the crowns leading to misfit.[38]

Measuring MG before or after cementation of crowns/FDPs could change the results of the measurement. Ural et. al.[13] study (previously discussed) also compared marginal adaptation between the five crown system (Cerec-3, Cercon, IPS Empress, In-Ceram, and metal ceramic restorations) before and after cementation using SEM. Cementation resulted in significant increase in the vertical marginal discrepancies in all groups that ranged between 16.46 µm and 21.03 µm.

Similarly, Wolfart et. al.[21] assessed the marginal adaptation of heat pressed lithium disilicate inlays (n=8) and FDP abutments (n=11). Replica technique was used to evaluate marginal adaptation before and after adhesive cementation. The marginal gaps increased from 96 µm to 130 µm for FDP abutments and from 89 µm to 92 µm for inlays following cementation. This increase was more significant in FDP abutments as compared to inlays, which could be due to reduced discharge of excess cement.

These findings suggest that cementation increases the marginal discrepancies. However, Wolfart et. al.[21] reported higher values for the marginal discrepancies following cementation as compared to Ural et. al.[13] This could be explained by the different experimental setups between the two studies. While Ural et. al.[13] conducted an *in vitro* study with standardized and optimized conditions, there are clinical challenges that could have affected the accuracy of MG measurements in Wolfart et. al.[21] study. Several factors such as bleeding, salivary contamination, configuration and location of the finish line could influence the quality of the marginal gap impression using the replica technique.[26] Moreover, the silicon material could tear during removal making it difficult to detect cement thickness at the crown margins.[21] Additionally, errors in the sectioning plane could potentially result in overestimated measurements.[30]

1.7 Summary of the Available Literature and Study Rational

There was no conclusive evidence on the best methodology to evaluate the marginal adaptation of crowns and FDPs. Furthermore, direct comparisons of the values for MG between studies were not always possible due to the lack of consistency regarding the definition of "fit". There were also differences in methods employed to determine the fit, experimental setups (*in vivo* vs. *in vitro*), sample size and number of measurements per specimen, preparation and finish line design, and the time when the gap was measured (before/after cementation).

Marginal adaptation also varied based on the method of fabrication. Laboratory fabricated crowns require multiple procedures that are prone to errors, with the potential of fabricating a crown with unacceptable fit to the tooth. The introduction of digital technology (digital impressions and computer-aided design "CAD" and manufacturing "CAM") reduces the need for multiple steps with potential errors compared to the traditional approach.[39]

Different studies employed various methods for measuring marginal discrepancies. The most commonly used *in vitro* techniques for MG measurements are the direct view and cross-sectioning techniques. The direct view method is non-destructive and cheap. However, projection error and difficulty identifying reference points for measurement and repeating measurements from an identical angle limit the direct viewing method. The cross-sectioning technique is a destructive method that allows for direct measurement of the internal gap and MG. However, it does not permit longitudinal assessment of the results before and after different manufacturing stages using the same specimens, and cannot be used to evaluate the crowns prior to clinical placement [7]. Therefore, more studies involving 3D analysis of the MG using micro-CT could provide a more realistic perception of MG within the range of a few micrometers at multiple sites and directions. The 3D data sets resulting from micro-CT could be used for both quantitative analysis and for visualization by specifying thickness as a function of color. Additionally, using a combination of two methods for measurement could be beneficial to verify and validate results.

Therefore, the objective of this thesis was to compare the 3D MG of crowns fabricated with digital and conventional methods, using a micro-CT technique.

1.8 Specific Aims

- To determine, using micro-CT, the vertical MG and 3D MG volume of LDS crowns fabricated using:
  - **Digital method:** Digital impression and digital manufacturing (**DD**)
  - **Combination method:** Digital impression and press manufacturing (**DP**)
  - **Traditional method:** Traditional impression and press manufacturing (**TP**)

- To determine, in each group, the incidence of common marginal discrepancies (MD), i.e. overextended margins, underextended margins, and marginal chippings.

1.9 Hypothesis

The **null hypothesis (H_0)** of this study was that there is no significant difference between digital and conventional methods of fabrication based on MG volume measurement, validated by 2D vertical MG measurements.

The **alternative hypothesis (H_1)** of this study was that there is a significant difference between digital and conventional methods of fabrication based on MG volume measurement, validated by 2D vertical MG measurements.

Chapter 2: Methods

2.1 Sample Size Calculation

Power analysis, based on a previous study,[25] indicated that a sample size of 15 was required to detect significant mean differences of 20 μm between the groups in the presence of 20 μm standard deviation. In this power analysis, γ was set to 0.05, β was set to 0.20, to allow for 80% power.

2.2 Crown Fabrication

Tooth #15 was prepared for the all-ceramic crown on an ivorine typodont. Tooth #15 was selected because it results in a curvilinear preparation that follows and conforms to the location of the gingival margin on buccal, lingual and interproximal surfaces. Therefore, this tooth was considered more suitable for assessing marginal fit as it has more complex preparation as compared to anterior teeth and is smaller in size as compared to molars. The maxillary typodont was then digitized, using a 3Shape D700 lab scanner (3Shape Inc., New Jersey, N.Y., USA) and the digital file was used to produce a replica of the maxillary arch milled in yttria-stabilized zirconia. A total of 45 LDS crowns were made from the master zirconia cast and die using three different methods (n=15/group): 1. digital impression and crown fabrication, 2. digital impression and traditional (manual) crown fabrication, and 3. traditional impression and crown fabrication. Digital impressions were taken using a LAVA C.O.S. scanning unit (3M, Lexington, KY). Scan files were exported as STL files and sent to the dental laboratory (Aurum Ceramics, Calgary, Canada) for digital articulation, digital wax up, and design of the final crown. No adjustments to the intaglio surfaces or to the horizontally overhanging margins were made following crown fabrication. Duplicate dies of master zirconia die were made in polyurethane enabling the assessment of the marginal gap using micro-CT, due to different radiopacity between ceramic, die and marginal gap.

2.3 Micro-CT Scanning

Micro-CT scans of the 45 crowns seated on their respective dies were done using Scanco Medical micro-CT100 scanner (Scanco Holding AG, Switzerland). Images were acquired at 90 kVp and 200 μA, through 180º with 0.36º rotation step using 0.5 mm aluminum filter and frame averaging of 2 to produce serial cross-sectional images of 20 μm resolution. Scan duration was 30 min per sample. Projected images were reconstructed using filtered back projection reconstruction software that is available with the scanner.

2.4 Marginal Fit Measurement

2.4.1 Marginal Gap (MG) Volume Measurements

The 3D volume of the gap measured circumferentially at the crown margin was based on a standardized number of slices (80 slices or 1.6 mm above the cavosurface margin) for the selected region of interest (Figure 2-1). Using MicroView software (GE Healthcare, Canada), the crown margin was aligned manually with the image axes (x, y, and z) to allow proper selection of the region of interest. Then, the top reference slice was set at the intersection of cavosurface margin with the axial wall of the preparation. The bottom reference slice was set at the intersection of the preparation finish line with the cavosurface angle of the preparation. Then, the marginal gap volume in the selected slices of each sample was segmented. Optimal threshold for segmentation (window width (W)= 16,750 HU and window level (L)= 11,990 HU) was selected based on gray-level histogram and was consistently used for segmentation of the marginal gap in all samples.[40] Segmentation was done using region-growing method (grow below) in which neighboring voxels were connected based on a suitable threshold value and highlighted in yellow in both the 3D and 2D images. The resultant volume of the connected of voxels was recorded as the 3D volume measurement for the marginal gap.

In order to ensure the accuracy of the volume measurements, the 3D MG was measured twice for three randomly selected samples and the resultant 3D volumes were compared using Pearson's correlation (r^2).

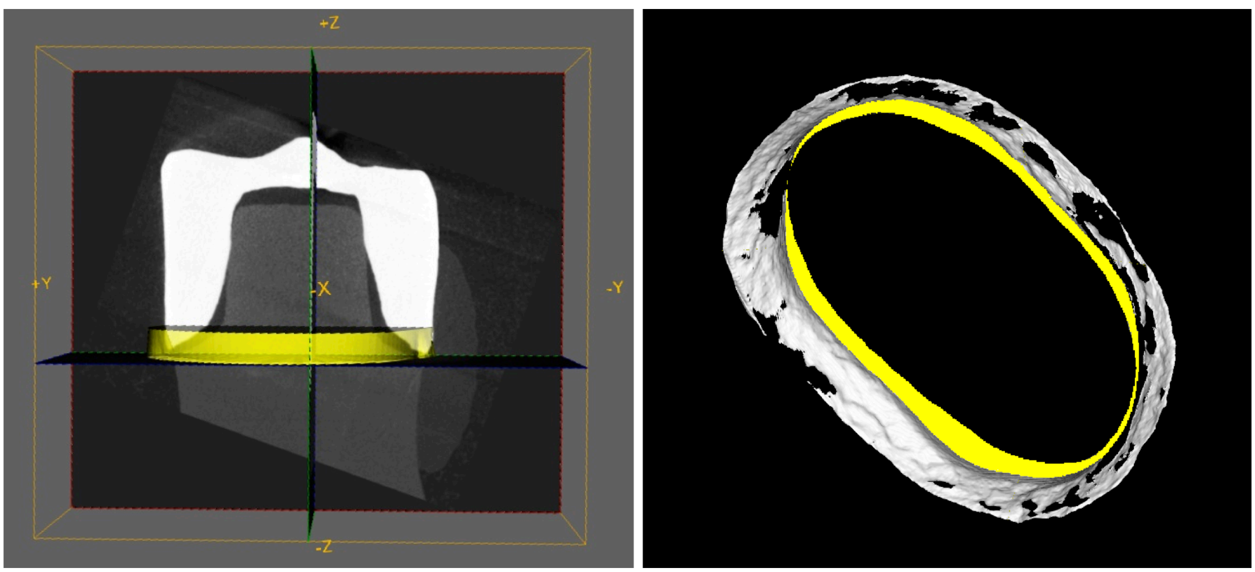

Figure 2-1: MG volume measurement: A- Micro-CT image of a representative crown seated on its corresponding dies showing standardized selection for the region of interest from the crown margin to the axial wall of the preparation in the 3D space with the three coordinate axes (x, y, and z), and B- 3D MG volume

2.4.2 Vertical MG Measurements

Vertical MG measurement (Gold standard) was done to validate the MG volume measurement. Vertical MG measurement was done according to Holmes et al.[15] and is defined as the perpendicular measurement from the cavosurface angle of the tooth to the opposing crown margin (Figure 2-2). Our study employed a systematic cross-sectional analysis of the vertical MG. This approach resulted in 20 measurements (5 mesial, 5 distal, 5 buccal, and 5 lingual) for each crown and a total of 300 measures per group around the circumference of the crown margins. Mesiodistal measurements were made every 70 slices, while buccolingual measurements were made every 50 slices (Figure 2-3).

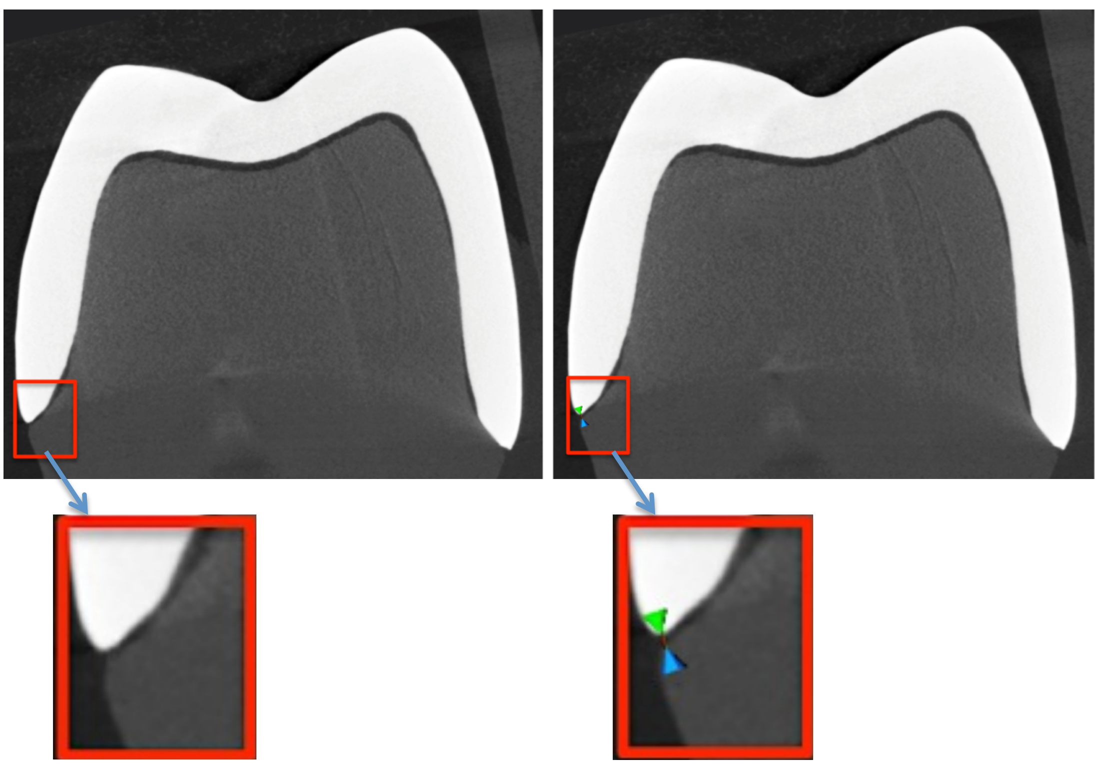

Figure 2-2: Vertical MG measurement from the cavosurface angle of the tooth to the opposing crown margin.

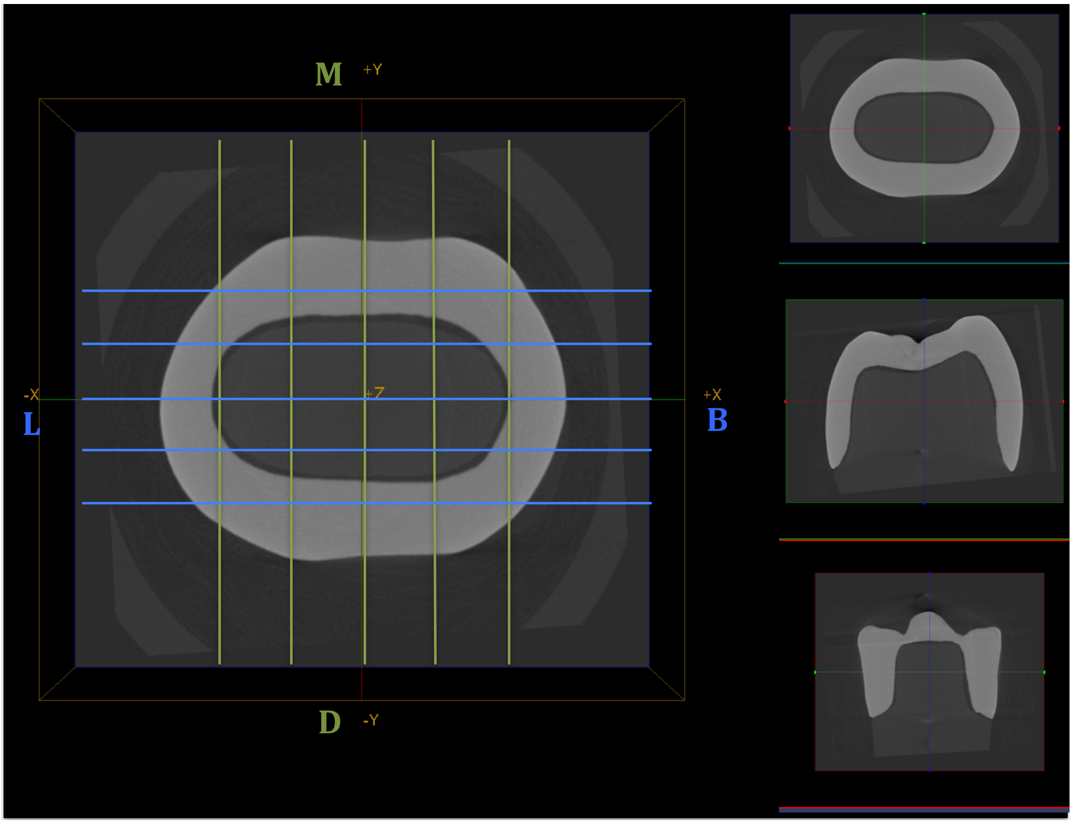

Figure 2-3: Standardized slice selection for circumferential vertical MG measurement obtained with 70 slices between buccolingual cuts and 50 slices between mesiodistal cuts. A total of 20 measurements were done for each crown (5 mesial, 5 distal, 5 buccal, and 5 lingual) using this approach.

2.5 Marginal Discrepancies

While measuring the vertical MG, we observed marginal discrepancies and reported the frequency of occurrence. These marginal discrepancies included over-extension (OE), under-extension (UE), and porcelain chipping. Incidences of marginal discrepancies were recorded at the same standardized points utilized for the vertical MG measurements (n= 20 points per crown), which resulted in a total of 300 points per group around the circumference of the crown margins. To minimize measurement error, vertical MG measurement was modified based on the type of discrepancy as described below:

- **Overextended margin:** recorded as the perpendicular measurement from the cavosurface angle of the tooth to the opposing crown margin (Figure 2-4).
- **Underextended margin:** recorded as the perpendicular measurement from the crown margin to the opposing cavosurface angle of the tooth (Figure 2-5).
- **Porcelain chipping:** recorded as the perpendicular measurement from the external crown margin to the opposing preparation line at the point in the shortest perpendicular distance (Figure 2-6).

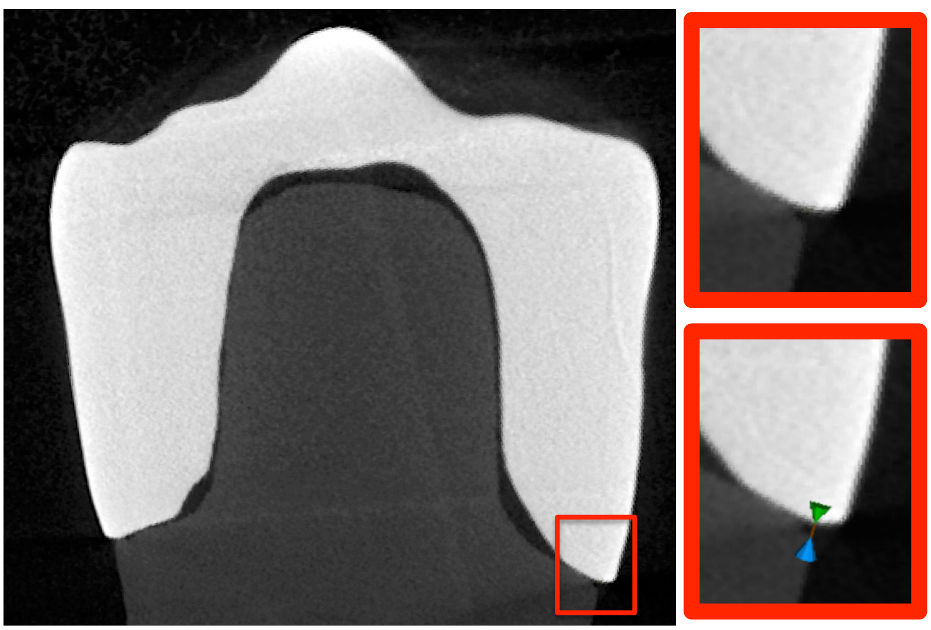

Figure 2-4: Cross-sectional Micro-CT images of crowns seated on their corresponding dies showing the MG measurements performed on crowns with overextended margins.

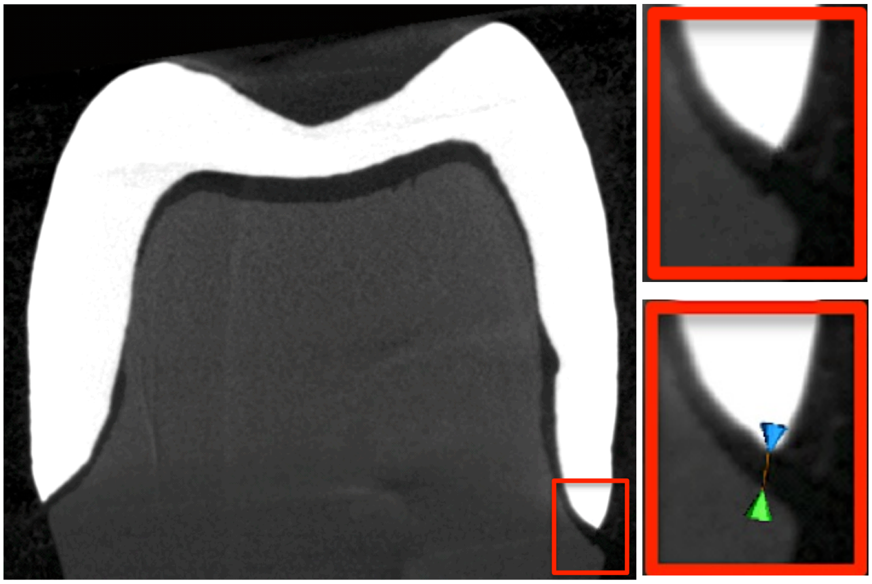

Figure 2-5: Cross-sectional Micro-CT images of crowns seated on their corresponding dies showing the MG measurements performed on crowns with underextended margins.

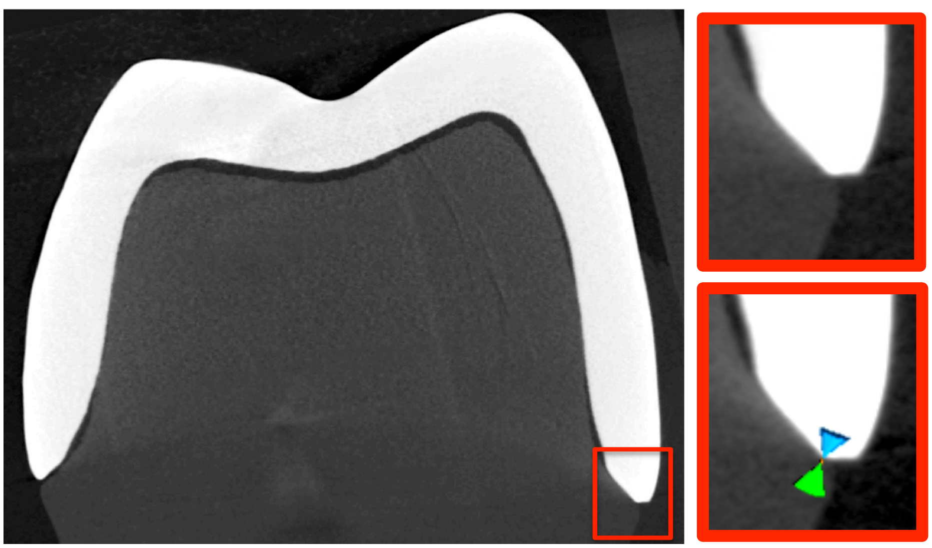

Figure 2-6: Cross-sectional Micro-CT images of crowns seated on their corresponding dies showing the MG measurements performed on crowns with porcelain chipping.

2.6 Acceptable and Unacceptable Crowns

As previously discussed, most *in vitro* studies [9, 10] claimed that the clinically acceptable MG should be less than 120 µm. Therefore, crowns with vertical MG ≤ 120 µm were considered acceptable, while crowns with vertical MG >120 µm at more than five points were deemed to be unacceptable and were rejected **(**Figure 2-7**).** MG volumes for the unacceptable crowns were also recorded for comparison.

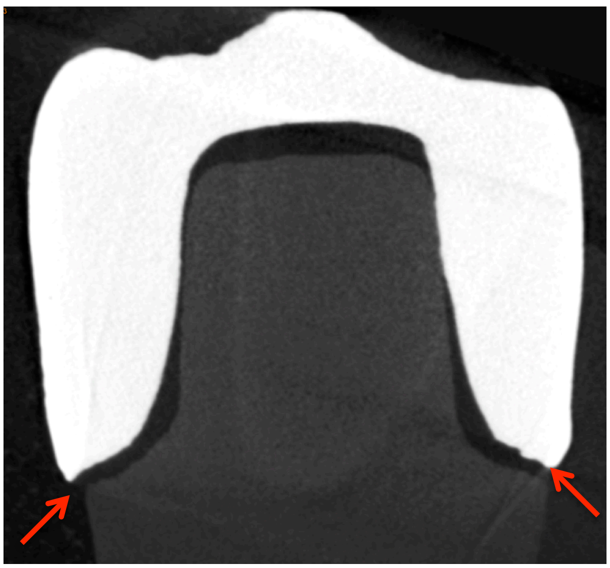

Figure 2-7: Micro-CT image of an unacceptable crown with open margins (vertical MG >120 µm at more than five points).

2.7 Statistical Analysis

Differences in vertical MG and MG volume between the three groups were analyzed by one-way ANOVA with Scheffe post hoc test using SPSS software package (SPSS, Chicago, IL, USA). Chi-square was used to assess differences between the groups in marginal discrepancies. Statistical significance was set at α =0.05.

Chapter 3: Results

3.1 MG Volume Measurements

Visualization of the 3D MG volume (Figure 3-1) demonstrated a clear increase in the MG thickness around the circumference of the crown margins between the 3 experimental groups (DD< DP< TP). Quantitative analysis of the MG volume demonstrated significantly smaller volume in DD group (3.32 ± 0.58 mm^3) as compared to TP group (4.16 ± 0.59 mm^3). However, the mean MG volume for DP group (3.55 ± 0.78 mm^3) was not significantly different from the other groups (Figure 3-2 and Table 3-1). Correlation between repeated 3D MG volume measurements was significant ($r = 0.97$).

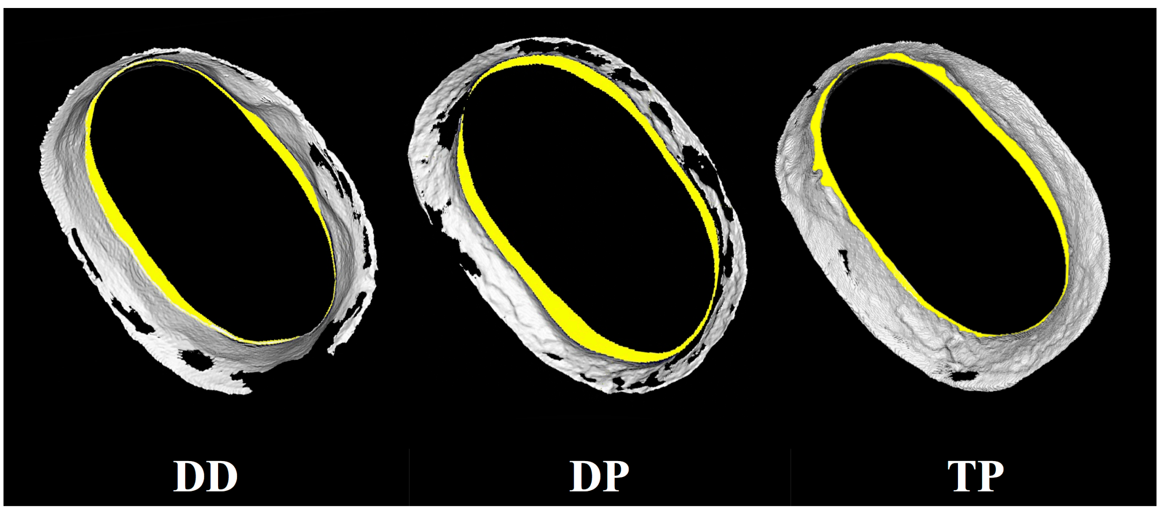

Figure 3-1: 3D MG volume for a representative sample in each group (DD, DP, and TP)

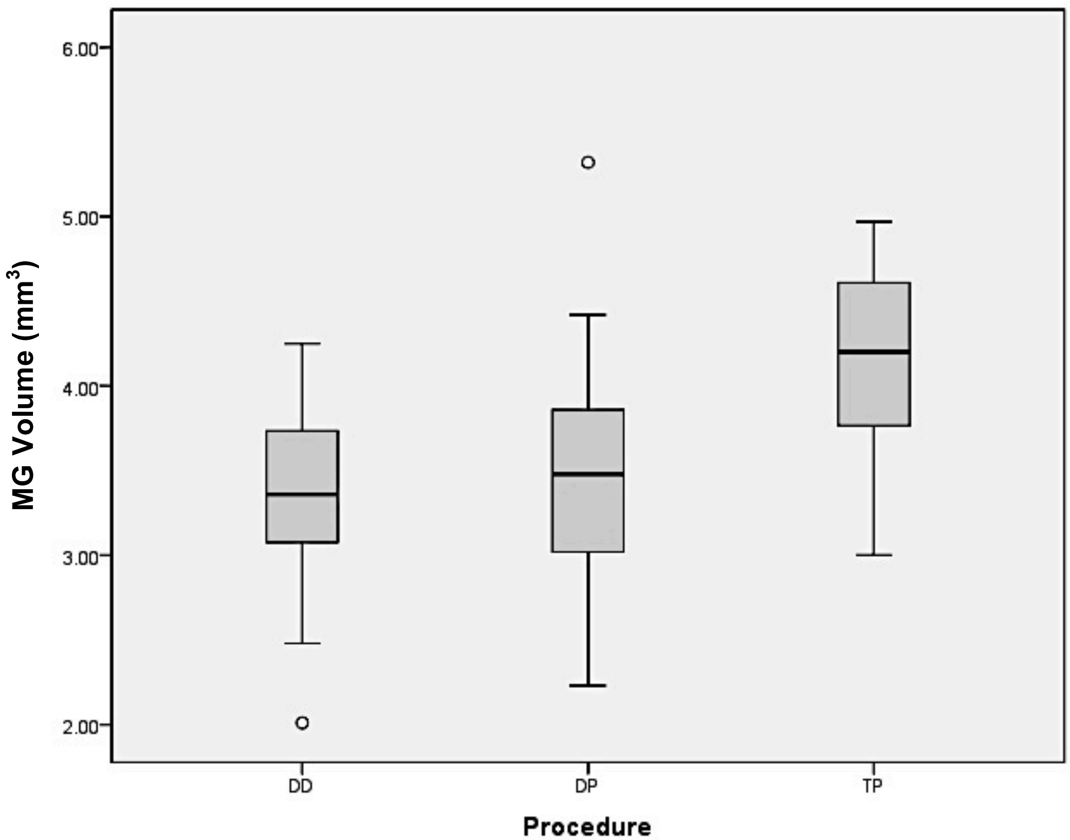

Figure 3-2: Box plot of the MG volume measurements (n=15 crown/group)

Table 3-1: MG volume measurements (n=15 crown/group)

		MG Volume (mm^3)	
		Mean	**STD**
Procedure	**DD**	3.32 [a]	0.58
	DP	3.55 [a, b]	0.78
	TP	4.16 [b]	0.59

Values with same superscript letters are not significantly different (p-values < 0.05)

3.2 Vertical MG Measurements

The results of the overall vertical MG measurements recorded at 20 standardized points per crown and a total of 300 measurement points per group are summarized in Figure 3-3 and Table 3-2. Crowns fabricated using DD group demonstrated significantly smaller vertical MG (33.3±19.99 μm) compared to DP (54.08±32.34 μm) and TP (51.88±35.34 μm) groups. For DD group, no statistically significant differences in MG measurements were noted among the different sites (buccal, lingual, mesial and distal). The buccal site in the DP and TP groups had a significantly lower vertical MG than the mesial, distal, and lingual sites (Table 3-3).

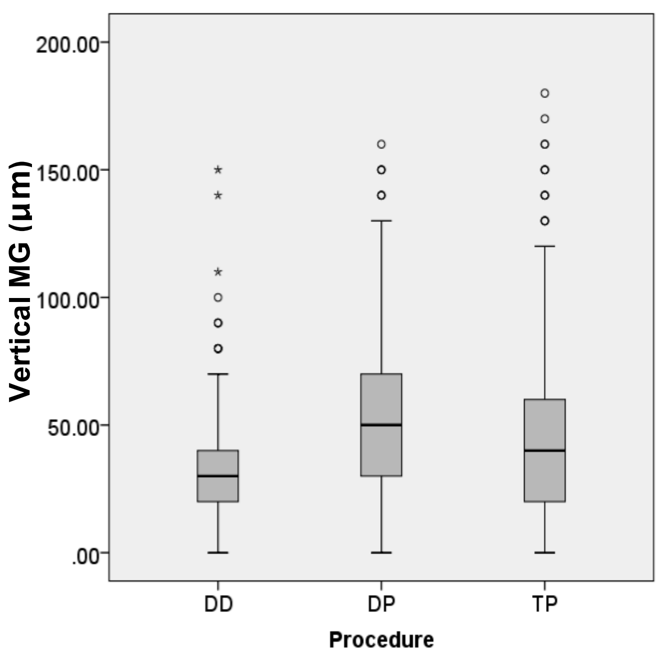

Figure 3-3: Box plot of the vertical MG measurements at 20 standardized points per crown (n=300 measurements/group)

Table 3-2: Mean vertical MG measurements for each group at 20 standardized points per crown (n= 300 measurements/group)

		Vertical **MG** (µm)	
		Mean	**STD**
Procedure	**DD**	33.30 [a]	19.99
	DP	54.08 [b]	32.34
	TP	51.88 [b]	35.34

Values with same superscript letters are not significantly different (p-values < 0.05)

Table 3-3: Mean vertical MG measurements on the buccal, lingual, mesial and distal surfaces (n= 75 measurements/Area/group)

		Vertical **MG** (µm)			
Area		**Buccal**	**Lingual**	**Mesial**	**Distal**
Procedure	**DD**	34.27 ± 23.89 [A, a]	33.73 ± 15.75 [A, a]	28.40 ± 16.77 [A, a]	36.80 ± 21.82 [A, a]
	DP	44.92 ± 28.95 [A, a]	61.38 ± 33.58 [B, b]	55.08 ± 34.06 [B, b]	54.92 ± 31.08 [B, b]
	TP	38.83 ± 29.41 [A, a]	55.33 ± 33.22 [B, b]	58.17 ± 40.94 [B, b]	55.17 ± 34.32 [B, b]

Values with same superscript letters are not significantly different (p-values < 0.05)
Capital letters denote differences within each column
Small letters denote differences within each row

3.3 2D *vs.* 3D Measurements

Cross-sectional analysis of the MG morphology was done to explore the relationship between 2D and 3D marginal gap measurements (Figure 3-4). Crowns fabricated using the DD demonstrated smaller vertical MG, but tended to have larger MG volume at the line angles of the preparations. On the other hand, DP and TP crowns showed larger MG measurements that were consistent with MG volume measurements. They also showed better internal adaptation at the line angle of the preparation as compared to the milled group.

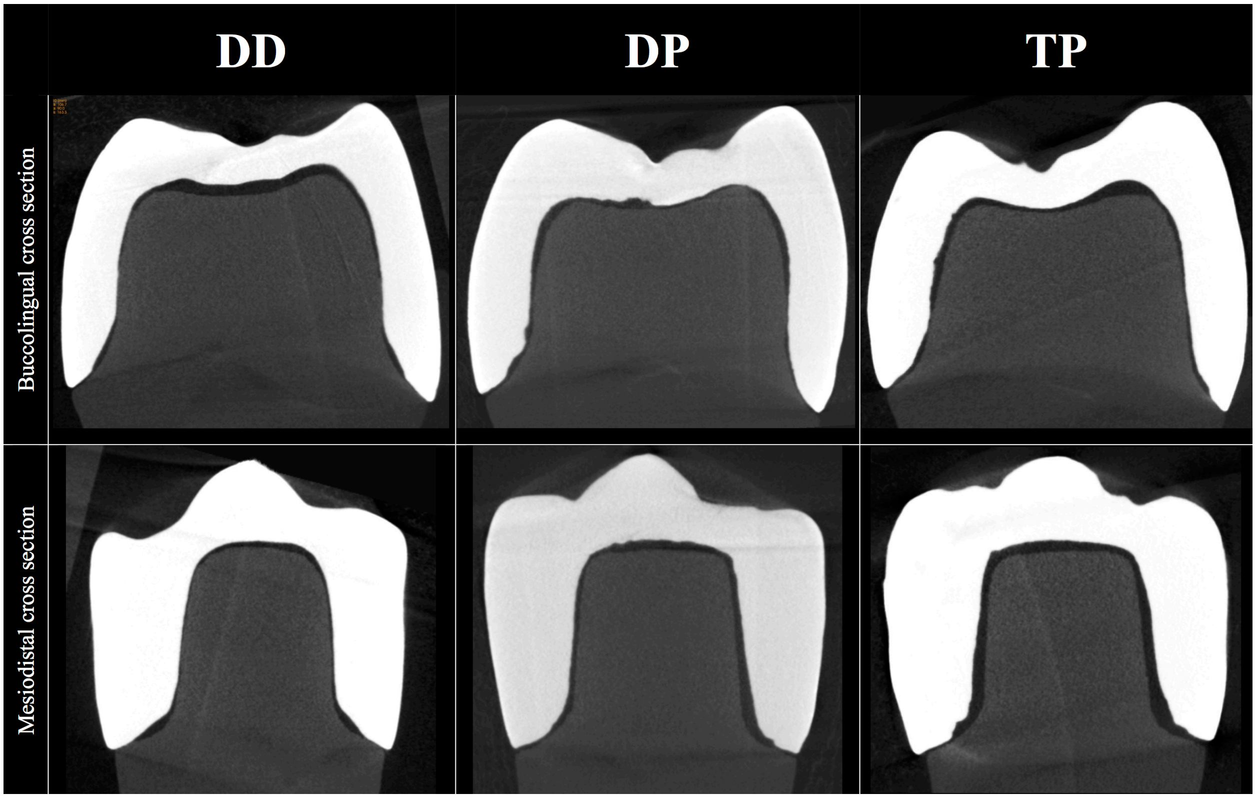

Figure 3-4: A cross-sectional analysis of the marginal gap morphology in buccolingual and mesiodistal directions for DD, DP, and TP groups.

3.3.1 Marginal Discrepancies

Incidence of marginal discrepancies was recorded at 20 standardized points per crown and a total of 300 points per group around the circumference of the crown margins is summarized in Table 3-4. Over-extension was the most frequent marginal discrepancy in all groups and it was more common in DD (37.7 %) group than in TP (28.9 %) and DP (18.8 %) groups. Under-extension was more frequent in DP (6.3 %) and TP (5.4 %) groups than in DD (0.3 %) group. However, there were no significant differences in the incidence of porcelain chippings between the three groups (DD, DP, and TP).

Table 3-4: Incidence rate for marginal discrepancies recorded at 20 standardized points per crown (n= 300 points per group)

		MG discrepancies		
		Over-extension (%)	**Under-extension (%)**	**Chipping (%)**
Procedure	**DD**	37.67 [a]	0.33 [a]	6.33 [a]
	DP	18.75 [b]	6.25 [b]	3.75 [a]
	TP	28.85 [c]	5.4 [b]	4.62 [a]

Values with same superscript letters are not significantly different (p-values < 0.05)

3.4 Unacceptable Crowns

Overall, four out of 45 crowns fabricated were deemed unacceptable based on MG measurements: three in TP group and one in DP group; all crowns in DD group were considered acceptable. This means that DD resulted in 100% acceptable crowns, while DP and TP resulted in 7% and 20% unacceptable crowns respectively. Mean marginal gap volume for unacceptable crowns was 7±1.3 mm^3.

Chapter 4: Discussion and Conclusion

There has been considerable debate in the literature about the accuracy of dental restorations fabricated using the digital technology. Results vary from improved fit to more misfits of digitally fabricated ceramic restorations when compared with the conventionally fabricated crowns. [11, 41, 42] Moreover, MG for ceramic restorations is widely diverse in the literature and ranges from 7.5 to 206.3 μm. Such variation can be mainly attributed to lack of coherence in the definition of "fit" along with differences in measurement methods, sample size and number of measurements per specimen and method of fabrication (conventional vs. CAD/CAM).[7] Therefore, the objective of the current study was to systemically assess and compare 2D and 3D marginal fit of LDS crowns fabricated with digital, conventional and combination methods using micro-CT. Moreover, incidences of different marginal discrepancies were recorded, including OE, UE, and porcelain chipping. Crowns with vertical MG>120 μm at more than five points were considered unacceptable and were rejected.

Every attempt was made in this study to minimize measurement error. No adjustments were made to the intaglio surfaces or to margins of the crowns following fabrication with DD, DP, and TP methods. This was based on the recommendations of the systematic review by Contrepois et al.[26] that indicated that adjustments made on the fitting surface of crowns prior to the evaluation of the marginal fit could result in measurement error. Micro-CT was utilized in this study as it offers a non-destructive method for 2D and 3D assessment of the MG at multiples sites and directions. The 3D measurements represented the 3D volume of the gap measured circumferentially at the crown margin.

It is important to mention that the number of sites and measurements needed for the assessment of marginal fit is controversial. Several studies based their results on 2 to 12 measurements per sample.[28, 35, 36, 43] However, Groten et. al.[37] recommended that 50 measurements are required per crown to obtain precise information about the marginal gap size (i.e. within ±5 μm variability for arithmetic means). Gassino et. al.[27] claimed that Groten et. al.[37] results were inaccurate and utilized a more sophisticated methodology that employed 360° MG measurements and concluded that 18 measurements are required to assess experimental crowns and 90 measurements are required for crowns fabricated from an intraoral impression. Other studies considered 20 measurements to be sufficient to evaluate the marginal fit for *in vitro* fabricated ceramic crowns.[33, 44] In the present study, the vertical MG measurements were done at 20 standardized points and according to Holmes et al.[15] even in the presence of MG discrepancies, to minimize measurement error.

An interesting finding in this study was that the crowns fabricated using DD method had statistically significantly smaller MG volume than those fabricated using TP method. However, no difference was found between the CAD/CAM crowns made from conventional impressions (DP) as compared to the other groups (DD and TP). Our results are different from Anadioti et al.[11] study, which demonstrated that crowns fabricated from the conventional impression and fabrication method produced the most accurate 3D marginal fits. Anadioti's study [11] presented a 3D colored map of the MG around the crown margin along with overall mean gap thickness (i.e. cement thickness) that is still a 2D measurement around the entire crown circumference. But, the present study is the first study that quantitatively measured 3D MG volume around the crown circumference. Due to the recent introduction of MG volume assessment and limited literature support, vertical MG measurements were done to validate the 3 D volume results.

For vertical MG measurements, DD group had significantly smaller MG as compared to the other groups, with no differences identified between DP and TP groups. These results are in agreement with those of two studies concurrent to this study, which also revealed that digital workflow had a more accurate marginal and internal fit in comparison to traditional techniques.[12, 42] Additionally, our results support the outcomes of other authors who have compared traditional and digital workflows and found that the digital workflow produces restorations with superior fit to those fabricated by traditional technologies.[41] Conversely, our results are again different from Anadioti et al.[11] study that reported better 2D marginal fit in crowns fabricated from conventional impression and fabrication as compared to other groups. Although Anadioti et al.[11] reported smaller 2D MG values than those reported in the present study for TP group (40 μm *vs.* 51.88 μm), their MG measurements were larger than this study for DD (74 μm *vs*. 33.3 μm) and DP (75 μm *vs.* 54.08 μm) groups. These differences could be attributed to the variations in the measurement methods, CAD/CAM systems, die spacer thicknesses and preparation designs. Another reason might be due to the fact that the technician for the conventional fabrication method was not standardized in the present study. This could account for the larger standard deviation in conventionally fabricated crowns as compared to digitally fabricated ones. However, this variation reflects the reality in the clinical practice where cases are sent to dental laboratories and are assigned to different technicians with various skills and experiences. Therefore, one of the main advantages of the DD technique is the consistency of the recorded marginal fit (33.3±19.99 μm) as compared to DP and TP groups (54.08±32.34 μm and

51.88±35.34 μm respectively), which could be attributed to the reduction of the human error during impression taking and crown fabrication when using digital technology.

A comparison between 2D and 3D MG measurement based on a cross-sectional analysis of the MG morphology was then pursued to provide a complete picture of the marginal fit of crowns fabricated using the three methods. This analysis revealed that DD group had smaller vertical MG, but it demonstrated larger gap at the line angles of the preparations. This could be attributed to milling inaccuracies due to the dimensions of the burs used. On the other hand, DP and TP groups demonstrated larger vertical MG that is consistent with MG volume and showed better adaptation at the line angles of the preparation as compared to the milled group. This could explain why DD group had significantly smaller vertical MG but not a significantly lower MG volume when compared to DP group. However, it is important to mention that external marginal fit is more important to minimize microleakage and biological complications, while small internal gaps at the line angle will be filled with cement.

We subsequently investigated the incidence of marginal discrepancies in each group (DD, DP, and TP). Overall, OE was the most frequent marginal discrepancy. It is important to mention that OE errors can be easily adjusted as compared to UE and marginal chippings that can only be closed with luting cement, which is prone to dissolution.[45] Incidence of OE was significantly higher in DD group (37.7 %) as compared to other groups (TP (28.9 %) and DP (18.8 %)). This could be due to marginal enhancement during computer-aided design for the crowns in the digital group, which is done to minimize chipping during milling. UE was significantly more frequent in DP (6.3 %) and TP (5.4 %) groups than in DD (0.3 %) group. However, there were no significant differences in the incidence of porcelain chipping between the three groups. In regard to comparison with the outcomes of other reports, there were no available data. This is the first study to report the incidence of marginal discrepancies in all-ceramic crowns fabricated using digital and conventional techniques.

Uncertainty exists in the literature regarding the ideal marginal adaptation. The ideal cement thickness for indirect restorations should be 25-40 μm based on the type of cement.[7] Although MGs in this range have been considered a clinical goal, they are difficult to achieve.[8] McLean et al.[9] suggested that a marginal gap less than 80 μm is challenging to identify under clinical conditions. Moreover, Fransson et al.[10] and McLean et al.[9] stated that the clinically acceptable MG after cementation should be less than 150 μm and 120 μm, respectively. Based on the available evidence, several *in vitro* studies considered MG up to 120 μm to be clinically acceptable.[11-14] Therefore, the current study considered any crown with vertical MG >120 μm at more than five points to be unacceptable. Four out of 45 crowns fabricated were deemed unacceptable based on MG measurements: three in TP group and one in DP group. Cross-sectional evaluation for the unacceptable crowns, revealed areas of internal interferences at the intaglio surface that prevented the complete seating of the crowns with subsequent open margin. This might be due to dimensional changes in the impression, wax shrinkage or ceramic shrinkage in the heat pressed groups (TP and DP). The complete digital workflow (DD group) resulted in 100% acceptable crowns, which could be attributed to milling from LDS monoblocks together with a reduction in human and processing errors.

Mean MG volume was 3.7± 0.65 mm^3 for the acceptable crowns and 7±1.3 mm^3 for unacceptable crowns. Based on the presented data, crowns with MG volume > 5 mm^3 could be considered unacceptable. This value could be utilized as a new criterion for unacceptable crowns in future studies.

Strengths and Limitations of The Study

Few studies utilized micro-CT as a non-destructive method for assessing marginal gap, marginal discrepancy, and/or internal fit of crowns based on 2D assessment similar to cross-sectioning method.[46-48] But, the current study is the first study that provided careful 2D and 3D assessment of MG, using micro-CT, of digitally and conventionally fabricated LDS crowns. This study also suggested that crowns with MG volume > 5 mm^3 to be unacceptable. A standardized and thorough approach was utilized for MG measurements, even in the presence of MG discrepancies. The standardization, the non-destructive nature, and data storage/availability of the micro-CT measurements enabled a thorough evaluation of the MGs for LDS crowns fabricated using DD, DP, and TP techniques. Further characterization of the MG morphology was done to further explain the relationship between vertical MG and MG volume measurements. Moreover, the incidence of marginal discrepancies (OE, UE, and porcelain chipping) was investigated, which was not previously reported in the literature.

The main limitation of the present study is the fact that the technician for the conventional fabrication method was not standardized. This could account for the larger standard deviation in conventionally fabricated crowns as compared to digitally fabricated ones. However, this variation reflects the reality in the clinical practice where cases are sent to dental laboratories and are assigned to different technicians with various skills and experiences. Therefore, one of the main advantages of the DD technique is the consistency of the recorded marginal fit due to the reduction of the human error during impression taking and crown fabrication when using digital technology.

Conclusion

This study compared the marginal fit of LDS crowns fabricated with digital impression and manufacturing (DD), digital impression and traditional pressed manufacturing (DP), and traditional impression and manufacturing (TP). Based on the outcomes of this study (summarized below), null hypothesis was rejected and alternative hypothesis deemed acceptable:

- DD group resulted in significantly smaller vertical MG than DP and TP groups and less MG volume than TP group.
- DD group was associated with more OE (easy to correct) and less UE than DP and TP groups.
- There were no significant differences in porcelain chipping between the three groups (DD, DP, and TP).
- Finally, DD resulted in 100 % acceptable crowns while TP resulted in 20 % unacceptable crowns.
- Crowns with MG volume > 5 mm^3 could be considered to be unacceptable.

Taken all together, digital impressions and CAD/CAM manufacturing (DD) is considered a suitable, better, alternative to TP.

Clinical Implications

Different combinations of impression and crown fabrication procedures affect the size and uniformity of MG. Digital workflow provides suitable, better, alternative to conventional impression and fabrication.

Future Directions

Micro-CT analysis presented in this study provides a non-destructive, standardized and thorough approach for assessment of 2D and 3D MG of dental restorations that could be employed for future bench-top studies and clinical trials. It can also be used to compare changes in the marginal fit of dental restorations before and after adjustments and/or cementation. Moreover, micro-CT technology could provide quantitative and qualitative assessment of cement thickness and morphology of cement space.

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