Microleakage Assessment of CAD/CAM Crowns with Various Marginal Fit Parameters

A Thesis

Presented to the Faculty of Tufts University School of Dental Medicine

in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Dental Research

By

Alaa W. AlQutub

April 2015

THESIS COMMITTEE

Thesis Advisor

Ali Muftu, D.M.D, M.S.

Professor

Department of Prosthodontics and Operative Dentistry

School of Dental Medicine

Tufts University

Committee Members

Matthew Finkelman, PhD

Associate Professor

Department of Public Health and Community Service

Tufts University School of Dental Medicine

Hans-Peter Weber, D.M.D., Dr. Med. Dent.

Professor and Chair

Department of Prosthodontics and Operative Dentistry

Tufts University School of Dental Medicine

Ekaterini Antonellou, D.M.D., M.S.

Associate Professor

Department of Prosthodontics and Operative Dentistry

Tufts University School of Dental Medicine

ABSTRACT

Aim & Hypothesis

This study aims to assess the amount of microleakage of CAD lithium disilicate crowns with different marginal fit settings and different finish line locations using E4D Dentist System. It is hypothesized that the amount of marginal microleakage for crowns fabricated at 0 mm and 0.25mm (factory default) marginal ramps will be higher than the crowns fabricated at 0.75mm marginal ramp. Moreover, the amount of marginal microleakage will be higher in dentin (below CEJ) than enamel (above CEJ).

Materials & Methods

A total of 51 extracted premolars received full crown preparations, and samples were randomly divided into 3 groups. All teeth were scanned with the E4D system and the crowns were designed with different marginal ramp settings for each group. Crowns were milled out of IPS e.max blocks and cemented using Rely-X Ultimate. Samples were subjected to thermocycling for 5,000 cycles and immersed in 50% silver nitrate dye before being sectioned from mid buccal to mid-lingual. Microleakage was assessed under a stereomicroscope at x10 magnification.

Results

The difference in microleakage for the three groups was not statistically significant ($p>0.05$). Dentin margins exhibited significantly more microleakage than enamel margins.

Conclusions

The marginal ramp setting has no significant effect on the amount of microleakage for crowns fabricated with the E4D scanning and design system. In addition, placing the preparation finish line on enamel reduces the amount of microleakage compared to dentin.

DEDICATION

To my husband and my best friend, Marwan. No words could express my appreciation for the sacrifices and the encouragement that you always provide. I couldn’t achieve my dreams without your support and unconditional love. Therefore, I dedicate all the success in my life to you.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Prof. Ali Muftu for his motivation and guidance.

My sincere thanks also goes to Dr. Matthew Finkelman for his continuous support and encouragement.

I also would like to acknowledge the rest of my thesis committee: Prof. Hans-Peter Weber and Dr. Ekaterini Antonellou.

Special thanks to Dr. Masly Harsono who always offered help throughout my research.

I would like to thank my family: my mother and two angel sisters for their prayers and endless emotional support.

Also, I thank my second family at the Implant Center, TUSDM for being there for me and for offering me the time to work on my master research.

Last but not least, I am grateful to Saudi Arabian Culture Mission (SACM) for the scholarship and the opportunity to proceed my postgraduate studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CAD/CAM ……………………...Computer-aided design and computer-aided manufacturing

FPDs…………………………….. Fixed partial dentures

3-D………………………………..Three dimensional

IOD ………………………………IntraOral Digitizer scanner

USPHS……………………..…… U.S. Public Health Service

CEJ……………………………….Cemento-enamel junction

Ni-Cr……………………………   Nickel-chromium

ZP………………………………… Zinc phosphate

RMGI……………………………... Resin-modified glass-ionomer

RC…………………………………. Resin cement

ZrO_2……………………………......Zirconium-dioxide

CrCo………………………………. Cobalt-chromium

ISO…………………………………International Organization for Standardization

GEE………………………………... Generalized estimating equations

LIST OF SYMBOLS

n…………………………………………………………………………………….Sample size

p…………………………………………………………………………………… *P*-value

μm…………………………………………………………………………………..Micrometer

Microleakage Assessment of CAD/CAM Crowns with Various Marginal Fit Parameters

Introduction

Historical background

After its use in various industries for more than 10 years, computer-aided design and computer-aided manufacturing (CAD/CAM) technology was introduced to the dental field in the 1980s.[1, 2] CAD/CAM technology in dentistry was pioneered by Dr. Bruce Altschule in the United States, Dr. Francois Duret in France, Dr. Werner Mormann, and Dr. Marco Brandestini in Switzerland in the 1970s.[1, 3]

In 1984, based on an optical impression of an abutment tooth, Dr. Duret produced the first dental CAD/CAM single unit full-coverage restoration with the functional shape of the occlusal surface and marketed his system as Sopha Bioconcept system (Sopha Bioconcept, Inc, Los Angeles, CA 90064). However, due to its complexity and high cost, this system did not succeed commercially in the dental market.[1, 3, 4]

In 1985, based on a similar concept, Mormann and Brandestini developed the first commercially available dental CAD/CAM system.[5] They fabricated the first chair-side inlay using a combination of an optical scanner and milling device and called the device CEREC® (Sirona Dental Systems, Charlotte, NC 28273). This system development was innovative because it permitted same-day ceramic restorations. The first CAD/CAM for composite veneered restorations were used by Dr. Andersson, the developer of the Procera® system (NobelProcera, Nobel Biocare, Zurich, Switzerland).[2, 3, 6]

In the 1990s, research concentrated on direct application of CAD/CAM technology for crowns and fixed partial dentures (FPDs).[2] Recently, CAD/CAM systems have been developed to provide FPDs, implant abutments and framework patterns for removable partial dentures and complete denture bases.[3]

In 2008, the E4D Dentist System ™ (D4D Technologies, Richardson, TX) was introduced as the only CAD/CAM system that uses a true laser for scanning hard and soft dental tissue, impression material, occlusal registration material, and dental stone. It presents the working principle of optical coherence tomography and confocal microscopy.[7] This system consists of a laser scanner, also known as the IntraOral Digitizer scanner (IOD), a design center and milling unit.[3] (Fig. 1) It has the ability to design multiple teeth at the same time, and it is considered the only other system besides CEREC® that permits same-day in-office restorations.[8, 9]

Traditional versus CAD/CAM techniques

The conventional fabrication process of porcelain-fused-to-metal crowns and FPD restorations is based on duplication of the prepared teeth via elastomeric impressions and stone casts. A wax pattern is made on the die(s), and a metal substructure is then fabricated using the lost-wax casting technique, followed by application of veneering porcelain.[10] (Fig. 2)

Currently, CAD systems construct virtual models based on data acquisition from intraoral digital impressions or via scanning of a traditional impressions or casts. The virtual model is used either to print a solid model via additive or subtractive manufacturing techniques, on which the desired restorations are made in professional dental laboratories. An alternative, in-office approach is to design the restoration digitally on the virtual model and mill it out of a block using a milling machine specific to the system. CEREC® is one of the earliest systems that utilized the in-office concept and became popular due the reduced treatment time in patient care.[3]

Other CAD/CAM concepts that enable dentists or laboratory technicians to outsource certain specialized procedures to processing centers using network connections have also been introduced.[2] The Procera® system is the first system to apply the outsourced fabrication of all ceramic crowns and currently has a network between the processing centers in Sweden, Canada, Japan, and the United States.[11] (Fig. 3)

Advantages of CAD/CAM technology include elimination of potential sources of errors such as impression distortions, die stone volumetric modifications, or casting imperfections.[12] Furthermore, it reduces treatment time since patients can often receive their definitive restorations in a single visit if an in-office milling machine is used.[3] Labor reduction, ease of automation, lack of cross-contamination and ease of data storage compared to storage of stone casts for dental laboratories are also advantages of CAD/CAM technology. In addition, due to the availability of newer all ceramic materials, CAD/CAM restorations offer better esthetics compared to percaline fused to metal restorations.[1, 2, 9]

Some challenges associated with dental CAD/CAM technology include software design, operator skill, and milling technologies, and ability of generating restorations that integrate functionally, esthetically, and biologically with the existing dentition as well as the entire stomatognathic system.[12]

Performance of CAD restorations

CAD/CAM restorations have been suggested as being superior to traditional techniques in terms of quality control, esthetics, time and accuracy.[3, 13] Recently, two main dental materials were introduced as innovative CAD/CAM ceramics: 1) lithium disilicate ceramics such as e.max CAD and 2) hybrid materials (partially ceramic and partially resin composite) such as Lava Ultimate.[14] Success and survival rates of these restorations have been reported in the literature.

In a systematic review of 16 articles that involved 1,957 restorations, Wittneben et al.[8] investigated the long-term clinical survival rates of single tooth restorations fabricated with CAD/CAM technology versus conventional restorations. The authors found no significant differences in 5-year survival rates between CAD/CAM single-tooth Cerec 1, Cerec 2, and Celay restorations and conventional restorations.

Henkel[15] conducted a blinded study on 117 subjects, fabricating one crown based on conventional impressions using standard trays and impression materials and another based on digital impressions for each subject. He reported that in nearly 70% of the cases, participating dentists preferred the marginal fit, contacts, occlusion, and time of adjustment of crowns made with CAD/CAM technology over crowns generated from conventional impressions.

Bindl et al.[16] evaluated the clinical quality of CAD/CAM-generated posterior crowns using the Cerec 2 CAD/CAM system and two different materials. Comparing 19 In-Ceram Spinell core crowns to 24 In-Ceram Alumina core crowns, they defined the clinical quality of both CAD/CAM generated crowns as excellent after a mean service time of 39 ± 11 months,

A nonrandomized longitudinal clinical trial was conducted by Fasbinder et al.[17] to evaluate the clinical performance of the IPS e.max CAD glass ceramic material (Ivoclar Vivadent Amherst, N.Y.) for chairside CAD/CAM-generated crowns cemented with two different cements. The crowns in the control group (n=23) were cemented with a self-etching, dual-curing cement (Multilink Automix Ivoclar Vivadent, NY, Amherst, NY) with a self-etching primer and adhesive, while the crowns in the second group (n=39) were cemented with an experimental self-adhesive, dual-curing cement (EC) developed by Ivoclar Vivadent. Two examiners used modified U.S. Public Health Service (USPHS)[18] criteria to evaluate the crowns at baseline, six months, one year and two years. The results revealed no incidences of crown fracture or surface chipping, and the authors concluded that lithium disilicate crowns show a good performance after two years of clinical service.

Bindl and Mörmann[19] compared monolithic ceramic crowns (Vitablocs Mark II, Vident, Brea, CA) fabricated with a CEREC 2 unit, with layered ceramic crowns (Vita In-Ceram Spinell, Vident) to assess the survival rate of the crowns in term of fracture. All crowns (n =18 in each group) were rated using (USPHS)[18] criteria at baseline and after a service time of 2–5 years. They reported that there was no significant difference between the two crown types for any of the USPHS scores. The survival rates were 91.7% for In-Ceram Spinell and 94.4% for Mark

II. They concluded that the clinical performance of mono-ceramic crowns were similar to ceramic core crowns.

Use of different success criteria, continuous change in restorative materials, and updates to CAD/CAM systems create challenges for the clinician to interpret the literature critically. Very often the CAD restorations are evaluated based on the accuracy of their internal and marginal fit over the prepared teeth.

Marginal accuracy of CAD restorations

Reporting and comparing studies related to marginal fit is confusing due to the lack of a clear definition of restoration fit among investigators. Holmes et al[20] reported that restoration fit can be defined best in term of the 'misfit' measured at various points between the restoration and the tooth including internal gap, marginal gap, overextended margin, underextended margin and absolute marginal discrepancy. They also stated that the absolute marginal discrepancy, which is the angular combination of the marginal gap and the extension error, will best reflect the total restoration misfit.

The American Dental Association requires that the fit of a dental restoration on the supporting abutment has to be within a range of 50 μm accuracy.[21] In vitro studies have revealed mean marginal gaps of 64–83 μm in CAD/CAM-generated all-ceramic single tooth restorations. [22, 23] Marginal discrepancy in the range of 100 μm have been reported to be clinically acceptable in term of longevity of the crowns.[24, 25]

Reich et al.[26] conducted a study to test the hypothesis that the marginal and internal fit of CAD/CAM fabricated all-ceramic three-unit fixed partial dentures (FPDs) can be as good as with metal–ceramic FPDs. They fabricated 24 all-ceramic FPDs and randomly subdivided them into three groups using the Digident CAD/CAM system (DIGI), the Cerec Inlab system (INLA) and the Lava system (LAVA). The means ± SDs of marginal gaps were 92 ± 52 μm for DIGI, 80 ± 50 μm for LAVA, 77± 44 μm for INLA and 67 ± 45 μm for conventional FPDs. The study results suggest that the accuracy of CAD/CAM generated three-unit FPDs is satisfactory for clinical use and that all CAD/CAM systems tested can compete well with conventional systems for clinical fit.

Nakamura et al.[27] examined the effect of the occlusal convergence angle of the abutment and the computer's luting space setting on the marginal and internal fit of Cerec 3 CAD/CAM all-ceramic crowns. A total of 45 mandibular second premolar all-ceramic crown with nine conditions were established by combining three different settings of luting space (10, 30, and 50 μm) with three different occlusal convergence angles (4, 8, and 12 degrees) of the abutments. After seating, the marginal gaps and the internal gaps were measured. They found that when the luting space was set to 10 μm, the marginal gaps of the crowns were greater than when it was set to 30 or 50 μm. When the luting space was set to 30 or 50 μm, the marginal gaps ranged from 53 to 67 μm and were not affected by the occlusal convergence angle of the abutment. They reached the conclusion that when the luting space was set to 30 μm, crowns with a good fit could be fabricated on the Cerec 3 system, regardless of the occlusal convergence angle of the abutment.

Neves et al.[24] reported that a difference in marginal fit between the heat-pressing process and the CAD/CAM systems could attribute to multiple steps of the heat pressing technique.

Cementation of CAD restorations

One factor that affects the clinical fit and contributes to the success of CAD restorations is the cementation process. During cementation of a restoration, incomplete seating may occur if adequate space for cement is not provided internally. For traditional restorations, various thicknesses of die spacer are applied on the die to provide space for the luting agent.[28-29] This space helps to reduce resistance of the cementing material to flow, which facilitates complete seating of the restoration and provides a good marginal seal. The resistance of cementing materials to flow may result in incomplete seat of the crown which may create marginal discrepancies and subsequent microleakage.[31]

On the other hand, with the CAD/CAM technology the clinician has the ability to set the internal 'cement space' parameters in the design software. For instance, when using the E4D Dentist System, the virtual die space defines the internal fit of the final restoration to the die or preparation. It is one parameter that can be set as a system default ahead of time or can be changed according to each case. These parameters include not only occlusal and axial surfaces of the preparation, but also the finish line (marginal ramp). In other words, all three parameters can be selected independently.[13] Therefore, if the luting space setting is too small, the crown might contact the abutment. In contrast, the cement thickness might become too great if the luting space setting is too large.

It is suggested that CAD/CAM ceramic materials have to be adhesively luted to tooth structure. The adhesion between restoration and tooth structure is based on the combined effects of micromechanical interlocking and chemical bonding. Interprismatic and intercrystalline interlocking on enamel and hybridization on dentin are the main retention elements in adhesive luting. Hydrofluoric acid is mainly used to increase the surface area and create microporosities within the glass phase of the ceramic substrate. Chemical bonding is achieved by the use of a silane agent through a bifunctional coupling molecule. Recently, a novel self-bonding resin luting agent, RelyX Unicem, has gained attention due to its ability to bond to tooth structure without using separate etchant and adhesive protocols.[14, 31] However, the optimal approach for cementation on enamel is still considered etch-and-rinse, whereas self-adhesive resin cements are less favorable. In case of dentin, the self-etch approach is reported to be the favorable method.[14, 32]

Frankenberger et al.[14] evaluated the potential of novel CAD/CAM materials to bond to different luting cements. They used four CAD/CAM materials: e.max CAD (lithium disilicate glass ceramic; Ivoclar Vivadent, Schaan, Liechtenstein), Celtra Duo (zirconia-reinforced lithium disilicate ceramic; Dentsply DeTrey, Konstanz, Germany), Lava Ultimate (resin nano ceramic; 3M ESPE, Neuss, Germany), and Enamic (resin infiltrated ceramic; Vita, Bad Säckingen, Germany).They also tested six different pre-treatment methods: silane, sandblasting, sandblasting + silane, hydrofluoric acid (HF), HF + silane and control untreated group. Luting agents under investigation were :1) Calibra Esthatic Resin Cement bonded with Prim&Bond XP + Self-Cure Activator (Dentsply DeTrey); and 2) RelyX Unicem (3M ESPE).

They found that, when untreated, RelyX Unicem performed better ($P < 0.05$). Moreover, sandblasting was the most effective method for Lava Ultimate ($P < 0.05$), whereas all other materials showed best bonding when HF etching was used, followed by silane treatment. The authors concluded that when following the manufacturers' recommendations for the pretreatment protocol, novel CAD/CAM materials showed a promising bonding capacity to different types of luting resin cements.

However, in a study conducted to evaluate the cervical fit of all ceramic crowns (IPS e.maxPress, Cergogold, and In Ceram) on bovine teeth with two luting agents before and after cementation, Borges et al.[33] prepared 90 bovine incisors for full coverage crowns with 30 crowns for each ceramic system. Then, 15 crowns of each ceramic system were luted with resin cement (Variolink II) or resin-modified glass ionomer cement (RelyX luting), and the marginal discrepancy was measured. The three ceramic systems showed a cervical fit after cementation that was significantly inferior to the cervical fit before cementation. It can be concluded that both cements studied increase the marginal discrepancy between the crown and the preparation for the three ceramic systems evaluated.

Microleakage

Although the principles of resin-based luting cementation will provide a chemical bond in addition to micromechanical bonding, the resistance of this bond to microleakage for various marginal seating parameters is not well known. Minimizing the marginal gap is also necessary to reduce cement dissolution and the potential for microleakage.[23,24] Microleakage is classically defined as the diffusion of substances, such as bacteria, oral fluids, molecules and/or ions, into a fluid-filled gap or a structural defect that is naturally present or that occurs between restorative materials and tooth structure.[31,34-37] The amount of microleakage is influenced by many factors such as complex interactions between variables related to dental the restoration, luting agent and tooth structure.[38] The type of tooth substrate has an effect on the degree of microleakage. Studies have shown that bonding to enamel is more predictable due to its higher mineral content than resin infiltration in dentin, which is characterized by a much higher hydrated collagen structure and less mineralized tissue.[39, 40] Bonding studies to dentin have demonstrated deficiencies on the sealing capacity compared to that of enamel.[41-43]

Different methods have been utilized to evaluate microleakage in tooth-restoration interface in vitro. One of these methods is thermocycling. Thermocycling is an in vitro process of subjecting an extracted tooth carrying a restoration to temperature extremes that comply with those found in the oral cavity. This technique is usually combined with the use of tracers such as dyes, radioactive isotopes, chemical tracers, and bacteria which aid in the detection of microleakage. The amount of leakage is then quantified via imaging or measuring of the affected areas in sectioned samples.[44]

Trajtenberg et al.[31] compared the amount of microleakage of bonded ceramic crowns using three different types of self-etching adhesive systems with and without a die spacer. They prepared 18 molars for all ceramic IPS Empress crowns and placed the finish line 1.5 mm below the cementum-enamel junction CEJ on the buccal side and 1.5 mm above the CEJ on the lingual side, creating margins in enamel and dentin. Two die-spacing techniques were used (three layers or no layer of die spacer) and each crown restoration was cemented with one of three self-etching resin luting agents (Panavia F 2.0, Multilink and RelyX Unicem). The specimens were thermally cycled for 1,000 cycles, then immersed in a 5% methylene blue dye solution for 24 hours. Analysis of microleakage was at x70 magnifications. The authors found that Panavia F 2.0 resin luting agent exhibited the least degree of microleakage compared to RelyX Unicem and Multilink at both the enamel and dentin margins. Also, the results showed that the use of a conventional relief technique did not improve the marginal seal of IPS Empress crowns against marginal leakage. The authors concluded that the degree of microleakage for the die spacer group was not significantly different from the group without die spacer ($p>0.1$). Another significant finding was the higher degree of microleakage on margins in dentin compared to those on enamel ($p<0.0001$).

Microleakage can be related to margin misfit, although no strong correlation between margin fit and microleakage scores in complete crowns has been demonstrated.[45-47] A study conducted by Rossetti et al.[38] to evaluate the existence of correlation between in vitro margin fit and microleakage for complete crowns cemented with three different luting agents. Thirty human premolars were prepared for full-coverage Ni-Cr cast crowns and then cemented with either zinc phosphate (ZP), resin-modified glass-ionomer (RMGI) or a resin based luting agent (RC). After thermocycling, margin fit (seating discrepancy and margin gap) was evaluated and microleakage was recorded at × 100 magnification. The authors concluded that cast crowns cemented with RMGI and RC had lower microleakage scores than ZP cement and that margin fit parameters and microleakage showed no strong correlations.

Contrasting results were presented by Yüksel E et al.[48] in a study that assessed the effects of both marginal fit and cementation with different luting agents on microleakage of all-ceramic crown systems. They prepared 36 extracted incisors for full coverage crowns and divided them into three groups: CAD/CAM-fabricated ZrO2, heat pressed lithium-disilicate, and cast Cr-Co copings as the control group. The restorations were cemented with either self-adhesive resin cement or glass-ionomer luting cement and subjected to thermocycling. Microleakage was scored using a five-point scale, and the marginal gap was measured using image analysis software. The results exhibited lower levels of microleakage self-adhesive resin cement, while CAD/CAM-fabricated ZrO2 copings showed smaller marginal discrepancy and less microleakage in comparison to cast Cr-Co. The authors found that both marginal discrepancy and cement type have significant effects on microleakage.

Studies on the effects of luting agents on microleakage,[31, 45, 49] and marginal fit of different crown systems have been conducted,[23, 24, 26] but the number of studies that examine the combined effects of luting agents and marginal fit of crown systems on microleakage is low.[38, 48] Moreover, the studies on lithium disilicate crowns made with the E4D system are limited.

In the present study, we examined the effect of different marginal fit parameters (marginal ramp) on micoleakage of lithium disilcate crowns made with the E4D system. Also, the effect of tooth structure on micoleakage was assessed. The study results have clinical significance as they address the optimal marginal fit parameters to minimize the amount of microleakage of crowns fabricated with the E4D system.

Aim and Hypothesis

Objective

This study aims to assess the amount of microleakage of CAD lithium disilicate crowns with different marginal fit settings and different finish line locations.

Variables to be tested

- CAD/CAM lithium disilicate crowns with marginal seating levels (marginal ramp) of 0 mm, 0.25 mm and 0.75 mm.

- Finish line location on enamel and dentin surfaces.

Hypothesis

It was hypothesized that:

- The amount of marginal microleakage for lithium disilicate crowns fabricated at 0 mm and 0.25 mm (factory default) seating settings (marginal ramp) will be higher than for crowns fabricated at 0.75 mm seating setting.

- The amount of marginal microleakage will be higher for crowns with margins in dentin (below CEJ) than for those with margins in enamel (above CEJ).

Primary outcome

Marginal microleakage at the tooth-cement interface.

Research Design

To determine the sample size for the proposed in vitro study, a pilot study with three samples per group was conducted. Based on the means and standard deviations obtained in the pilot study, a power calculation was performed using nQuery Advisor (Version 7.0). A sample size of n=17 per group was found to be adequate to obtain a Type I error rate of 5%, a power of 80% to detect a difference between marginal ramps, and a power of 92% to detect a difference between finish line locations in term of microleakage.

Inclusion criteria

- Extracted human first or second premolar teeth

- Caries free, unrestored teeth (extracted for orthodontic or periodontal reasons)

Exclusion criteria

- Endodontically treated teeth

- Teeth with restorations

- Teeth with root caries

- Cracked teeth (if the crack extended beyond the dentin-enamel junction)

Materials and Methods

Tooth Preparations

First, each tooth was mounted in a plaster stone block. (Fig. 4) All premolars received a similar full crown preparation using a 1.2 mm diameter diamond bur with a high speed air rotor handpiece and water spray coolant. A chamfer margin of 1.2 mm circumferentially was prepared 1.5 mm below the CEJ on the buccal side and 1.5 mm above the CEJ on the lingual/palatal of each tooth. Occlusal reduction of 2 mm for all samples with rounded axio-pulpal line angels. (Fig. 5) All preparations were performed by the same operator.

CAD/CAM process

All teeth were removed from the stone blocks and the samples randomly assigned to three groups. Teeth were subsequently scanned by the same operator using the E4D system (D4D Technologies, Richardson, TX). Each tooth was embedded in a stone model duplicated from the typodont. The adjacent teeth were also scanned to aid in the scanning process using the IntraOral Digitizer (IOD).

For designing, the E4D Design Center powered by the DentaLogic™ software version 4.5 was used. All internal space parameters (axial and occlusal spacer thickness) for the intended restorations were set at 0.12 mm, except for the ‘marginal ramp’, which was set as follows: group 1: marginal ramp of 0.0 mm (Fig. 6), group 2: marginal ramp of 0.25 mm (Fig. 7), and group 3: marginal ramp of 0.75 mm (Fig. 8).

All virtual designs were subsequently milled out of IPS e.max CAD lithium disilicate ceramic blocks (Ivoclar, Schaan, Liechtenstein) using the D4D three-axes milling machine. Samples underwent crystallization firing using a Programat® CS Furnace (Ivoclar, vivaden). (Figs. 9-11)

Cementation

Before cementation, the root surfaces were sealed with a layer of varnish for insulation to a level of 1 mm below the preparation margin and embedded in acrylic resin blocks. All crowns were then cemented using adhesive universal resin-based luting cement RelyX™ Ultimate (3M ESPE, St. Paul, MN) by the same investigator as follows: at room temperature, a thin layer of cement was applied to the internal aspect of the crowns as evenly as possible and the crowns were seated immediately with finger pressure. Excess cement was removed after tack curing with 2 seconds at 1-mm distance with a light intensity of 400 mW/cm^2 (Optilux; Dabi Atlante, Ribeirao Preto, SP, Brazil). While under finger pressure, crowns were light cured on their buccal and lingual surfaces for 40 seconds each and were then allowed to self-cure for an additional 5 minutes.

Microleakage Testing

All samples were subjected to thermocycling for 5000 cycles between two water baths at 5°C and 55°C with a dwell time of 15 seconds in each bath and 10 seconds of transfer time between the two baths as recommended by the International Organization for Standardization (ISO) for testing the adhesion of a crown to the tooth structure.[48, 50] After thermal cycling, crowns were immersed in 50% silver nitrate dye solution for 2 hours in a dark room and then rinsed under running water. The samples were then immersed in developer solution for 4 hours under florescent light followed by rinsing again under running water.[51] To assess the microleakage, the samples were longitudinally sectioned in the midbucco-lingual plane with a low-speed diamond saw (Isomat 1000 Precision Saw; Beuhler, 41 Waukegan Rd, Lake Bluff, IL 60044).

Dye penetration was recorded at ×10 magnification using a stereomicroscope (Olympus SZX16, Tokyo, Japan). Microleakage was assessed by measuring the dye penetration through the margin and along the axial and occlusal surfaces at the cement-tooth interface in µm. A score assessment was then made using the method of Tjan et al.[52] : 0= no microleakage; 1= microleakage to one-third of the axial wall; 2= microleakage to two thirds of the axial wall; 3= microleakage along the full length of the axial wall, and 4= microleakage over the occlusal surface.

Statistical Analysis

For the continuous measurements, a mixed-effects model (using SAS version 9.4, SAS Institute Inc., Cary, NC, USA) was used for statistical analysis to compare the amount of microleakage in µm between the three marginal ramp groups (0 mm, 0.25 mm and 0.75 mm) and to compare the amount of microleakage between dentin (finish line below CEJ) and enamel (finish line above CEJ) aspects of each tooth among the groups.

Generalized estimating equations (GEE) (using SAS version 9.4, SAS Institute Inc., Cary, NC, USA) were used to compare microleakage between the three marginal ramp groups' score and to compare the scored microleakage between the buccal and lingual aspects of each tooth among the groups. Descriptive statistics were conducted for both statistical analyses.

Results

Six samples were excluded from the study after the theromcycling step as they had multiple cracks that resulted in complete diffusion of silver nitrate dye with 100% microleakage. They were considered outliers and excluded from the statistical analysis.

The lowest microleakage mean ± SD was found in the 0.25 mm marginal ramp group with 25.6 ± 18.8 μm, followed by the 0 mm marginal ramp group with 28.3 ±11.8 μm. The highest mean ± SD was in the 0.75 mm marginal ramp group with 29.3 ± 25.6 μm. The mixed-effects model analysis revealed no statistically significant difference in the amount of microleakage between the three marginal ramps groups ($p = 0.8$).

On average, crown margins on dentin exhibited more microleakage compared to margins on enamel. The amount of microleakage in dentin (finish line located below the CEJ) and enamel (finish line located above the CEJ) showed a statistically significant difference ($p<0.001$) with a mean ± SD of 32.9 ± 21.7 μm for dentin and 22.6 ±15.8 μm for enamel. Means and SDs are summarized in Table 1.

Analogous results were obtained from GEE analysis of the score assessment. Among the three groups, 19.4% of the 0.75 mm marginal ramp group were scored as 0 microleakage, whereas 14.3% of the 0.25 mm and 3.4% of the 0 mm marginal ramps had scores of 0 microleakage. On the other hand, 12.9% of the 0.75 mm marginal ramp group had a score of 3 microleakage, whereas 3.6% of the 0.25 mm group and 0% of the 0 mm group scored as 3 microleakage. The difference in the amount of microleakage among the three groups was not statistically significant ($p = 0.96$).

For dentin margins, 45.5% of the total samples had a microleakage scores of 2 and 3 microleakage compared to 22.8% for enamel margins. This difference in the amount of microleakage was statistically significant ($p < 0.001$). Counts and percentages are reported in Table 2 and Table 3.

Discussion

Marginal openings and subsequent microleakage are among the primary causes of any fixed restoration failures. Microleakage due to large marginal gaps can be caused by the increase in the amount of cement exposed to oral fluids. Moreover, the mechanical properties of the luting cement and the adhesion between cement and tooth structure can also promote microleakage.[48]

In this study we were testing whether the marginal ramp, which can be defined as the contact line between the crown and the preparation finish line, could affect the amount of microleakage. Basically, the assumption is that the higher the marginal ramp of the crown, the broader the contact with the tooth finish line.

It was hypothesized that crowns designed with a marginal ramp of 0.75 mm would exhibit less microleakage as they would have more contact with the preparation finish line, thus a smaller marginal gap with less cement exposure to oral fluids. On the other hand, crowns with a marginal ramp of 0 mm would show more microleakage as there is a greater chance for marginal gap formation with such limited contact between crown and finish line with an increased amount of cement.

The study results showed that there was no statistically significant difference ($p>0.005$) in the amount of microleakage among the three groups with different marginal ramp, as all the samples exhibited comparable amounts of microleakage.

There is limited data in the literature about the effect of the marginal ramp on marginal gap size and crown microleakage. Mously et al.[53] reported that differences in marginal gap could be attributed to the difference in the marginal ramp setting when using the E4D software.

In this study, microleakage was measured in micrometers using a computer program as well as with a score assessment. The metric measurement is considered more accurate than the score assessment as it permits quantitative as well as parametric statistical analyses of data.[54]

Various parameters have been documented to contribute to crown microleakage such as alteration of the interfacial pressure as a resultant of a difference in coefficient of thermal expansion between tooth structures and restorative material.[55] Temperature variations, inadequate moisture control leading to moisture absorption and polymerization shrinkage, water absorption by the restorative material known as 'hygroscopic absorption', as well as masticatory forces may also affect microleakage.[44]

Operator errors and/or the type of CAD/CAM system used may affect marginal gap accurancy of the restoration due to differences in scanning, design and milling steps. For instance, the Cerec Bluecam scanning process is based on blue-light scanning technology, which uses short wavelengths resulting in a high accuracy level. On the other hand, the E4D system uses red laser with a higher wavelength and captures images from different angles for accurate scanning. Cerec Bluecam requires powder in the scanning process to prevent reflection during capturing the images, while scanning in E4D system is a powder free process. Moreover, both CAD/CAM milling machines contain similar 3-axis milling unit, but they differ in the shape of the cutting burs. The E4D mill has ellipsoidal diamond bur to mill the intaglio surface and a tapered diamond bur to mill the external surface. The CEREC mill uses a small diameter tip step rotary bur to mill the intaglio surface and a cylindrical diamond bur to mill the external surface.[24]

The relation between microleakage and marginal gap is controversial in the literature. Yüksel et al.[48] reported that the marginal gap has a significant effect on microleakage. On the other hand, Rossetti et al.[38] and Piwowarczyk et al.[47] found no strong correlation between microleakage and margin gap in full crowns. White et al.[55] found that the marginal opening did not directly correlate with marginal microleakage.

Generally, the amount of microleakage in this study was expected to be low due to the application of adhesive resin cement that has low solubility compared to other cements, which plays an important role in providing a better marginal seal.[56, 57] In addition, the use of lithium disilicate glass ceramic blocks (IPS e.max CAD, Ivoclar, vivaden) was expected to decrease the amount of microleakage due to their etchable glassy phase, which can enhance bonding to the cement layer. There are several studies that proved the clinical efficacy of IPS e.max CAD restorations.[16, 17, 26] However, Neves et al.[24] reported that lithium disilicate crowns fabricated using with the E4D system exhibited more vertical and horizontal misfit compared to the CEREC 3D Bluecam scanner and heat-pressing technique.

The amount of microleakage in this study was 78.5% of the total sample which is considerably higher than reported in other studies. There is more than one reason to explain this high amount of microleakage and could have an impact on microleakage assessment process. The disinfection method and storage conditions of the extracted teeth used in the study as well as is the storage time of restored teeth before thermocycling are variables that could have affected the outcome. The International Organization for Standardisation (ISO) recommends to store cleaned teeth in distilled water or 0.5% chloramin-T trihydrate solution for a week maximum and thereafter in distilled water at 4 ◦C or −5 ◦C. The temperature during preparation should be (23±2) ◦C followed by a 24h period of storage in water at (37±2) ◦C before thermocycling .[50] The samples in this study were stored in distilled water for more than a week.

Another variable is the number of cycles and temperature used in the thermocycling process. Although thermocycling is a widely acceptable method used in in vitro microleakage studies, some researchers still consider it questionable. The literature shows that there is a wide range in temperature extremes, transfer times between baths and dwell times. In brief, there is no standard for thermocycling methodology in microleakage studies, which permits divergent interpretation of results between various laboratory studies.[54] Also, the number of cycles used in different published studies vary and seems to be selected by convenience. In this study, an increased number of cycles was selected. It is reported in the literature that 10,000 cycles represent one year of function in the oral cavity based on the fact that cycles might occur between 20 and 50 times per day.[58] Nevertheless, some researchers reported that the degree of dye penetration did not significantly depend on the number of thermal cycles to which the sample was subjected.[54]

Microleakage along the tooth-restoration interface is still considered an observed problem in clinical and laboratory studies. Moreover, bonding of dental materials to enamel is a well-known reliable procedure while bonding to dentin is somewhat more complex due to the complexity of its substrate and the difference in mineral contents.[54] The current study results revealed that the amount of microleakage on the buccal aspect of the teeth, where the preparation finish line was located below the CEJ, i.e., on dentin, was significantly higher compared to the lingual aspect, where the finish line was above the CEJ, i.e., on enamel. This result is in line with the data reported by Trajtenberg et al.[31] Also, Uludag et al.[59] reported that microleakage for restorative margins in dentin was higher than in enamel, regardless of the ceramic system and self-adhesive resin cement used.

There is no standardized method to measure the marginal fit and subsequent microleakage. The most common methods are the cross sectional view, the direct view of the crown on a die, the impression replica technique, and clinical examination.[60] In this study, the cross-section method was used to measure the marginal microleakage, which enables the measurement of cemented restorations. Ferrari et al.[41] mentioned that the cross-section method is an easier and better way to assess the microleakage compared to direct viewing of the margins.

Furthermore, current literature showes that there is no restoration that could reproduce a perfect marginal fit to the prepared tooth.[61] Luting cements are used to fill the gap discrepancy between the restoration and the tooth. Nevertheless, none of the available bonding agents could provide a complete marginal seal and eliminate microleakage. The best marginal sealing and the lowest degree of microleakage were observed with crowns cemented with resin cement. The location of the preparation margin significantly influence the rate of microleakage.[31]

There were some limitations in this study; lack of standardization in the sample preparation, unknown storage condition of the samples, milling machine calibration and application of standard mode of milling might have affected the amount of microleakage. Moreover, we did not measure the vertical and horizontal gaps before cementation, so we can compare the marginal fit before and after the cementation.

Future studies with standardized preparation and application of different types of cement that differ in their solubility can be conducted to assess the effect of different marginal ramp setting on microleakage.

Conclusion

Within the limitations of the study, it can be concluded that the marginal ramp setting had no significant effect on the amount of microleakage for crowns fabricated with the E4D scanning system. Other factors should be considered such as tooth preparation, type of cement and crown material in order to obtain a clinically acceptable marginal fit and a decreased amount of microleakage. In addition, placing the preparation finish line on enamel will reduce the amount of microleakage compared to finish line in dentin.

References

1. Liu PR. A panorama of dental CAD/CAM restorative systems. Compend Contin Educ Dent. 2005 Jul;26(7):507-8, 510, 512.
2. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience.Dent Mater J. 2009 Jan;28(1):44-56.
3. Davidowitz G, Kotick PG. The use of CAD/CAM in dentistry. Dent Clin North Am. 2011 Jul; 55(3):559-70.
4. Duret F, Preston JD. CAD/CAM imaging in dentistry. Curr Opin Dent 1991;1(2):150–4.
5. Mormann WH. The evolution of the CEREC system. J Am Dent Assoc 2006;137 (Suppl):7s–13s.
6. Andersson M, Carlsson L, Persson M, Bergman B. Accuracy of machine milling and spark erosion with a CAD/CAM system. J Prosthet Dent 1996; 76(2):187–93.
7. Anadioti E, Aquilino SA, Gratton DG, Holloway JA, Denry I, Thomas GW, Qian F. 3D and 2D marginal fit of pressed and CAD/CAM lithium disilicate crowns made from digital and conventional impressions. J Prosthodont. 2014 Dec;23(8):610-7.
8. Wittneben JG, Wright RF, Weber HP, Gallucci GO. A systematic review of the clinical performance of CAD/CAM single-tooth restorations. Int J Prosthodont 2009; 22(5):466–71.
9. Birnbaum N, Aaronson HB, Stevens C, Cohen B. 3D digital scanners: A high-tech approach to more accurate dental impressions. Inside Dentistry. 2009:5(4).
10. Miyazaki T, Hotta Y. CAD/CAM systems available for the fabrication of crown and bridge restorations. Aust Dent J. 2011 Jun;56 Suppl 1:97-106.
11. Andersson M, Oden A. A new all-ceramic crown: a dense-sintered, high purity alumina coping with porcelain. Acta Odontol Scand 1993; 51: 59-64.
12. Marinescu C. CAD/CAM restorative principles. Dent Today. 2012 Apr;31(4):130, 132-3.
13. McLaren EA, Culp L, White S. The evolution of digital dentistry and the digital dental team. Dent Today. 2008 Sep; 27(9):112, 114, 116-7.
14. Frankenberger R, Hartmann VE, Krech M, Krämer N, Reich S, Braun A, Roggendorf M. Adhesive luting of new CAD/CAM materials. J.Int J Comput Dent 2015;18(1): 9-20
15. Henkel GL. A comparison of fixed prostheses generated from conventional vs digitally scanned dental impressions.Compend Contin Educ Dent 2007; 28 (8):422–4, 426–8,430-1.
16. Bindl A, Mörmann WH. An up to 5-year clinical evaluation of posterior in-ceram CAD/CAM core crowns. Int J Prosthodont. 2002 Sep-Oct; 15(5):451-6.

17. Fasbinder DJ, Dennison JB, Heys D, Neiva G. A clinical evaluation of chairside lithium disilicate CAD/CAM crowns: a two-year report. J Am Dent Assoc. 2010 Jun; 141 Suppl 2:10S-4S.
18. Cvar JF, Ryge G. Criteria for the clinical evaluation of dental restorative materials. San Francisco: U.S. Department of Health, Education and Welfare, Public Health Service, National Institutes of Health; 1971. USPHS publication 790-244.
19. Bindl A, Mörmann WH. Survival rate of mono-ceramic and ceramic-core CAD/CAM-generated anterior crowns over 2-5 years. Eur J Oral Sci 2004; 112(2):197-204.
20. Holmes JR1, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent. 1989 Oct;62(4):405-8.
21. Estafan D, Dussetschleger F, Agosta C, Reich S. Scanning electron microscope evaluation of CEREC II and CEREC III inlays. Gen Dent. 2003 Sep-Oct; 51(5):450-4.
22. Bindl A, Windisch S, Mo¨rmann WH. Full ceramic CAD/CIM anterior crowns and copings. Int J Comput Dent 1999; 2:97-111.
23. Sulaiman F, Chai J, Jameson LM, Wozniak WT. A comparison of the marginal fit of In-Ceram, IPS Empress, and Procera crowns. Int J Prosthdont 1997; 10: 478–484.
24. Neves FD, Prado CJ, Prudente MS, Carneiro TA, Zancopé K, Davi LR, Mendonça G, Cooper LF, Soares CJ. Micro-computed tomography evaluation of marginal fit of lithium disilicate crowns fabricated by using chairside CAD/CAM systems or the heat-pressing technique. J Prosthet Dent. 2014 Nov;112(5):1134-40.
25. Shiratsuchi H, Komine F, Kakehashi Y, Matsumura H. Influence of finish line desing on marginal adaptation of electroformed metal-ceramic crowns. J Prosthet Dent. 2006 Mar; 95(3):237-42.
26. Reich S, Wichmann M, Nkenke E, Proeschel P. Clinical fit of all-ceramic three-unit fixed partial dentures, generated with three different CAD/CAM systems. Eur J Oral Sci. 2005 Apr; 113(2):174-9.
27. Nakamura T, Dei N, Kojima T, Wakabayashi K. Marginal and internal fit of Cerec 3 CAD/CAM all-ceramic crowns. Int J Prosthodont. 2003 May-Jun; 16(3):244-8.
28. Carter SM, Wilson PR.The effects of die-spacing on post-cementation crown elevation and retention. Aust Dent J. 1997 Jun; 42(3):192-8.
29. Gegauff AG, Rosenstiel SF. Reassessment of die-spacer with dynamic loading during cementation. J Prosthet Dent. 1989 Jun;61(6):655-8

30. Passon C, Lambert RH, Lambert RL, Newman S. The effect of multiple layers of die-spacer on crown retention. Oper Dent. 1992 Mar-Apr;17(2):42-9.
31. Trajtenberg CP, Caram SJ, Kiat-amnuay S. Microleakage of all-ceramic crowns using self-etching resin luting agents. Oper Dent. 2008 Jul-Aug;33(4):392-9.
32. Van Meerbeek B, Yoshihara K. Clinical recipe for durable dental bonding: why and how? J Adhes Dent 2014;16:94.
33. Borges G, Faria J, Agarwal P, Spohr A, Correr-Sobrinho L, Miranzi B. In vitro marginal fit of three all-ceramic crown systems before and after cementation. Oper Dent. 2012 Nov-Dec;37(6):641-9.
34. Lyons K M, Rodda JC, Hood JAA. Use of a pressure chamber to compare microleakage of three luting agents. Int J Prosthodont. 1997 Sep-Oct;10(5):426-33.
35. Kidd EA. Microleakage: A review. J Dent 1976 Sep;4(5):199-206.
36. Kidd EA. Microleakage in relation to amalgam and composite restorations. A laboratory study. Br Dent J 1976;141:305–10.
37. Taylor MJ, Lynch E. Microleakage. J Dent. 1992 Feb;20(1):3-10.
38. Rossetti PHO, Valle AL, Carvalho RM, Goes MF, Pegoraro LF. Correlation between margin fit and microleakage in complete crowns cemented with three luting agents. J Appl Oral Sci. 2008 Feb;16(1):64-9.
39. Paul SJ, Welter DA, Ghazi M, Pashley D. Nanoleakage at the dentin adhesive interface vs microtensile bond strength. Oper Dent. 1999 May-Jun;24(3):181-8
40. Alster D, Feilzer AJ, de Gee AJ, Davidson CL. Polymerization contraction stress in thin resin composite layersas a function of layer thickness. Dent Mater. 1997 May;13(3):146-150
41. Ferrari M, Dagostin H, Fabianelli. Marginal integrity of ceramic inlays luted with a self-curing resin system. Dent Mater. 2003 Jun;19(4):270-276.
42. Hahn P, Attin T, Gröfke M, Hellwig E. Influence of resin cement viscosity on microleakage of ceramic inlay. Dent Mater. 2001 May;17(3):191-196.
43. Dietschi D, Magne P, Holz J. An in vitro study of parameters related to marginal and internal seal of bonded restorations Quintessence Int. 1993 Apr;24(4):281-291.
44. Schmid-Schwap M, Graf A, Preinerstorfer A, Watts DC, Piehslinger E, Schedle A. Microleakage after thermocycling of cemented crowns--a meta-analysis. Dent Mater. 2011 Sep;27(9):855-69.
45. Gu XH, Kern M. Marginal discrepancies and leakage of allceramic crowns: Influence of luting agents and aging conditions. Int J Prosthodont. 2003 Mar-Apr;16(2):109-16.

46. Pilo R, Cardash HS. In vivo retrospective study of cement thickness under crowns. J Prosthet Dent. 1998;79:621-5.
47. Piwowarczyk A, Lauer HC, Sorensen JA. Microleakage of various cementing agents for full cast crowns. Dent Mat. 2005;21:445-53.
48. Yüksel E, Zaimoğlu A. Influence of marginal fit and cement types on microleakage of all-ceramic crown systems. Braz Oral Res. 2011 May-Jun;25(3):261-6.
49. RelyX™ Unicem self-adhesive universal resin cement- technical product profile. Found at http://multimedia.3m.com/mws/mediawebserver?mwsId=66666UF6EVsSyXTtlxMy4xfaEVtQEVs6EVs6EVs6E666666--&fn=unicem_tp_ebu.pdf
50. International Organization for Standardisation (ISO). Dental materials—testing of adhesion to tooth structure. ISO/TS 11405:2003 (E).
51. Alaghemand H, Abolghasemzadeh F, Pakdel F, Judi Chelan R. Comparison of Microleakage and Thickness of Resin Cement in Ceramic Inlays with Various Temperatures. Journal of Dental Research, Dental Clinics, Dental Prospects. 2014;8(1):45-50.
52. Tjan AHL, Peach KD, VanDenburgh SL, Zbaraschuk ER. Microleakage of crowns cemented with glass ionomer cemment: Effects of preparation finish and conditioning with polyacrylic acid. J Prosthet Dent. 1991 Nov;66(5):602-6.
53. Mously HA, Finkelman M, Zandparsa R, Hirayama H. Marginal and internal adaptation of ceramic crown restorations fabricated with CAD/CAM technology and theheat-press technique. J Prosthet Dent. 2014 Aug;112(2):249-56.
54. Pazinatto FB, Campos BB, Costa LC, Atta MT. Effect of the number of thermocycles on microleakage of resin composite restorations. Pesqui Odontol Bras 2003;17(4):337-41.
55. White SN, Ingles S, Kipnis V. Influence of marginal opening on microleakage of cemented artificial crowns. J Prosthet Dent. 1994;71:257-64.
56. Arami S, Shahabi S, Tabatabaie M, Chiniforush N, Morshedi M, Torabi S. Assessing microleakage of composite restorations in class V cavities prepared by Er:YAG laser irradiation or diamond bur. J Conserv Dent. 2014;17:216–9.
57. Bönecker-Valverde G, Maniglia-Ferreira C, Abi-Rached GP, Gomes BP, Mesquita MF. Seal capability of interim post and core crown with temporary cements. Braz Oral Res. 2010 Apr-Jun;24(2):238-44.
58. Gale MS, Darvell BW. Thermal cycling procedures for laboratory testing of dental restorations. J Dent 1999;27:89–99.

59. Uludag B, Yucedag E, Sahin V. Microleakage of inlay ceramic systems luted with self-adhesive resin cements. J Adhes Dent. 2014 Dec;16(6):523-9.
60. Balkaya MC, Cinar A, Pamuk S. Influence of firing cycles on the margin distortion of 3 all-ceramic crown systems. J Prosthet Dent. 2005 Apr;93(4):346-55.
61. Gwinner FP, Bottino MA, Nogueira-Junior L, Della Bona A. Effect of finish line on marginal fit of sintered gold copings. Braz Dent J. 2013;24(4):322-5.

APPENDICES

Appendix A: Tables

Ramp	Location	Mean (µm)	Std. Deviation(µm)	N
0.0 mm	Below CEJ	31.8	11.4	14
	Above CEJ	25.0	11.6	15
	Total	28.3	11.8	29
0.25 mm	Below CEJ	30.6	23.1	14
	Above CEJ	20.5	11.9	14
	Total	25.6	18.8	28
0.75 mm	Below CEJ	36.0	27.5	16
	Above CEJ	22.2	22.1	15
	Total	29.3	25.6	31
Total	Below CEJ	32.9	21.7	44
	Above CEJ	22.6	15.8	44
	Total	27.8	19.6	88

Table 1 Means and Standard Deviations of Microleakage for different ramps settings

		Score				Total
		0	1	2	3	
Ramp	0 mm	1 3.4%	20 69.0%	8 27.6%	0 0%	29 100%
	0.25 mm	4 14.3%	13 46.4%	10 35.7%	1 3.6%	28 100%
	0.75mm	6 19.4%	14 45.2%	7 22.5%	4 12.9%	31 100%
Total		11 12.5%	47 53.4%	25 28.4%	5 5.7%	88 100%

Table 2 Count and percentage of microleakage scores for different marginal ramp groups

			Score				
			0	1	2	3	Total
Location	Below CEJ (Dentin)	Count	4	20	16	4	44
		%	9.1%	45.5%	36.4%	9.1%	100%
	Above CEJ (Enamel)	Count	7	27	9	1	44
		%	15.9%	61.4%	20.5%	2.3%	100%
Total		Count	11	47	25	5	88
		%	12.5%	53.4%	28.4%	5.7%	100%

Table 3 Count and percentage of microleakage scores in enamel and dentin

Appendix B: Figures

Figure 1 The E4D Dentist System (D4D Technologies)

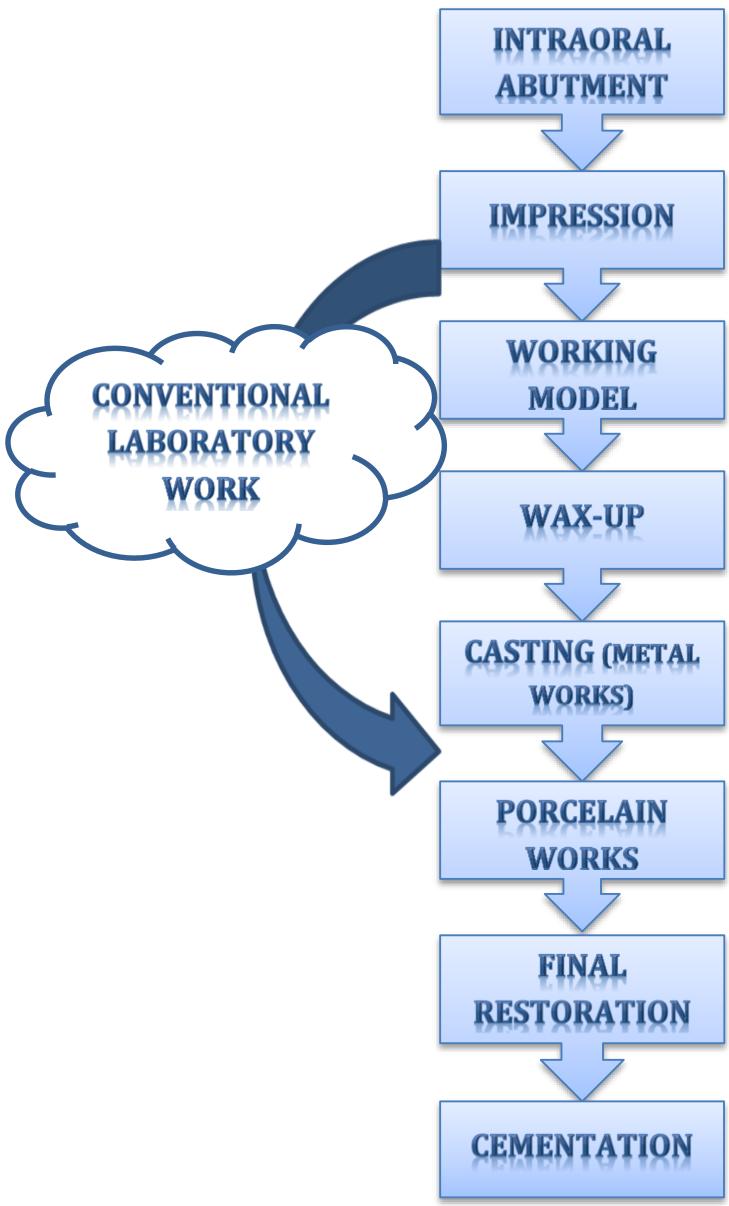

Figure 2 Conventional fabrication process of dental restoration

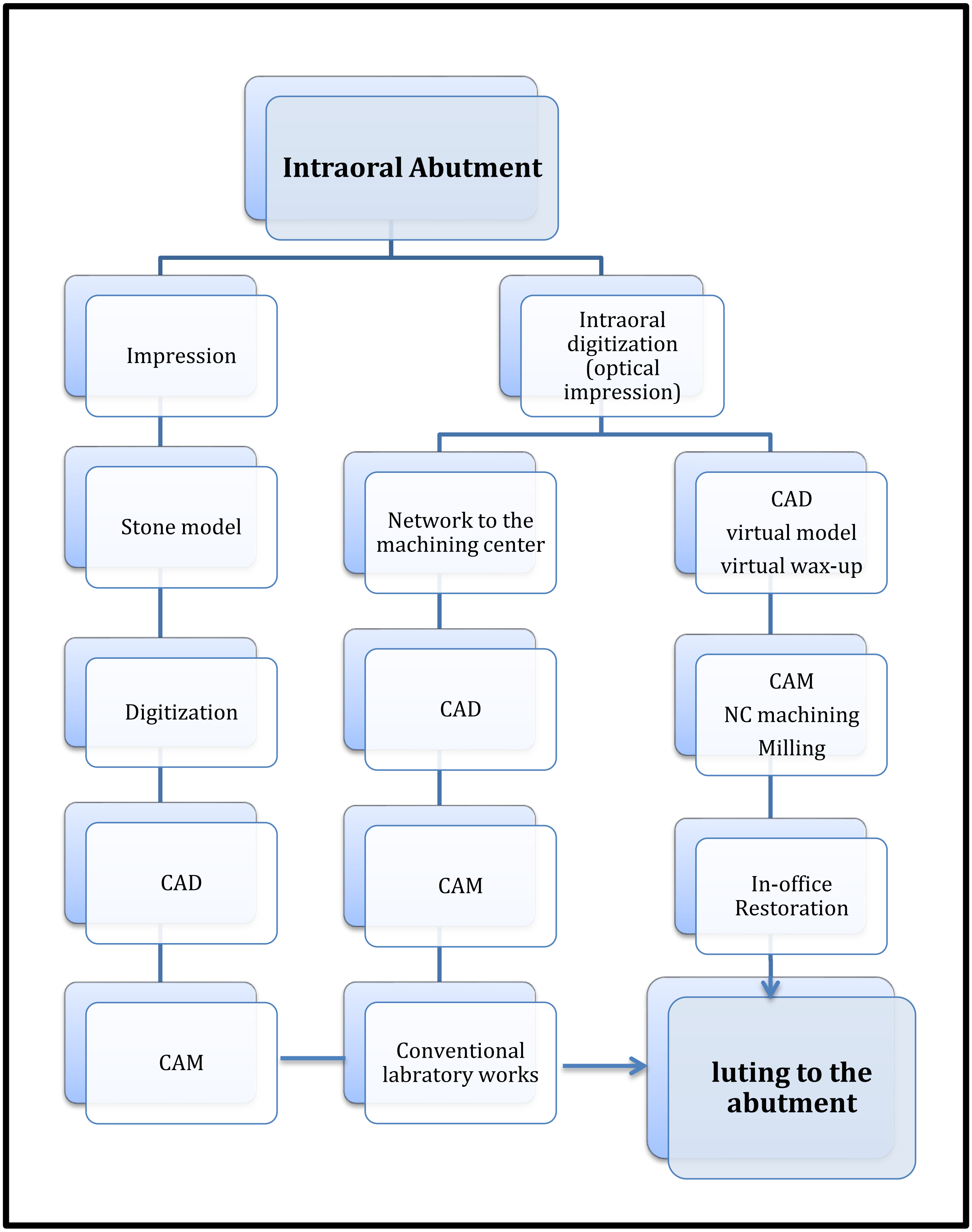

Figure 3 An overview of current dental CAD/CAM systems used for the fabrication of crown-bridge restorations

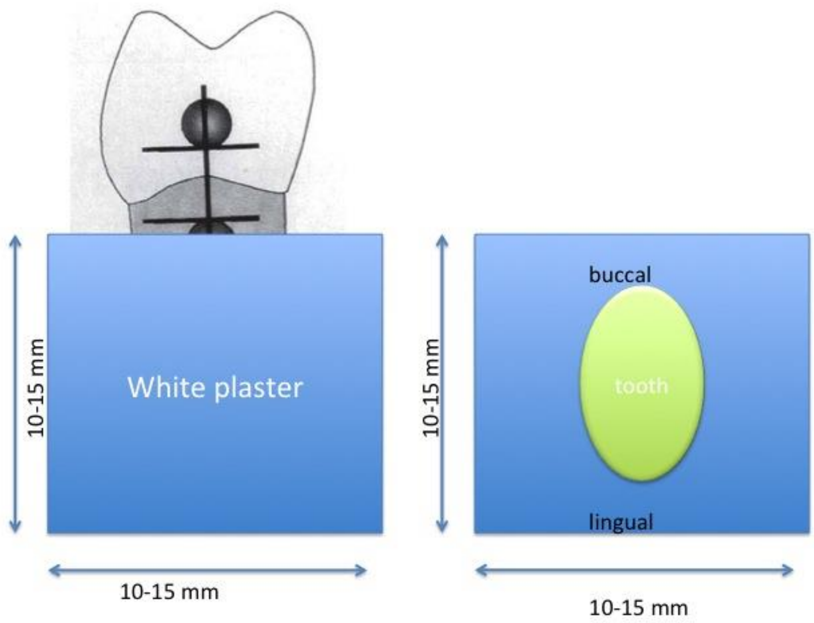

Figure 4 Mounting technique

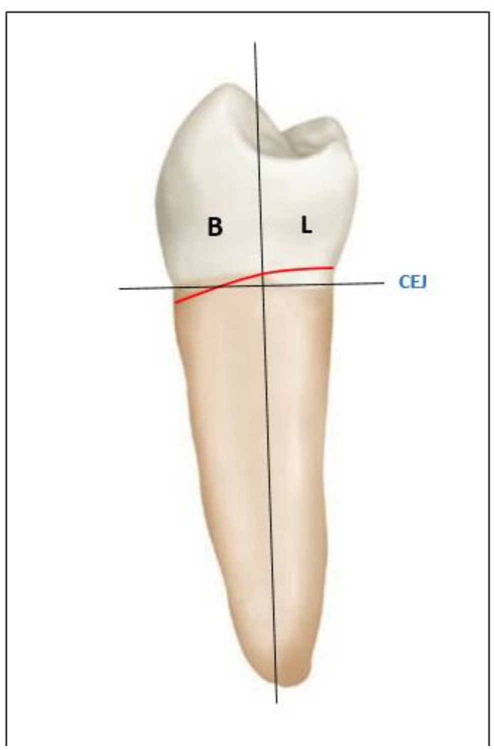

Figure 5 Preparation design

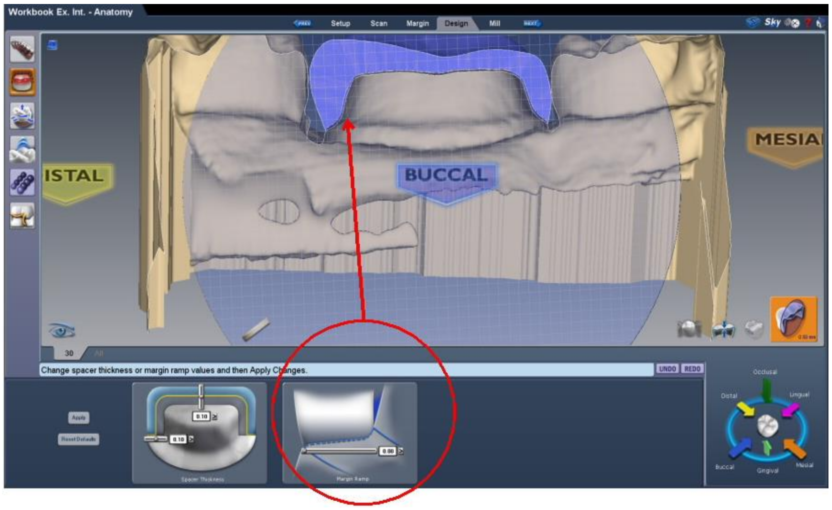

Figure 6 Group 1: marginal ramp 0 mm

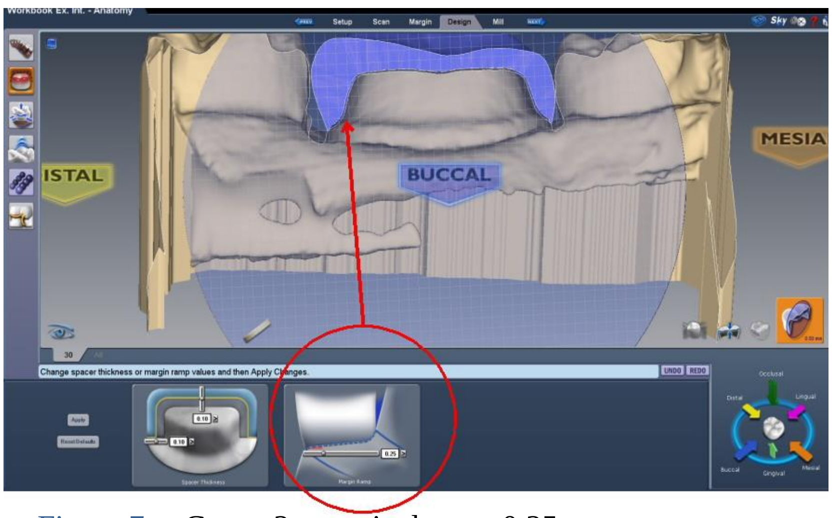

Figure 7 Group 2: marginal ramp 0.25 mm

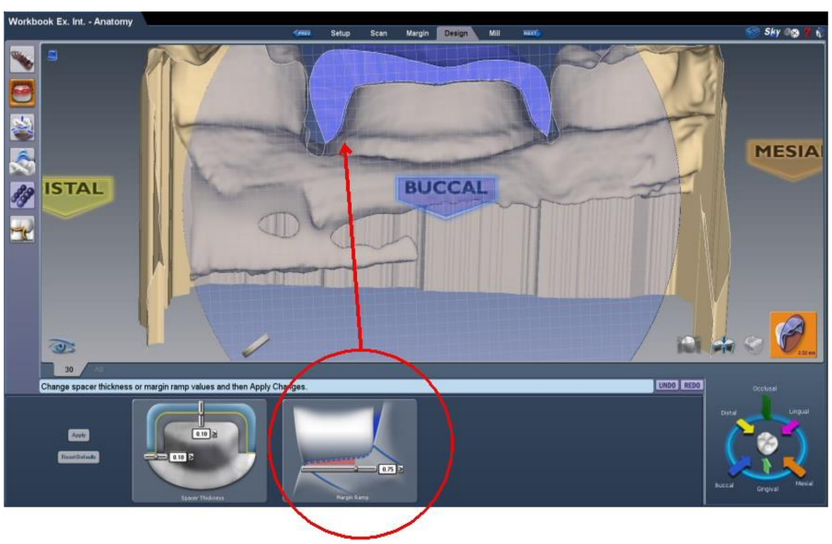

Figure 8 Group 3: marginal ramp 0.75 mm

Figure 9 Tooth sample ready for scanning

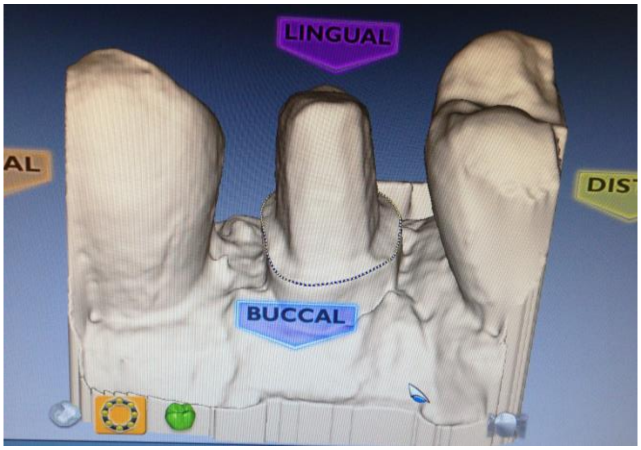

Figure 10 Crown design with E4D software

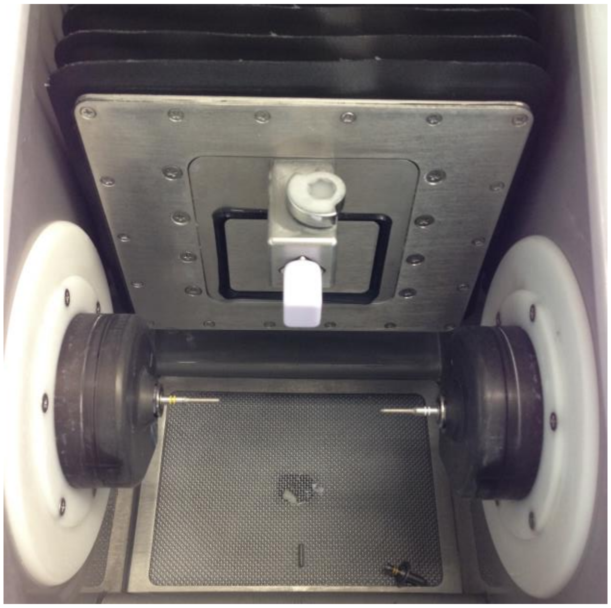

Figure 11 Milling the sample using the D4D three-axes milling machine