The Effect of Crown Cementation on The Marginal Fit using a Micro-CT Measurement Technique

by

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The Effect of Crown Cementation on The Marginal Fit using a Micro-CT Measurement Technique

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in Craniofacial Science

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Abstract

Objectives: To study the effect of cementation on the marginal gap of lithium disilicate (LDS) crowns made with digital impression and manufacturing (DD), digital impression and traditional pressed manufacturing (DP) and traditional impression and manufacturing (TP).

Methods: Ivorine typodont tooth #15 was prepared for an all-ceramic crown. The prepared tooth was scanned, and 45 dies were produced and used for fabricating 45 LDS crowns using three methods: DD, DP, and TP. Micro-CT was utilized to evaluate the 2D marginal gap before adjustment, after adjustment and after cementation. RelyX-Ultimate resin cement was used to cement the crowns on each of the 45 dies with 20 N application force using a universal material testing machine. The 2D vertical marginal gap (MG) evaluations were made at 20 designated positions along the crown margins. The results were analyzed using a linear mixed effect model with the interaction method x cementation as fixed effect, and crown as a random effect, as well as post hoc analysis (CI=95%).

Results: Clinical adjustments of unacceptable crowns (4 from the TP and 2 from the DP) which showed at least 5 measurement points of MG of more than 120 μm resulted in reduction of the marginal gap to an acceptable level. Cementation resulted in an average increase in the marginal gap of 20 μm (95 % CI= 22-18), irrespective of the method of fabrication. All crowns had clinically acceptable crown margins, irrespective of the method of fabrication after cementation.

Conclusion: Clinical adjustments to intaglio surface of crowns reduced MG, while cementation increased MG regardless of the method of fabrication. The DD group did not require any clinical adjustment prior to cementation. Only two crowns of the DP group and four crowns of the TP group required adjustment prior to cementation

Lay Summary

Marginal fit of any indirect restoration is crucial for its success. Cementation is an essential step in the delivery of ceramic crowns but is known to have a negative effect on marginal fit. In this study, the effect of cementation on the marginal fit of 45 ceramic crowns made from lithium disilicate material produced with various techniques was investigated. It was concluded that cementation caused an increase in the marginal gap regardless of the method of fabrication. This effect is due to the cement layer which has a specific thickness.

Preface

Chapter 1 “Introduction”, chapter 2 “Study Objectives”, chapter 3 “Materials and Methods”, chapter 4 “Results”, chapter 5 “Discussion” and chapter 6 “Conclusion” were written by Mohamed Gebril. Dr. Chris Wyatt, Dr. Dorin Ruse and Dr. Nesrine Mostafa provided revisions and edits.

Experiments were designed by Dr. Chris Wyatt. All studies were performed by Mohamed Gebril. Micro-CT measurements were conducted in Dr. Nancy Fords’s Lab. Cementation was done in Dr. Dorin Ruse’s Lab.

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List of Abbreviations

ADA	American Dental Association
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
µm	Micro-meter
OE	Over-extension
RMGI	Resin modified glass ionomer cement
SC	Secondary Caries
SEM	Scanning electron microscopy
STD	Standard deviation
TP	Traditional impression and manufacturing
UE	Under-extension
USPHS	United States Public Health Service

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I would like to extend my thanks to all the faculty, staff and my colleagues at the Graduate Prosthodontics Program at UBC for their help and support.

Dedication

I would like to dedicate this thesis to

My father (Ibrahim Gebril) who would be very proud to see me succeed in my life and achieve this degree. I really wish he was here to share this moment with me. Although he is no longer in our world, I believe that he can see and feel. Rest in Peace Father.

My mother (Maha ElDeeb) who always supported me during the journey and gave me the strength to achieve every step.

My brother (Osman Gebril) and my sisters (Aliaa Gebril and Lamyaa Gebril) for their unconditional love and support.

Chapter 1: Introduction

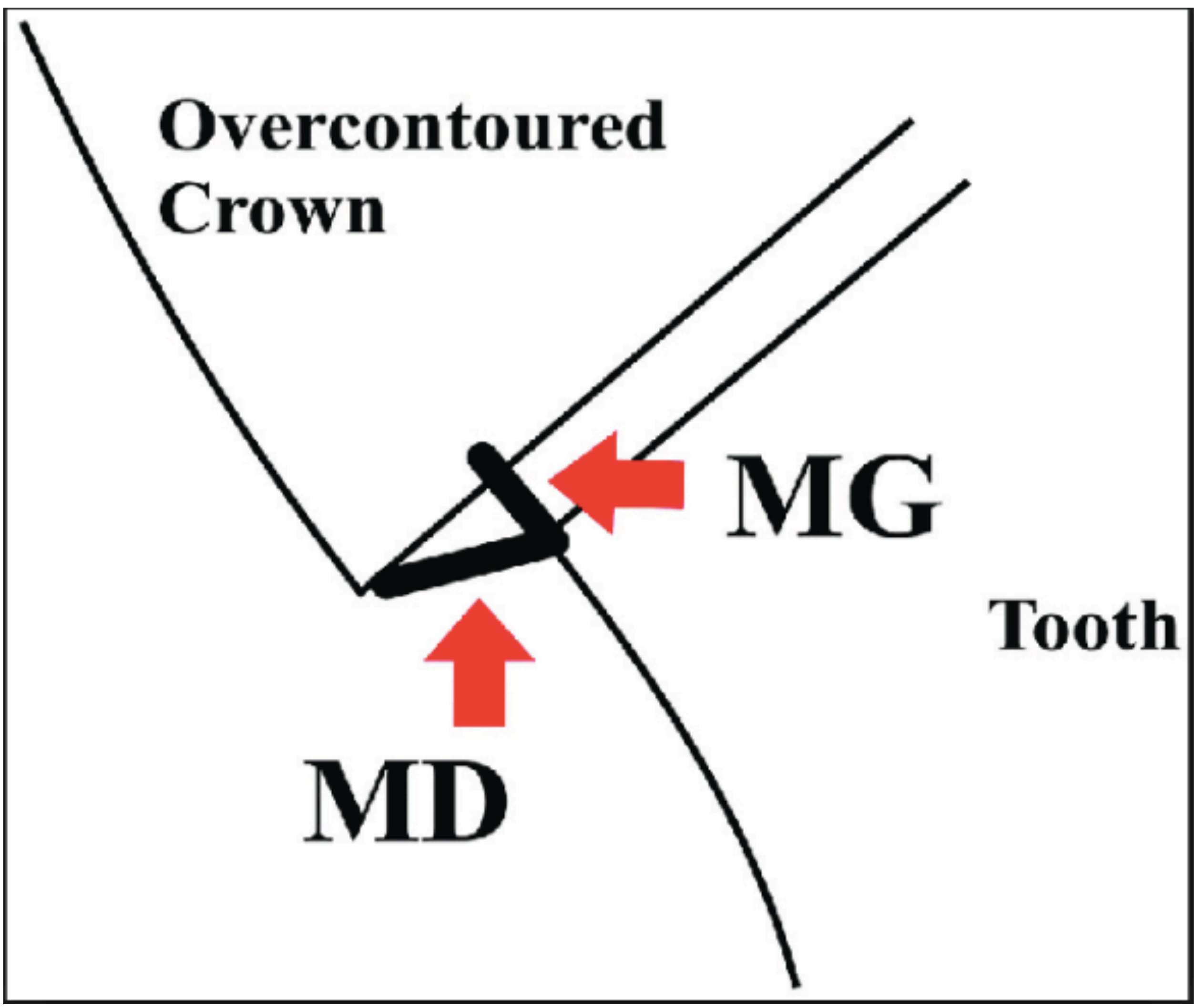
The conventional technique of manufacturing dental crowns involves multiple steps: obtaining an elastomeric impression of the prepared tooth, creating a master cast in a gypsum material, die separation and margin identification, waxing-up of the crown, investing in dental stone, melting the wax and centrifugal casting, all of which could introduce potential errors. More recently, digital impression techniques and CAD/CAM (computer aided design/computer aided manufacturing) have been introduced to dentistry. Irrespective of the method of crown fabrication, conventional or digital, the final cemented restoration has to fit the prepared tooth to ensure clinical success. The "marginal gap" has been described as the perpendicular measurement from the tooth preparation to the edge of the restoration at the margins and is considered to be a critical aspect for the success of indirect restorations. (1)

The purpose of this study was to assess the marginal fit of lithium disilicate crowns fabricated by a completely digital process, a partially digital process, and a traditional process, before and after adjustment and cementation.

1.1 Marginal Gap

The "marginal gap" has been defined as "the perpendicular measurement from the edge of the restoration to the tooth preparation at the margins" as shown in figure 2.(2) McLean et al.(1) stated that MG of < 80 μm are challenging to identify under clinical conditions (soft tissue, tongue and salivary flow). Fransson et al. (3) and McLean et al. (1) recommended that the cast restorations should have a MG no greater than 120 μm and 150 μm after cementation. Moreover, removal of excess cement has a critical impact on the adaptation of the indirect restoration. Proper seating of the crown during cementation is essential to minimize the MG. Minimizing the MG is critical to minimize the dissolution and mechanical wear of the cement which is more likely to occur when the cement is exposed to the oral cavity.(4)

Figure 1 The "marginal gap" has been defined as the perpendicular measurement from the edge of the restoration to the tooth preparation at the margins. *Printed from https://www.researchgate.net/figure/The-drawings-of-marginal-gap-and-marginal-values_fig1_269774565*



1.1.1 Factors affecting Marginal Gap

Multiple factors have a direct effect on the impact of cementation on the marginal fit of indirect restorations including type of cement, cementation technique, method of crown fabrication, cement film thickness, preparation design, as well as load application during seating. (5)(6)

In the literature, multiple studies examined the influence of cementation on the marginal fit of digitally and conventionally produced restorations. (4-6) Studies have used different evaluation methods for the assessment of the marginal fit of indirect restorations including direct view, impression replica, profilometery and cross-sectioning, but none utilized micro-CT. Micro-CT offers a non-destructive, repeatable, and reproducible measurement technique. (7)

1.1.1.1 Die Spacer/ Cement Film Thickness

Retention and fit of the indirect restoration are influenced by the die spacer used in the fabrication of the crown. Without die spacer, the crowns may be too tight and unable to seat on the die and tooth, while too much die spacer will decrease intimate fit for retention of the crown on the tooth. The improvement of seating was reported for indirect restoration with a die spacer to of 25-40 μm in thickness. The inadequate seating of the restoration during cementation may occur as a result of using of die spacer of less than 30 μm. Digital designing and fabrication of crowns introduced the possibility of designing and fabricating crowns with the incorporation of virtual cement space (die spacer), consequently improving accuracy. (1)(8)(9)

In 2016, Kale et al. (8) investigated the impact of the cement space (die space) on the marginal adaptation of the CAD-CAM monolithlic zirconia crowns before cementation. Fifteen teeth were distributed into 3 groups of 30 µm, 40 µm and 50 µm cement space. Eight points were selected for measurement of the MG of the crowns. It was noted that the crowns with cement space of 50 µm had the superior marginal fit compared to those crowns with less die space. This results were in agreement with the outcomes of several studies reported in the literature. (8)(10) (11)

An et al. (10) compared the MG of zirconia copings fabricated using iTero digital scanner and conventional impression techniques. It was concluded that indirect restorations fabricated using the digital method had significantly higher MG compared to the conventionally fabricated ones. In this report, a 60 µm die spacer was set for conventionally as well as digitally fabricated groups. The MG between the definitive die and zirconia coping was significantly lower for conventional impression compared to the digital impression, yet they were all within the clinically acceptable ranges.

1.1.1.2 Method of Fabrication, Cementation Technique and Type of Cement

Multiple studies have shown that crown marginal fit before and after cementation is affected by cement selection, i.e. zinc phosphate, zinc polyacrylate, glass-ionomer, and resin. (12) (13) (14) (15) (16) However, Yüksel et al.(12) discovered no significant variance between the marginal discrepancy of the crowns cemented with resin cement and glass ionomer cement

Sakran et al. (14) concluded that marginal fit of three groups, as shown in Table 1 was significantly higher after cementation compared to before cementation with self-adhesive luting cement. The measures of the MG reported for the three investigated groups were 56.3, 56.16, 60.16 µm and 84.2, 95.22, 84.22 µm before and after cementation respectively. Albert et al. (15) stated that the use of resin cement resulted in less values of MG as well as less scores of microleakage.

Table 1 Effect of cementation on the MG using Resin cement (14)

	MG Before Cementation Mean (µm)	**MG After Cementation Mean (µm)**	**The difference in MG before and after Cementation (µm)**
Copy-milled zirconia	56.3 µm	84.20 µm	27.90
In-Ceram Zirconia	56.16 µm	95.22 µm	39.06
Indirect composite resin crowns	60.16 µm	84. 22 µm	25.06

Ferier et al. (17) concluded that CAD lithium LDS (IPS e.max CAD) had superior adaptation (62.09 µm) compared to injection molding (IPS e.max Press), which showed 70.65 µm of MG. This was explained as a result of the multiple steps and materials involved in the process of fabrication of the injection molding crowns, such as type of the impression material as well as operator factors. CAD ceramics required fewer laboratory steps, thereby reducing the extent of the errors in fabrication.(4) (11) Thompson et al. (18) indicated that increasing the cement thickness would impact the flexural failure load of the crowns. The relative strength of the indirect ceramic restoration can be dropped by 50 % due to cement thickness from 20 to 200 µm. It was reported that thick cement layer accompanied with slow crack growth within the cement may place restorations at risk to failure.(19)

Clinically, factors such as the cement viscosity and its appropriate handling procedure must be considered. (11) (20) Borges et al. (21) conducted a study evaluating IPS e.max Press, Cergogold and In-Ceram crown marginal fit after cementation with resin modified glass ionomer cement (RMGIC) or resin cement. A light microscope was used to assess the MG and the results showed that there was a significant increase in the value of the MG of all ceramic systems after cementation, irrespective of the type of cement. The IPS e. maxPress crowns cemented by either type of cement resulted in MG larger than the clinically accepted range (Table 2).

Table 2 Effect of cementation on the MG using resin cement and RMGI (21)

	Effect of Cementation on MG (Resin Cement)	**Effect of Cementation on MG (RMGI)**
IPS e.max Press	36.30 µm	40.07 µm
Cergogold	36.87 µm	61.06 µm
In-ceram	23.78 µm	33.24 µm

Albert et al. (15) determined that Procera Ceramic crowns cemented with zinc phosphate or RMGI had higher microleakage compared to those cemented with resin cement. In this study, 80 extracted molars were distributed equally in 2 groups for the manufacture of metal-ceramic crowns and Procera All-Ceram crowns, and cemented under 50 N of force. Multiple studies indicated that 50 N is enough for seating crowns and any further forces have no positive effect on the seal of the crowns. (9)(22) Good et al. (23) concluded that there were no significant differences in the MG between different four cement groups after application of 20 N standard forces during cementation.

A study evaluating the influence of MG and cement types on microleakage (12) used 36 crowns cemented on extracted upper central incisors. The crowns (heat pressed lithium-disilicate, CAD/CAM-fabricated ZrO_2 and Cast Cr-Co) were cemented with glass-ionomer cement or self-adhesive resin cement. The samples were exposed to thermocycling, and the crowns sectioned. A stereomicroscope was used to photograph the surface of each section. Marginal fit was evaluated by image analysis software. The MG of each set was 82.7 ± 7 µm, 92.6 ± 4 µm and 96.5 ± 7 µm, respectively. CAD/CAM-fabricated ZrO_2 presented significantly superior fit compared to the control group ($P = 0.042$). It was concluded that crowns cemented by self-adhesive material have superior marginal fit. (12)

1.1.1.3 Measurement Methods

There are multiple methods to measure the MG using non-destructive techniques, including direct view, impression replica, and profilometery. (23) (24) In addition, there are destructive means of measuring the MG such as the cross-sectioning technique, which are limited by the number and location of the measurements.

The most reproducible non-destructive method for measurement of MG utilized is the direct viewing technique. Optical or scanning electron microscope are used to measure the MG under magnification. (11) (24) Replicating measurements from the same position and angulation are the main limitations of this technique.

The impression replica technique provides an alternative non-destructive method for indirect MG measurement. Light body silicone is utilized to fill the cement space to reproduce the cementation procedure. Subsequently, sectioning of the replica is done in order to assess the thickness of the impression material at various points. (25) This technique is economic and feasible. However, this technique introduces various limitations, such as improper representation of the overall MG, difficulty in detecting the crown margins, destroying of the elastomeric layer upon removal from the crown. (26) Profilometry is a non-destructive technique, which uses a well-defined focus plane of the crown on which MG measurements can be made. (23)

Cemented crowns can be cross-sectioned to measure the MG in horizontal and vertical plane under microscope. (26) However, sectioning of the crowns introduces the risk of distortion of the margins.(26)

Evaluating the internal and MG of indirect restorations at different points and planes can be accomplished by the micro-CT measurement technique. This technique offers a non-destructive method which produces a 3D data set for comprehensive evaluation of the overall fit of indirect restorations. (7) (27)

1.1.1.4 Number of Measures

Proper study design, including suitable sample size, as well as satisfactory number of measurements per specimen is crucial for the strength of the study and its conclusion. There is no clear agreement regarding the optimal number of measures required for the evaluation of crown marginal fit.

Groten et al. (30) indicated that 50 methodically or arbitrarily designated assessment points are required per crown to precisely evaluate the MG. However, Gassino et. al (24) asserted that the conclusions of Groten et al. (30) outcomes were imperfect. They engaged a more complex procedure of including 360 gap measurements at 360 degrees and determined that 18 measurements were essential to evaluate trial crowns. The very high number of measures provides a very clear representation of the marginal fit, yet it also introduces a complex and impractical approach that cannot be applied in every situation. The main advantages of the micro-CT measurement technique are that it offers a 3D data set that can be used to accurately analyze and assess the marginal fit of indirect restorations in a reproduceable nondestructive manner. (7)

1.2 Dental Ceramics

Dental ceramics are prepared from nonmetallic inorganic materials processed by firing at a high temperature to achieve desirable properties. Porcelain covers a specific compositional range in the kaolin (clay), quartz (silica) and feldspar compositional diagram. Ceramics are hard, brittle, stiff and are poor thermal and electrical conductors. (19)(31)

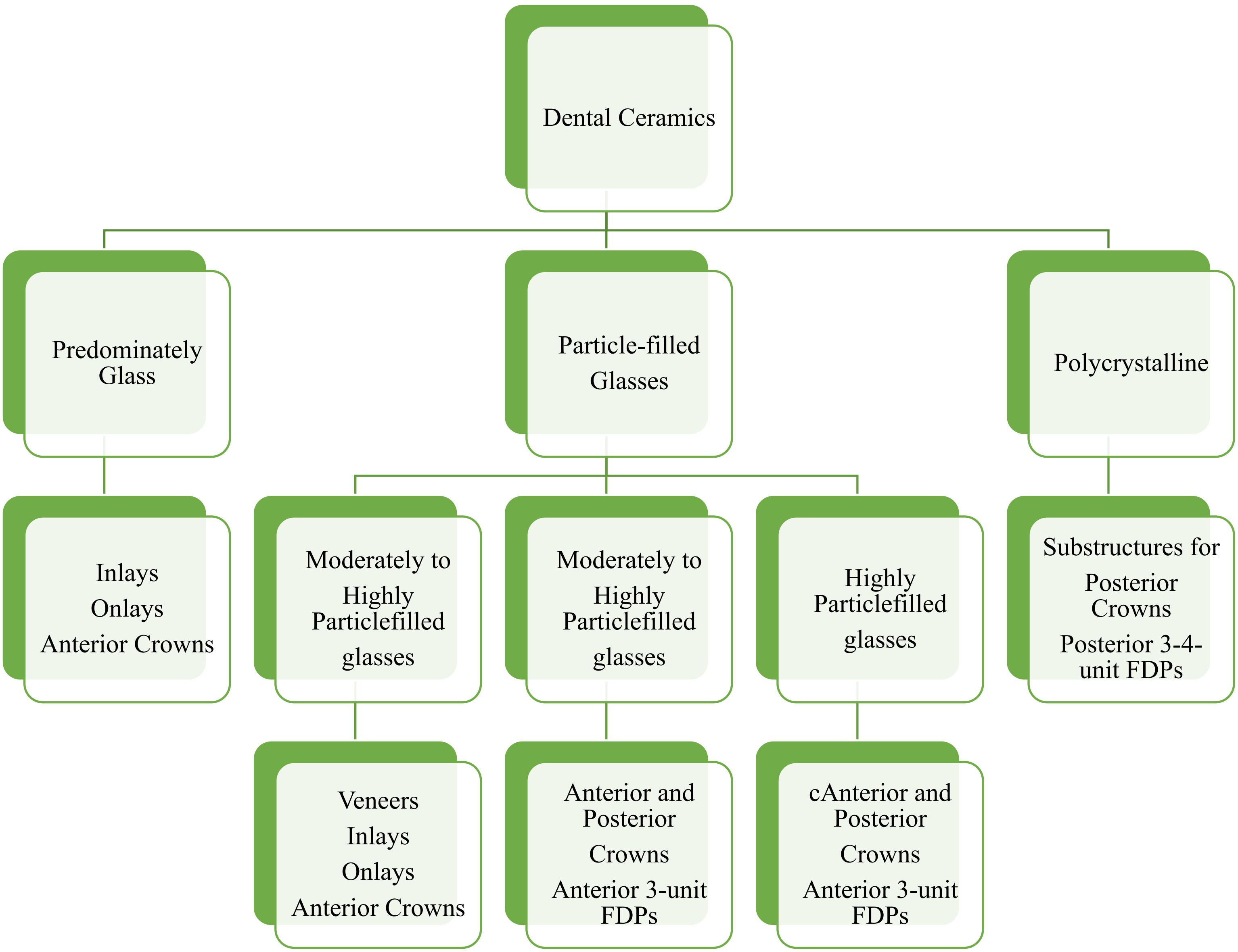
Ceramics are biocompatible, able to resist occlusal forces, and have optical properties that are alike to those of dental tissues.(32) (33) Owing to their properties, dental ceramics are widely used materials for the restoration of compromised teeth, as inlays, onlays and crowns. (18) Different potential applications of various dental ceramics are shown in Figure 2.

The application of all ceramic restorations initially presented dissatisfactory clinical performance in the posterior regions of the mouth. A strategy to improve the mechanical properties of all ceramic restorations by introducing crystalline phases that augment the fracture toughness and flexural strength of the materials has been developed. Leucite, in concentrations of 35-45 %, has been used as a reinforcing phase and these restorations have been found to be clinically acceptable in all regions of the mouth. (31) (34) Lithium disilicate (LDS), first introduced to the market in 1998 (19), is another alternative to further improve the physical properties of all ceramic restorations. The concentration of LDS has been reported to be up to 70 %, yielding a material that is no longer primarily glass. This increase in crystalline component improves the mechanical properties, in comparison to unfilled or leucite reinforced ceramics. (31)

1.2.1 Lithium Disilicate for Dental Restorations (Pressed and Milled)

LDS ceramics are siliceous materials than can be etched using hydrofluoric acid, and bonded after application of silane. (20) These glass-ceramics are fabricated by two methods, either the CAD/CAM system or isostatic injection molding. Ivoclar Vivadent markets two varieties of LDS-glass ceramics: IPS e.max Press and IPS e.max CAD. The former is intended to be utilized with the traditional lost wax casting technique while the latter is designed to be used with CAD/CAM milling technology. Pressable LDS can be utilized for crowns, or anterior 3-unit bridges and can be used either monolithic and full contour, or as a core. LDS CAD is milled in a partially sintered phase (with decreased flexural strength and fracture toughness), which allows for easier milling and adjustment. It is then fully sintered after milling and adjustment, obtaining its final optical and physical properties. LDS CAD can be utilized as monolithic prosthesis that is stained, or as a core material veneered with feldspathic porcelain. It can be prescribed for crowns, onlays, inlays, and veneers. (19)(31)

Figure 2 showing different types of dental ceramics and their potential applications (35)



1.3 Dental cements

Dental cements are materials that set via an acid – base reaction to form solids that can be used as liners, bases, luting agents, and restoratives (intermediary). They can be classified based on chemistry or based on usage (liners, bases, luting agents, and restorative). The main application of dental cements, dental luting agents, is to hold indirect restorations on tooth structure.(36) Proper mechanical and chemical characteristics of any luting agent are essential for clinical application. Cements should have no harmful effect on teeth, should have adequate working time, adequate strength to withstand occlusal forces and have low solubility in the fluids of the oral environment. (19) According to Rosentiel and colleagues (37), the properties of an ideal cement include strong bonding, proper working and setting time, esthetic, radiopaque, being adhesive, easy to manipulate and having low viscosity at mixing and, more importantly, low rate of dissolution in the oral cavity to assure proper function, avoiding the risk of recurrent “secondary” dental caries.(32) Multiple complications could result due to marginal misfit and exposure of the cement to the oral cavity, causing plaque accumulation, cement dissolution, recurrent dental caries, gingivitis and periodontitis as well as marginal staining. (20) (34) Since resin cement were used in our study so they will be the focus of the following review section.

1.3.1 Resin Cements and adhesive resin cements

Owing to the capability of resin cements to bond to both tooth structure and the restoration, they have become widely used in clinical application. (38) The effective application of resin cements is based on multiple factors associated to the bonding techniques to the restoration as well as the tooth structure. Resin-based luting cements are founded on the chemistry of composites and adhesives. (39) There are two key classes of resin luting cements: the self-adhesive resin cements, that do not necessitate an independent bond to the dental restoration as well as the conventional resin cement, that has no inherent adhesion to tooth structure and necessitate a bonding agent. (40) Resin cements have the potential to provide an insoluble, well supported, and strong adhesion between the tooth structure and all-ceramic restorations. Accurate application of the bonding agent of adhesive cements to different ceramic systems and dental tissue is critical for the indirect restorations longevity.(41)

Resin cements can be either light-cured, chemical cured, and dual-cured. The light-cured resin cement is used in situations where the light is able to pass through the restoration, such as in cases of veneers or shallow all ceramic indirect restorations. It also gives more control over the working time. On the other hand, the use of dual-cure resin cement is more common in most clinical situations, and involves both auto-curing as well as light curing. (40) (42) However, when cementing full-coverage crowns, light curing is compromised, and the full mechanical properties of dual cured cements are not achieved. It is therefore better to use a chemically cured cement for full-coverage crowns.

The solubility as well as the water absorption decreases the flexural strength and ultimately the success of resin cements. (41) The absorbed water acting as a plasticizer, which creates unsupported areas under the restorations. (43) This is more critical in case of thick cement film which can also compromise the bonding ability of the resin cement to the ceramic restoration. (44) Another important factor that can also affect the overall fracture strength of the restoration is the film thickness of the cement. It was noted that cement film thickness of 300 μm or more significantly reduces the overall fracture resistance of the all-ceramic restoration. (45)

Chapter 2: Study Objectives

2.1 Rationale of the study

There is evidence that crowns created using digital impressions, and CAD/CAM manufacturing fit better than conventionally created crowns. (4) (7) However, no studies have been published to determine the influence of cementation on the fit of digitally and conventionally fabricated crowns.

2.2 Research Question

Do crowns fabricated using digital technologies fit better than conventionally fabricated ceramic crowns after cementation?

2.3 Specific aim of the study

The aim of this study was to use micro-CT to evaluate the 2D marginal fit change as result of the cementation of ceramic crowns manufactured by the following three methods:

- Digital method: digital impression and digital manufacturing (DD)
- Combination method: digital impression and press manufacturing (DP)
- Traditional method: traditional impression and press manufacturing (TP)

2.4 Hypothesis

1 **The null hypothesis (H_0)** of this study was that there is no significant difference in the MG between the three investigated groups before and after cementation.

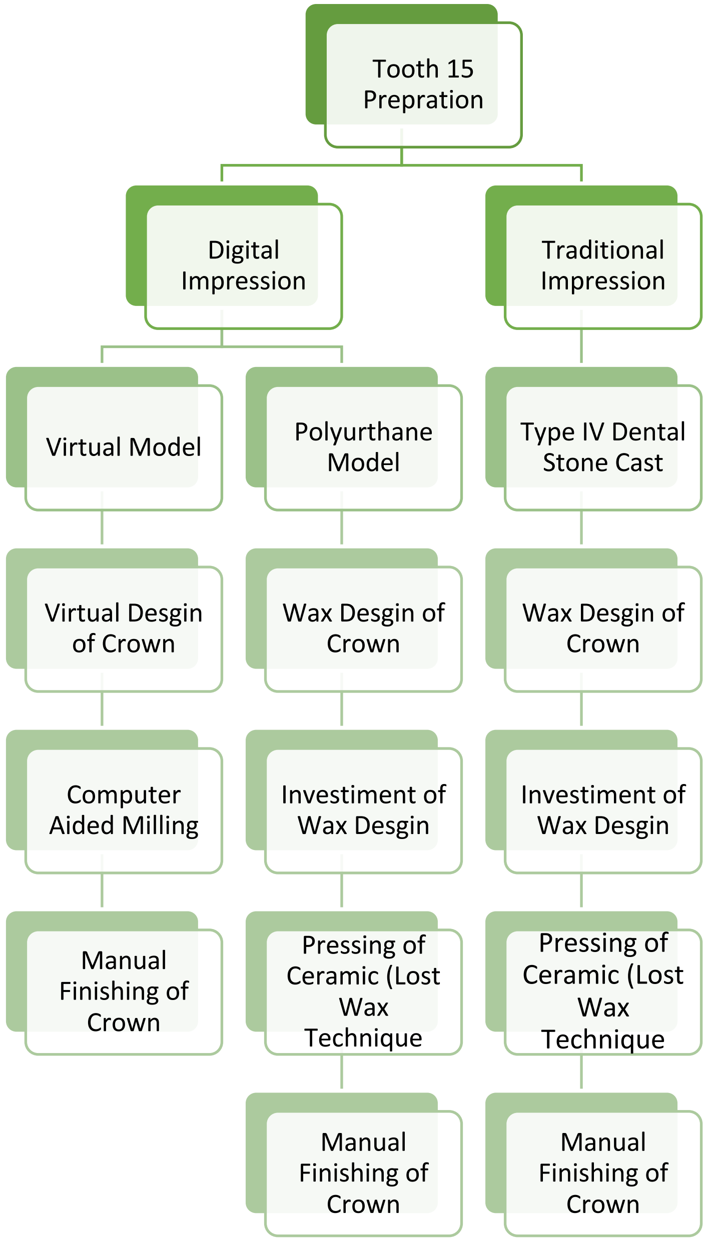
2 **The alternative hypothesis (H_1)** of this study was that there is significant difference in the MG between the three investigated groups before and after cementation.

Chapter 3: Materials and Methods

3.1 Crown Fabrication

A total of 45 LDS crowns were fabricated as part of previous studies as Figure 3. (4)(7) All the impressions were made on a zirconia model; the three experimental groups consisted of: 15 digital impressions and digital crown fabrication (DD), 15 digital impression and traditional crown fabrication (DP), and 15 traditional impression and traditional crown fabrication (TP). A 3M LAVA C.O.S. intraoral scanner (3M, Lexington, KY) was utilized to acquire digital impression of the prepared tooth on the zirconia model. STL files were obtained and emailed to a dental laboratory (Aurum Ceramics, Calgary, Canada) for digital wax up, and designing of the final crown. Duplicate dies of zirconia model die were digitally printed in polyurethane. (4)(7)

Figure 3 Workflow for the fabrication of the fully digital, traditional as well as digital- traditional crowns (4)



3.2 Pre-Cementation Micro-CT Scanning

Forty-five crowns placed on their respective dies, with 3 dies and 3 crowns in each scanning tube, were scanned using a Scanco Medical micro-CT100 scanner (Scanco Holding AG, Switzerland). Scans were developed 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 create serial cross-sectional images of 20 µm resolution.(46) Scan duration was 30 minutes per sample. Filtered back projection reconstruction software that is available with the scanner was used for image reconstruction.

3.3 Unacceptable Crowns and Acceptable Crowns

Although there are multiple studies reporting on crown marginal fit, it is agreed that MG of clinically acceptable crowns should not exceed 120 µm. (1)(2) Crowns with vertical MG >120 µm at more than five points were deemed to be unacceptable and were subjected to clinical adjustments in order to enhance their fitting, while crowns with vertical MG ≤ 120 µm were considered acceptable. Clinical adjustments were done based on fit checker (silicone indicator paste) in order to identify the points of interferences that compromise the seating of those crowns. This was done by application of fit checker in the crown's intaglio surface then seating the crown on the die. After setting of the fit checker, pressure points or points of interference were detected and accordingly adjusted till proper seating was achieved, as shown in Figure 4.

The flowchart shows the crowns investigated with total number of 45 LDS distributed into 3 sets (15TP, 15DP and 15 DD). Four crowns of the TP group and two crowns of the DP group were unacceptable clinically with MG >120 µm at more than five points out of the 20 points investigated per crown. On the other hand, all of the DD group crowns were clinically acceptable.

Figure 4 Fit Checker was used to identify points of interference and achieve proper seating of the crowns on the die.

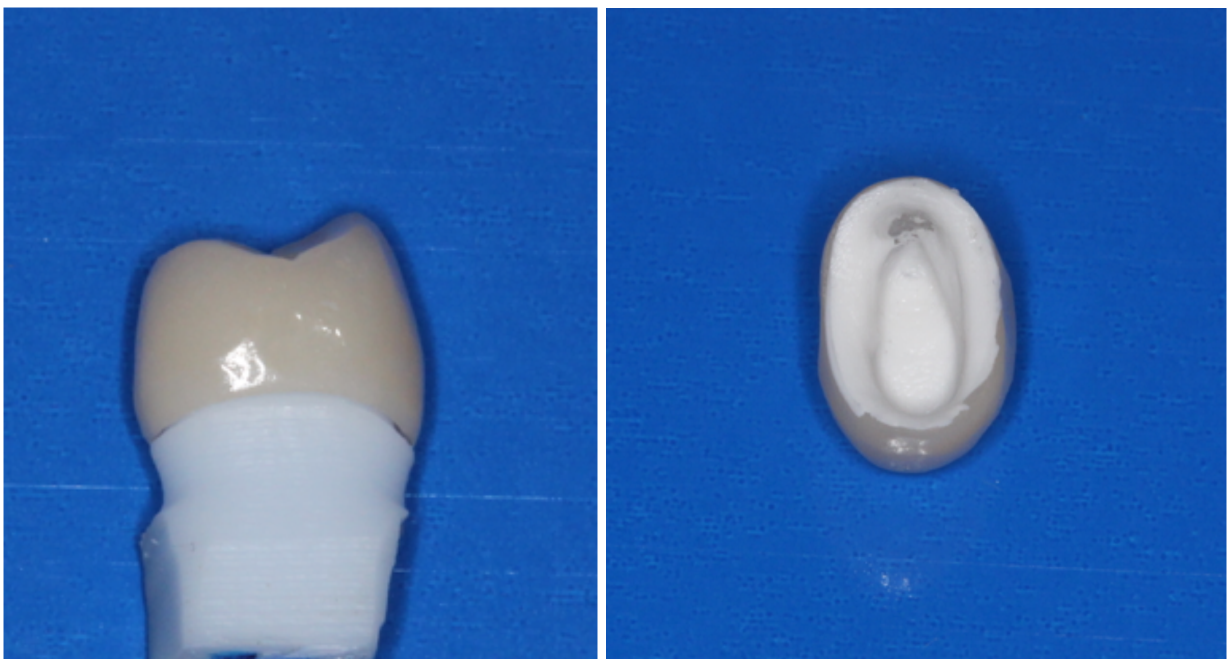
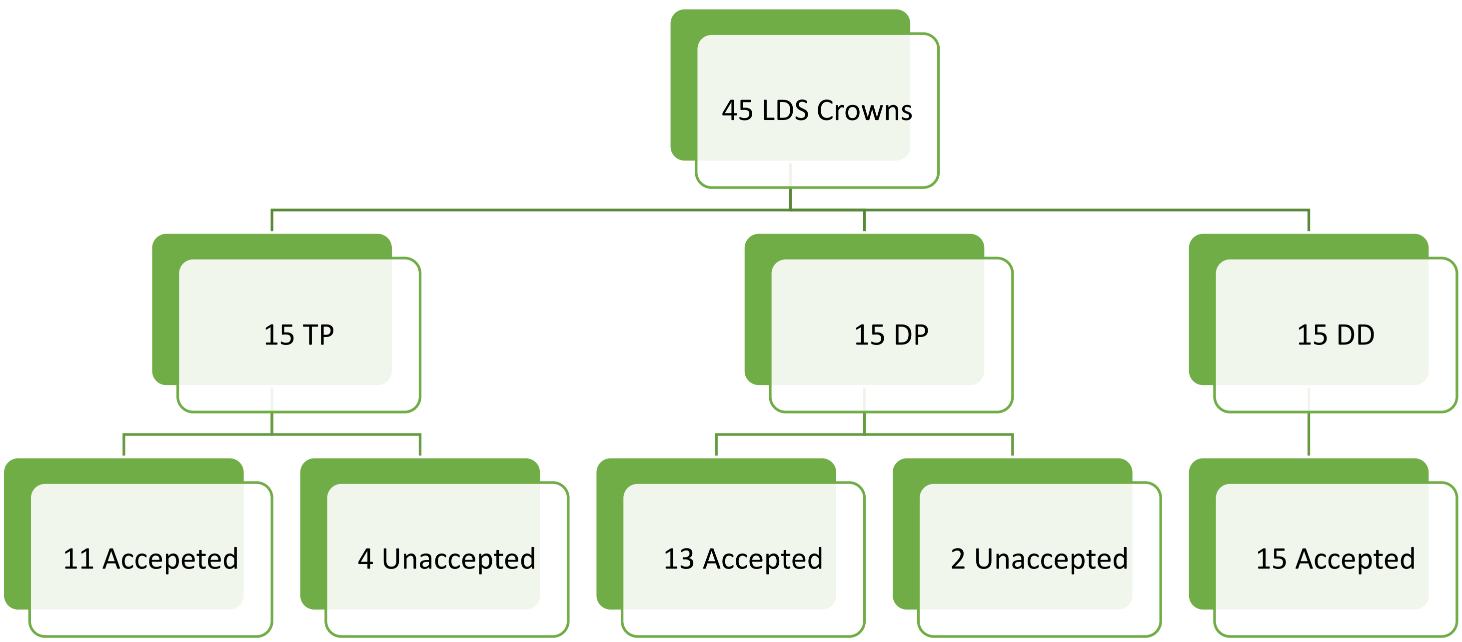


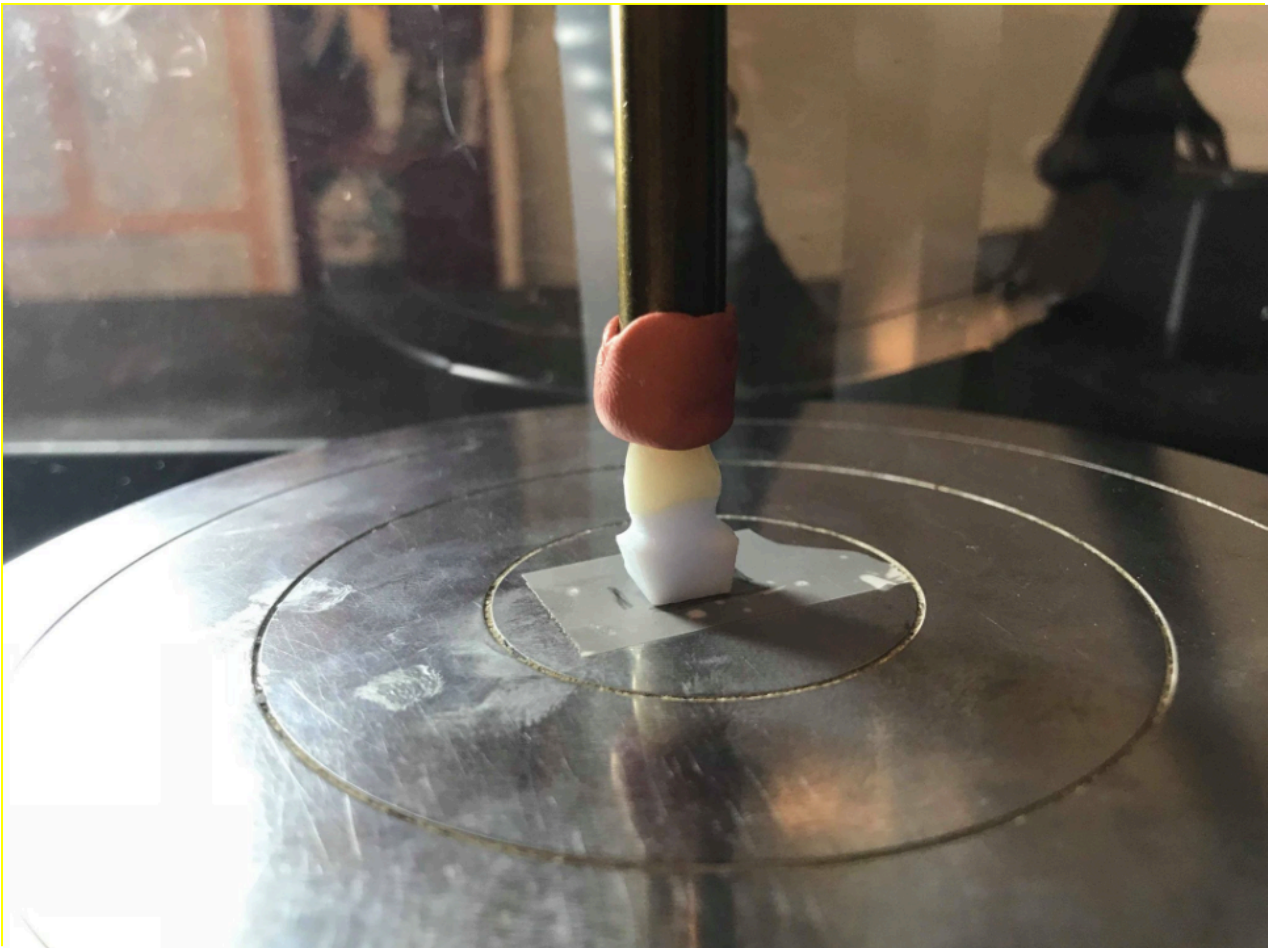
Figure 5 Total Number of crowns included in this study including accepted and unaccepted crowns (15TP-15DP-15DD)



3.4 Crown Cementation

An additional micro-CT scan was performed on the adjusted crowns to measure their marginal fit and to calculate the effect of adjustments. Thereafter, cementation of the crowns to the dies using 3M “RelyX Ultimate” adhesive resin cement was done following the manufacturer’s recommendations. The crowns were seated on the dies using an applied force of 20 N with a universal material testing machine (Instron 4201), as shown in Figure 6.

Figure 6 Crown seating on the die using Universal Materials Testing Machine



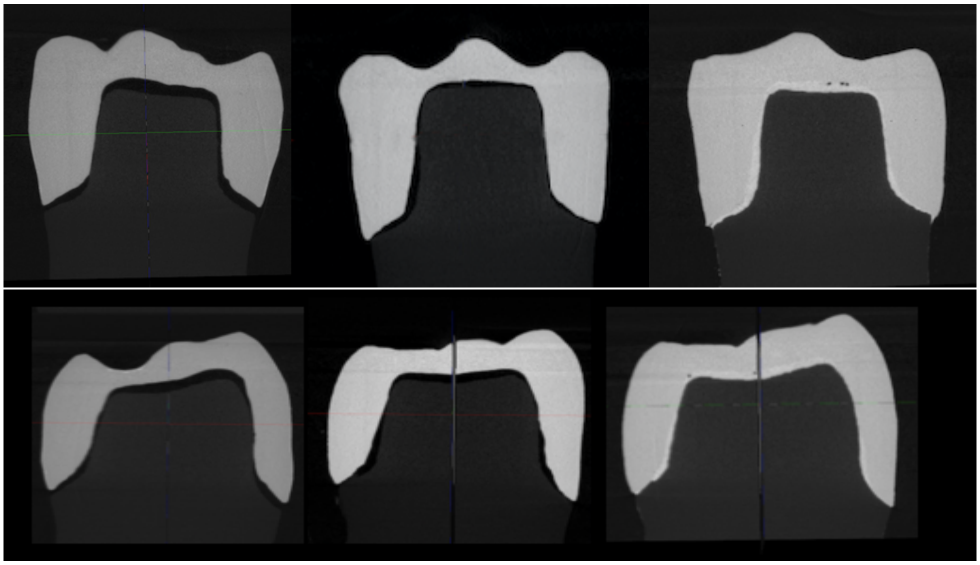
3.5 Sample Size Calculation

A sample size of 15 was based upon a power analysis of a previous studies.(4)(7) This sample size was determined in order to identify significant mean differences of 20 μm among the samples in the presence of 20 μm standard deviation. In this power analysis, γ was set to 0.05 and β was set to 0.20, to allow for 80 % power.

3.6 Micro-CT Measurement

Vertical MG measurement was performed according to Holmes et al. (2), and is defined as "the perpendicular measurement from the cavosurface angle of the tooth to the opposing crown margin". A total of 20 measurements (5 mesial, 5 distal, 5 buccal, and 5 lingual) were made for each crown. Buccal and lingual measurements were made every 50 slices, while mesial and distal measurement were made every 70 slices. This measurement protocol was developed by Mostafa et al. (7) Following a similar protocol, proper alignment of each scan was done prior to assessment. This was done to ensure accurate analysis of the MG at the desired points. Micro-CT measurements were made prior to cementation, and crowns that were adjusted were remeasured, and after cementation as shown in figure 7.

Figure 7 A cross-sectional analysis of the MG a) before adjustment, b) after adjustment, and c) after cementation



a b c

3.7 Statistical Analysis

Effect of cementation on the MG was analyzed using a linear mixed effect model with the interaction Method x Cementation as fixed effect, and Crown as a random effect. Using Crown as a random effect considers for the correlations within each crown with post hoc test. Statistical significance was set at α =0.05.

Chapter 4: Results

A total of 6 crowns (4 crowns in TP group and 2 DP group) had unacceptable marginal fit and required intaglio surface adjustments. After adjustment, all 6 crowns were determined to be clinically acceptable. The MG mean measurements before adjustment was 130 µm, which was reduced to 61 µm after adjustment of the crown's intaglio surface.

The results of the overall vertical MG measurements documented at 20 standardized points per crown and a total of 300 measurement points per group before and after cementation are summarized in Table 3. Crowns fabricated using DD group revealed significantly smaller vertical MG before (30.7 ±16.51 µm) and after (49.96 ± 20.51 µm) cementation, compared to DP (before cementation: 49.89 ±24.35 µm; after cementation:70.78 ±27.35 µm), and TP (before cementation: 49.5±25.31 µm; after cementation: 69.92 ±26.63 µm).

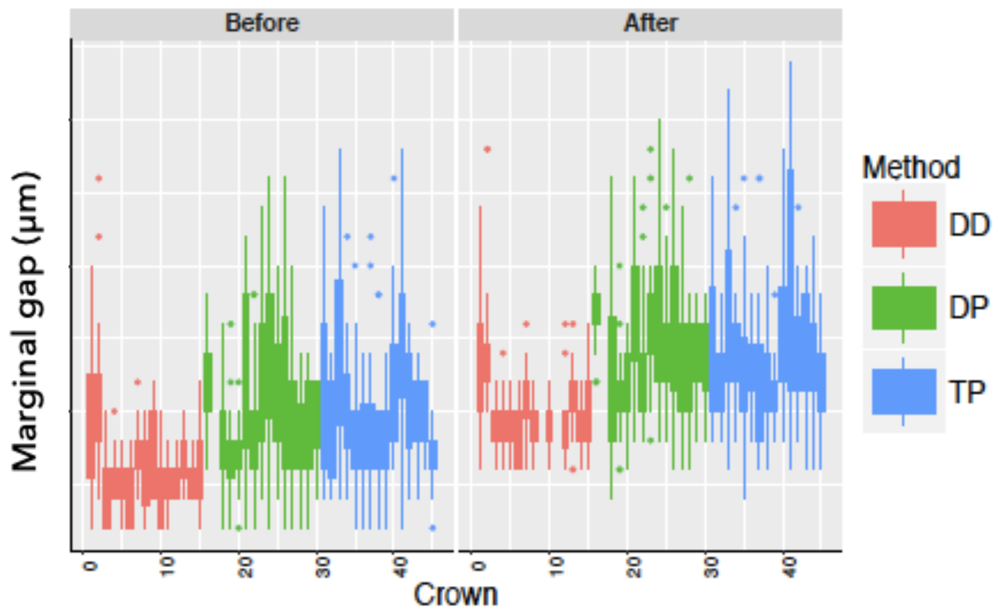
Table 3 Vertical MG before and after cementation, and the difference in marginal gap *(µm)*

Procedure	MG before cementation mean±SD (µm)	MG after cementation mean±SD (µm)	Difference in MG mean (µm)
TP	49.5 ± 25.31	69.92 ± 26.63	20.42
DP	49.89 ± 24.35	70.78 ± 27.35	20.89
DD	30.70 ± 16.51	49.96 ± 20.51	19.26

4.1 Descriptive plots

Descriptive boxplots in Figure 8 show MG measurements for each crown, before and after cementation, from left to right, respectively. Different colors, corresponding to different methods, indicate that MG measurements are higher after cementation for all groups investigated. MG for the DD is lower than that of the DP and TP before and after cementation. The plots also demonstrate that there was variability within crowns, which was considered by the mixed effect model.

Figure 8 MG variability within each crown before and after cementation.



Interaction plots for effect of Method x Cementation on MG (Figure 8 and Figure 9) indicate that there is not a significant interaction effect. The graph shows that MG distance drastically increases after cementation for all the three methods, DD, DP and TP, with method DD exhibiting the smallest MG. MG for the DD method is significantly different than that of the DP and TP before and after cementation. There was negligible difference between the methods DP and TP before the cementation, and this difference becomes only slightly bigger after the cementation. The 95% confidence intervals of the DP and TP groups are overlapping indicative of no statistical difference between DP and TP. The interaction effect Method x Cementation was insignificant, and, therefore, both main effects, Method and Cementation, are expected to be statistically significant.

Figure 9 Interaction plot for effect of Method x Cementation on MG

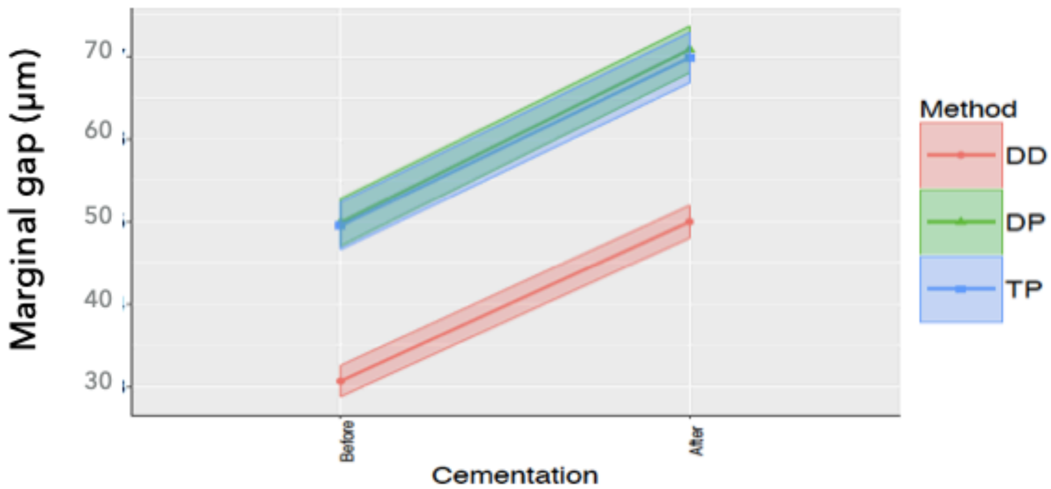
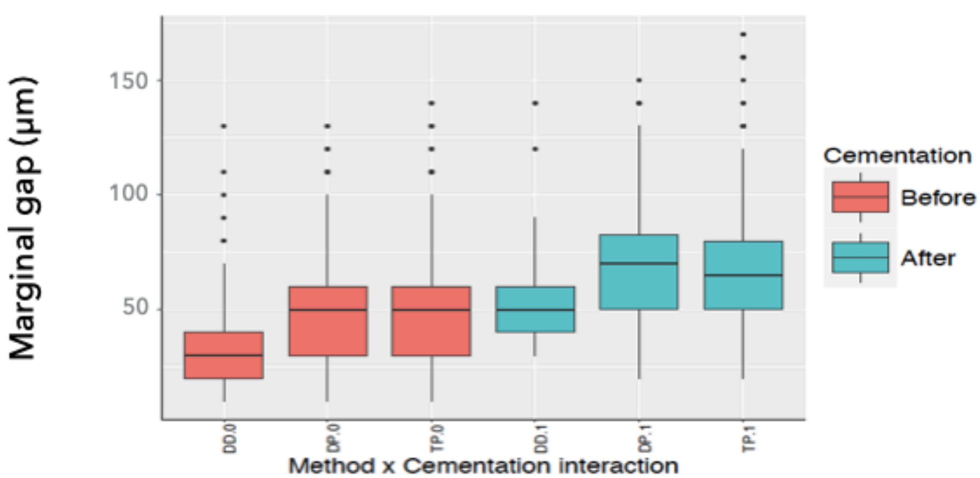


Figure 10 Boxplots of MG by Method x Cementation interaction



4.2 Model fitting

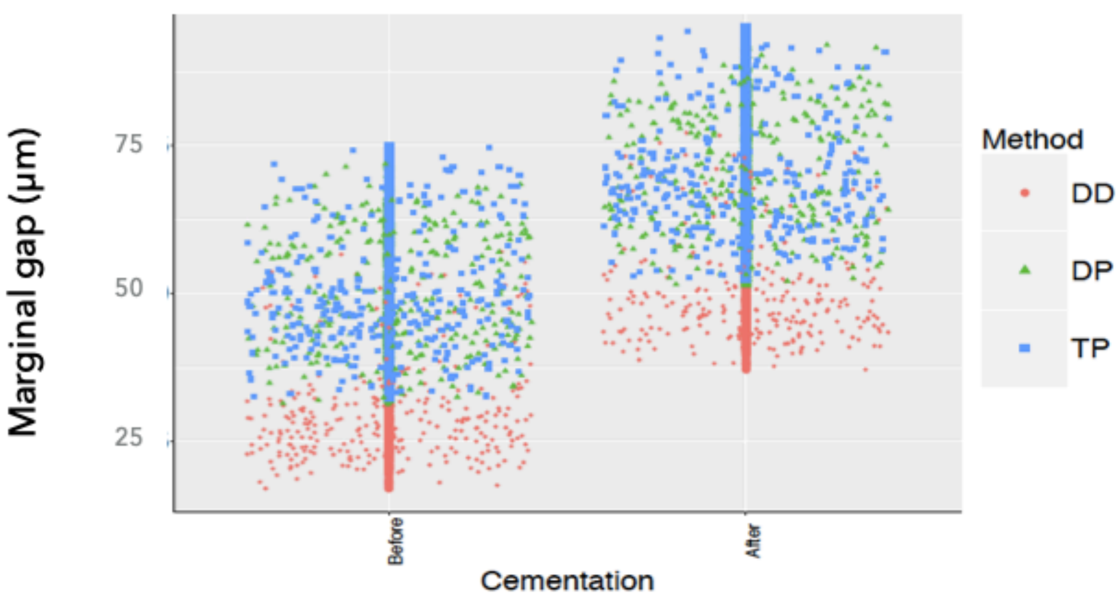
The effect of the interaction Method x Cementation on the MG was tested using a linear mixed effect model with the interaction Method x Cementation as fixed effect and Crown as a random effect (Site and Crown were specified as crossed random effects and also Slice nested within Orientation was specified as random effects). Using Crown as a random effect considers the correlations of the MG within each Crown. The interaction was insignificant according to the likelihood ratio test, and hence we selected the model without the interaction (Table 4).

Table 4 Estimated effects from Model1: MG ~ Method +Cementation + Random Effect (Crown +Site +Orientation /Slice)

	Estimate (µm)	Std. Error (µm)
(Intercept)	30.10	3.10
Method DP	20.10	3.80
Method TP	19.40	3.80
Cementation1	20.10	1.00

The plot in Figure 11 represents a scatterplot of estimated MG from the model by cementation and method, with cementation on x axis and different colors for the three groups. The plot demonstrates that estimated MG is higher after the cementation for all three groups. Furthermore, while group DD (points in red color) had the lowest estimated MG than groups DP and TP, groups DP and TP (green and blue color) were overlapping. Conclusions obtained from the model estimates are consistent with the conclusions obtained from the descriptive plots, which means that the proper statistical model was applied for data analysis.

Figure 11 Estimated mean MG by Method x Cementation interaction



4.3 Post-hoc analysis

Since the interaction Method x Cementation was insignificant and main effects for Cementation and Method were significant, we conclude that cementation significantly affected MG regardless of the method of fabrication. In other words, cementation had an equal effect on MG for all fabrication methods investigated. The post hoc-analysis showed that the mean MG estimate before cementation was 43.30 µm (95 % CI = (0.0369-0.0497)) and after cementation was 63.50 µm (95 % CI = (0.0569-0.0698)). The estimated difference of the mean MG before and after cementation was significant, 20.10 µm (95 %CI= (-0.022- -0.0182)) which indicated that the MG increased on average by 20.10 µm for all of the three groups (Tables 5).

Table 5 Estimated differences in MG before and after cementation in (*µm*)

Contrast	Mean	Lower. CL	Upper. CL
1-0	20.10	22	18.2

4.4 Unacceptable crown as a result of cementation

Overall, two crowns out of 45 cemented crowns were excluded based on MG readings which exceeded the clinically acceptable measure of 120 µm. These crowns, which were in the DD group, were eliminated from the study. These crowns were improperly seated during cementation process.

Chapter 5: Discussion

The objective of this study was to determine the effect of adjustment and cementation on the MG of digitally and conventionally fabricated crowns. The null hypothesis of this report that there is no significant difference in the MG between the three investigated groups before and after adjustment and cementation was rejected. The mean MG of crowns investigated ranged between 43.30 µm before cementation and 63.50 µm after cementation and were clinically acceptable. The MG were similar to those reported in previously published studies. (47) (48) In the literature, there are different numbers reported regarding the MGs of different ceramic systems. (34) An explanation of these variations could be due to the different measurement techniques, number of measurements per crown, different types of cements used and different sample sizes.

In this study, micro-CT was utilized as the measurement technique as it was considered as a reliable and a non-destructive approach that permits high-resolution analysis of both marginal and internal gap. Multiple studies have utilized micro-CT measurements as it permits 2D and 3D evaluation. (27) (49) (50) Mostafa et al. (7) reported that the 2D marginal gap of the fully digitally manufactured crowns group was (33.3±19.99 µm) compared to the digital-pressed (54.08±32.34 µm) and the traditional pressed (51.88±35.34 µm) groups. The findings of Mostafa et al. (7) support the outcomes of our study since the marginal gap before cementation was identified as Crowns fabricated using DD group revealed significantly smaller vertical MG before (30.7 ±16.51µm), compared to DP (49.89 ±24.35 µm) and TP (49.5±25.31 µm).

Several studies reported that cementation causes significant increase of the MG (29) (30) (50) (51) Demir et al. (50) explored the effect of cementation on the MG of restorations fabricated using

Cerec inLab feldspathic porcelain, Cerec inLab aluminum oxide, and traditional pressed LDS. The study used micro CT to assess the MG before and after cementation in the three groups investigated. It was shown that significant increase in the MG occurred as a result of cementation, with MG varying between 50 to 160 µm before cementation and 140 to 340 µm after cementation resulting in a marginal gap change of 90 to 180 µm. However, the increase of MG as result of cementation in our study only ranged between 18 to 22 µm. This variation in the effect of cementation on the MG can be explained as a result of lack of proper seating technique of the crowns during cementation, which was not clearly explained in the Demir's study. It is important to mention that Demir's study included 5 teeth per group and performed 80 measurement per crown. There was no clear explanation for the reason of using 80 points and how those points were selected.(50) On the other hand, in our study, 15 crowns per group were used and the rational of selecting 20 measurement points per sample was clearly explained.

Borges et al. (21) studied the marginal fit of IPS e.max Press, Cergogold and In-Ceram crowns after cementation with RMGI or resin cement. A light microscope was used to measure the MG at 16 points around the crown. The measurements were done 4 times at each of the 16 points. It was concluded that there was a significant increase in the value of the MG of all ceramic systems after cementation, irrespective of cement. The IPS e.max Press crowns cemented by either type of cement resulted in a larger MG with average values of 82.87 µm before cementation and 121 µm after cementation, resulted in a marginal gap change of 38.13 µm. This agrees with the findings of our study that cementation has a direct effect on the MG.

Wolfart et al (51) reported that adhesive cementation significantly increased the MG of heat pressed LDS crowns from 96 μm before cementation to 130 μm after cementation, resulting in a marginal gap change of 34 μm. In this study, a replica of the margins of the restorations was used for SEM analysis. In this way, the MG can be evaluated before and after cementation. The main limitations of the replica technique are deep subgingival portions of the preparation, mostly interproximal, that often cannot be evaluated, as well as the defects in the silicone material during replication of the margins. This study showed similar results as those reported in the literature, with regards to an increase in the MG in all groups cemented with resin luting cement. The reported increase in MG was on average 13-50 μm (14) (51)(52)(53), which is comparable to our study findings of average increase of 20 μm as a result of cementation. Guess et al. (53) described an average increase in the MGs after cementation of Vita-PM9 (VP, Vita- Zahnfabrik) and heat-pressed IPS-e.max-Press* (IP, *Ivoclar-Vivadent), as well as CAD/CAM fabricated IPS-e.max-CAD* (IC, Cerec 3D/InLab/Sirona) allceramic materials with resin luting cement (Variolink II). In their study, only finger pressure was applied on crowns during cementation, which could introduce an unstandardized approach for the crown seating. Replica technique was used for the assessment of the MG, which was reported to increase as result of cementation by 17.35 μm for IPS-e.max-Press, 14.45 μm for IPS-e.max-CAD and 13.25 μm for Vita-PM9. This agrees with the findings of our study that cementation resulted in average MG increase of 20 μm. (53)

Sakrana et al.(14) inspected the fit of two types of all-ceramic single crowns and indirect composite resin full coverage crowns. They reported an increase in the MG of 24-40 μm after cementation using stereo microscope. In this study a total number of 12 measures were obtained per crown. The 12 measures were based on 3 measures at 4 different locations (mid facial-mid distal-mid lingual- mid mesial). In this study, the cross-sectional technique was used in order to obtain the measurements since it is a simple and fast method. However, this method introduces multiple potential errors during the sample sectioning that can result in inaccurate readings. (14)

Stappert et al. (54) indicated that the MG of e.max press restorations increased by from 20-50 μm after cementation with a resin luting cement (Variolink II). Replica method was used for the assessment of the MG before and after cementation. Stereo light microscope was used for MG analysis using 200x magnification. There was no specific number of measures per tooth due to anatomical variations. Yet, an average number of 400-500 measures per tooth were done. In our study, total number of 20 measures were included, based on mesiodistal and buccolingual sectioning of each crown and use of 2 measures per slice.

The main finding that was identified in this study as well as other study that cementation resulted in an increase in the MG. This can be explained as a result of the cement film thickness which consequently increase the MG of indirect restorations. Kious et al. (55) investigated the film thickness of different luting agents. In their study, a comparison of film thicknesses of six different cements was done. The cements investigated included 2 self-adhesive resin (Maxcem and RelyX Unicem) cements, 2 resin-modified glass ionomers (FujiCEM and RelyX Luting Plus), 2 composite resin (Panavia 21 and RelyX ARC). They reported that all cements investigated offered film thickness of less than 26 μm at 2 minutes and under 30 μm at 3 minutes. Considering the results of this study and the different numbers of increase in the MG, ranging between 15- 50 μm as a result of cementation, it can be concluded that the main reason of the increase in the MG of indirect restorations is film thickness of the luting agent. Considering the findings of Kious et al.

(55) study as well as Kale et al (8), who reported that 50 μm cement space resulted in superior fit compared to 30 and 40 μm, study it can be determined that both the cement film thickness as well as the cement space have a direct influence on the seating of indirect restorations which accordingly influence the fit. In our study, the increase in the MG post cementation can be explained as a result of the film thickness of cement, yet this increase was not clinically significant.

One important factor to consider is the amount of cement applied and the pressure or force applied on the crowns during cementation. Excessive cement application can result in excessive increase in the MG which does not reflect the true effect of proper cementation. Improper seating or lack of adequate force during seating of the crowns can also result in increased MG. This was seen in our study, since 2 crowns of the DD group were excluded due to improper seating of the crowns during cementation, which resulted in increased MG and the 2 crowns were deemed unacceptable.

Chapter 6: Conclusion

6.1 Summary and Conclusion

This study evaluated the impact of adjustment and cementation on the MG of LDS crowns produced with traditional impression and traditional pressed manufacturing (TP), digital impression and digital manufacturing (DD) and digital impression and traditional pressed manufacturing (DP). It was noted that all the crowns in the fully digital (DD) group were clinically acceptable and did not require any clinical adjustments of the intaglio surface prior to cementation. In the DP group, only two crowns required clinical adjustments. On the other hand, the TP group had four crowns that required clinical adjustment prior to cementation. The null hypothesis was rejected as result of the finding of this study, Clinical adjustment to the intaglio surface of the crowns that were deemed unacceptable resulted in a decrease in the MG. Cementation significantly increased the MG of all investigated crowns, regardless of the method of fabrication by average of 20.10 μm. DD group resulted in significantly smaller vertical MG than DP and TP groups, both before and after cementation. The mean MG for all crown groups (before and after cementation) were within the clinically acceptable range of MG.

6.2 Limitations

This study only investigated the effect of cementing e.max crowns fabricated with DD, DP, and TP techniques and cemented with RelyX-Ultimate cement. Therefore, the outcomes may not be applicable to other restorations or cements. The MG measurements were done using micro-CT, which offers a greater level of accuracy than microscopic measurement technique. Micro-CT also offers non-destructive, repeatable, and reproducible measurement technique. However, a main disadvantage of this method is image artifacts, which are triggered by the variation in the coefficient of radiation absorption among the different materials inspected including the die, the crown and the cement. The MG was measured at 20 different points for each crown. The points selection was based on slicing the images into 5 slices buccoligually and 5 slices mesiodeistally and have 2 measures per slice. This in vitro study was free of the clinical challenges that include the presence of soft tissues and saliva, which make intraoral tooth preparation and impression fabrication more challenging. As such, the results may have decreased external validity.

6.3 Future Directions

Future studies are essential to determine the in-vivo MGs of different ceramic crowns fabricated using various techniques, before/after adjustments and before/after cementation with different types of resin cements.

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