Clinical Outcomes of Three Different Crown Systems using CAD/CAM Technology

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Abstract

EMILY R. BATSON, DDS: Clinical Outcomes of Three Different Crown Systems using CAD/CAM Technology
(Under the direction of Lyndon F. Cooper DDS, PhD)

CAD/CAM technology has opened many doors for dental restoration fabrication. Improvements in intraoral scanning technology and the use of newer esthetic materials have brought many questions to the forefront. Concerns over restoration fit and quality have been expressed, as well as accuracy of digital methods involved for crown fabrication[1]. This clinical study examined three different crown materials for posterior teeth in need of full coverage restoration. Crown preparations were scanned intraorally using the E4D or iTero scanner and crowns digitally designed and fabricated. Teeth received porcelain fused to metal, lithium disilicate or monolithic zirconia restorations. Gingival parameters and modified USPHS criteria were recorded for each crown and marginal integrity was examined using micro-CT analysis. An 18.8% rejection rate was noted for crowns due to poor marginal adaptation. Overall, acceptable results were obtained for all three systems.

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LIST OF ABBREVIATIONS

CAD/CAM……Computer-Aided Design/Computer-Aided Manufacturing

PFM……..……Porcelain fused to metal

Zr……..……..Zirconia

BOP……..…….Bleeding on probing

GCF…..…….Gingival crevicular fluid

Micro-CT……Micro-computed tomography

USPHS…….……United States Public Health Service

FPD……..Fixed dental prosthesis

Chapter 1 INTRODUCTION

CAD/CAM technology entered the dental arena almost thirty years ago, and has seen a dramatic evolution of its capabilities throughout the past two decades. CAD/CAM advancements have incorporated multiple types of dental restorations including orthodontic appliances, implant prostheses and single or multiple tooth restorations. Currently, there are numerous dental CAD /CAM systems available for clinicians and laboratories, and the choices of design applications continue to increase. Restorative dentistry has not only been affected by the infiltration of CAD/CAM technology, but the advancement of esthetic materials for use with CAD/CAM systems. All-ceramic materials have evolved alongside CAD/CAM technology, as the demand for esthetic restorations continues to grow. Moreover, the search for viable alternatives to expensive alloys has further contributed to the evolution of newer materials. A recent survey on laboratory fabrication projections for restorative materials estimates by the year 2017 all-ceramic materials will be used to fabricate approximately 42% of crown and bridge restorations.[2] This will reflect a 20% increase over a ten-year span. Today two materials are dominating the stage for esthetic restorations; zirconia and lithium disilicate. Furthermore, with the advances in milling technology, dental practitioners can create an efficient mode of restoration delivery using in-office fabrication methods. Concerns over the use of CAD/CAM technology and newer materials still exist. Long-term clinical

studies involving the use of CAD/CAM generated restorations are sparse, in addition to controlled clinical trials involving the use of newer materials.

1.1 Benefits of Intraoral CAD/CAM Technology.

Numerous benefits are mentioned from manufacturers of intraoral dental CAD/CAM systems. These include increased efficiency in restoration production, increased patient comfort due to elimination of impression materials, and in-office control of restoration fabrication for systems utilizing milling technology. One important benefit is an instant 3-dimensional chairside view to evaluate tooth preparations. This benefit may become part of dental education as students and faculty continue to find new evaluation methods to compare preparations to accepted standards.[3] Clinicians benefit from the ability to evaluate tooth preparations chairside and make necessary modifications prior to restoration fabrication. Theoretically this could lead to better fitting and more esthetic restorations. Other benefits include multiple pathways to lead to the final product or restoration. Following similar principles used in reverse engineering, data acquisition takes place either intraorally by direct capture of a prepared tooth, or extraorally from an impression or gypsum cast of a prepared tooth. Many scanning softwares use the common Standard Triangulation Language (STL) format for data files which can be incorporated into a CAD program for either model fabrication or direct digital design of a restoration without a solid model.[4] Following restoration design copings can be printed using Rapid-Prototype (RP) technology or milled. Depending on the type of material and restoration, full-contour restorations may also be milled.

1.2 Limitations of CAD/CAM Technology

Questions still remain unanswered in regards to the quality of digitally fabricated dental prostheses and whether one CAD /CAM system shows superior results to another. Early developers focused their efforts on creating single tooth restorations, mainly inlays, onlays, and full coverage crowns.[5] Optical scanning of an abutment tooth was historically the limiting factor in obtaining a well-fitting restoration.[6] The prepared tooth presents challenges for optical scanners and CAD software systems. As discussed in a recent review by Miyazaki et al[7] crown margins can be difficult to capture with intraoral scanning not only because of their design, but their proximity to gingival tissues, adjacent teeth, and sulcular fluids. In addition, prepared teeth tend to show geometries that test the boundaries for optical scanners. Because of these intraoral limitations, many practitioners continue to use conventional impression techniques and allow dental laboratories to create restorations using CAD software, and if necessary CAM for fabrication. In a recent study by Güth et al[8] accuracy of digital models was examined using an in vitro set-up. The direct intraoral capture of a prepared abutment showed more accuracy than the scanned polyether impression or gypsum cast. Other studies have concluded no significant difference between intraoral scanning, a scan of an impression, or gypsum cast.[9,10] Factors to consider when choosing to use an intraoral scanning device include location of restoration margins (ie. supragingival vs. subgingival), location of restoration (mandibular vs. maxillary; posterior vs. anterior) and inclusion of internal modifications (retentive grooves, slots, potential undercuts). The accuracy of a scan can be considered the first and most important variable when utilizing CAD/CAM

technology for dental restorations. Scanning manufacturers continue to make improvements in their technologies by designing smaller, lighter-weight scanners that can capture fine detail quickly. Practitioners, however, are still required to use careful and meticulous techniques when obtaining an intraoral scan. A dry field and a clean, well-isolated tooth preparation are of utmost importance in obtaining an accurate scan.

1.3 Fit of Restorations

The fit of dental restorations has been an historically controversial topic. Fit can have many definitions in regards to appropriate adaptation of a restoration to the prepared tooth as a whole, but more commonly fit often refers to the marginal adaptation. Holmes et al stated that many different terms can be applied to describe the marginal fit of a dental restoration including internal gap, vertical and horizontal marginal gap, and under- or overextended margins.[11] Although no published numeric standard value or definition has been agreed upon, the marginal fit, or adaptation of a single tooth crown at the margin interface commonly gets noted as 50-100 microns as an acceptable value. In 1966, Christensen[12] published clinically acceptable ranges of marginal discrepancies from 2-119 microns for cast gold inlay restorations, but the least acceptable occlusal margin was determined to be 39 microns. These figures were based on an in vitro study examining the gingival, proximal and occlusal surfaces of inlays. Lofstrom and Barakat[13] found marginal discrepancies ranging from 7-65 microns of cast gold crown restorations based on SEM analysis. Belser et al[14] demonstrated marginal gaps ranging from 18-46

microns before and after cementation of PFM restorations. Felton et al[15] examined cast gold and PFM restorations retrospectively using SEM analysis and found an average marginal discrepancy of 160 microns but a range from 5-430 microns. In addition, this study found a relationship between the gingival index and marginal discrepancy values.

CAD/CAM fabricated restorations have been found to have similar readings for marginal discrepancies and fit. Many in vitro studies show average marginal discrepancies ranging between 35-71 microns, and clinical studies showing equivalent values using SEM analysis.[9,16-18] A recent clinical study by Brawek et al[19] reported mean marginal discrepancy values of 51 microns for veneered Zr crowns fabricated using intraoral scanning techniques and digital fabrication. Sailer et al[20], however, reported a recurrent caries rate of 21.6% in Zr based fixed dental prostheses (FDPs) that were hand-designed but digitized and then milled. One may conclude that even with the additional all-ceramic materials available today, marginal discrepancies can be held to the same standards as traditional gold and PFM technologies when using CAD/CAM systems.

1.4 Zirconia

In its elemental form Zirconium, or Zr, lies as the 40th element in the periodic table and is a grayish-white transition metal. It is commercially available for many uses including kitchen cutlery, gemstones, and in nuclear energy applications. In the dental industry it has become one of the most popular new materials used for all-

ceramic applications. The two most common ores of zirconium are zirconium silicate ($ZrSiO_4$), also known as zircon, and zirconium dioxide (ZrO_2), or zirconia. In its unalloyed state and as with most of the transition metals, zirconia can have three different forms that are temperature dependent. The monoclinic form (m) exists from room temperature to ~1170 ^oC, the tetragonal form (t) from 1170^oC-2370^oC, and the cubic (c) from 2370^oC to the melting point of 2715^o C.[21] It is the tetragonal form that has gained the most interest for the dental industry, due to a phenomenon referred to as transformation toughening. When stabilizing oxides, such as CaO, MgO, or Y_2O_3 are added to the tetragonal phase and subsequently cooled, stress-induced cracking will occur due to volumetric expansion. As phase transformation from the t-form to the m-form is occurring, crack propagation is halted under compressive stresses.[22] This leads to an increase in the mechanical properties of zirconium. Flexural strength values of 1200 MPa are averaged and greater than 5 MPa fracture toughness is achieved. These mechanical properties are what have drawn interest from the medical and dental field. Three main types of zirconia are available for use for dental applications; 3% mol yttrium cation-doped tetragonal zirconia polycrystals (3Y-TZP), magnesium cation-doped partially stabilized zirconia (Mg-PSZ), and zirconia-toughened alumina (ZTA).[21] 3Y-TZP is seen most commonly in dental applications but Mg-PSZ and ZTA exist as well. In addition to the different types of zirconia available for dental applications, two different machining methods exist. Presintered blocks of zirconia can be milled in what is considered the soft-state. Sintering volume shrinkage between 25-35% is accounted for with the milling, and coloration of restorations can be achieved during the sintering process. The second

method is referred to as hard-machining. This occurs with fully-sintered 3Y-TZP or Mg-PSZ blocks and requires a more intensive milling process since the blocks are already at their full hardness. As with all other dental materials drawbacks exist. For zirconia, low temperature degradation (LTD) is a concern, as this phenomenon has been documented to occur in the presence of water, leading to aging and surface cracking.[23] In addition, due to the inherent properties of zirconia, dental restorations are often quite opaque in nature and do not allow for light transmission. Much like metal based restorations this can be overcome with proper porcelain addition techniques. There have been studies showing high chipping rates of veneered porcelain for zirconia based restorations, with some reporting between 15-25% of fractured or chipped veneering porcelain [20, 24]. Further research has led to a change in firing protocols such that the differences in coefficients of thermal expansion and cooling are compensated for zirconia. Additional research has been conducted on the type of stabilizer added to zirconium during the transformation toughening phase with the intention of altering heating and cooling rates to coincide with those of the veneering porcelain. Research, however, is inconclusive as to whether this will decrease the incidence of veneer fracture. Because of the technical complications involved with veneering zirconia, a monolithic zirconia restoration may appear to resolve some of the problems. Research involving monolithic zirconia restorations is limited at this time although the use of these types of restorations is increasing.

1.5 Lithium Disilicate

Glass-based dental ceramics have shown changes in their formulations over the past three decades in order to reach desired outcomes of high esthetics and good clinical performance. In the late 1980's leucite was added as a reinforcement to improve mechanical properties of glass-based ceramics. IPS Empress is an example of a commonly used leucite-reinforced ceramic used for esthetic restorations and shows flexural strength values of 120-180 MPa.[25] More recently lithium disilicate crystals have been incorporated into dental glass ceramics and show improved mechanical properties, such as flexural strength values nearing 350-400 MPa. Today, eMax CAD and eMax Press (Ivoclar, Vivadent) are two varieties of lithium disilicate based ceramics that can be used to fabricate single and multiple tooth restorations. In addition, CAD/CAM based systems aid in the fabrication of these types of restorations, as blocks for CAM are distributed for many milling apparatuses. As with most all-ceramic studies involving dental restorations, clinical data is limited for newer materials because of the relatively short time these materials have been in use. However, concerns about failure mechanisms for lithium disilicate restorations are similar to other glass-based ceramics. Fasbinder et al[26] reported a 100% survival rate of 62 eMax CAD crown restorations in 43 patients over a two-year recall period. There was no incidence of crown fracture or chipping reported, and relatively high alpha scores for color and marginal adaptation. A 94.8% 8-year survival rate was reported by Gehrt et al[27] for 94 single tooth for veneered eMax Press restorations. Furthermore, Wolfart et al published 8- and 10-year data on monolithic eMax Press 3-unit FDPs. A 93% survival rate at 8-years was

demonstrated and an 87.9% survival rate at 10-years.[28,29] These results are comparable to published results for conventional metal-based FDPs.[30] Although these results are promising, more long-term randomized clinical trials are needed to determine survival and complication rates. In addition, concerns over placing reinforced glass-based restorations in posterior teeth have been expressed. Of the studies previously mentioned, both anterior and posterior teeth were included. The manufacture currently recommends eMax Press and eMax CAD for anterior and posterior single unit restorations, but for multiple tooth FPDs, eMax Press is currently recommended only for anterior tooth replacement. Replacement of posterior teeth with lithium disilicate restorations is currently not recommended by the manufacture, as more long-term clinical studies are needed.

1.6 Rational for a clinical study using newer materials and CAD/CAM Technology

Although many in vitro studies have been conducted and published using newer all-ceramic materials and various CAD/CAM systems, there lies a need for more clinical studies examining variables that can affect restoration success. In vitro studies have shown laboratory values for hardness and flexural strength however these results cannot always be applied clinically. In vitro studies examining fit of restorations demonstrate what theoretically should be possible in ideal clinical situations. Long-term data cannot be extrapolated from these types of studies. This study focused on the use of two newer all-ceramic materials in conjunction with an accepted control material for posterior single tooth restorations. Intraoral scanning was used for digital

impressions and CAD/CAM technology was used for restoration fabrication. The primary aims of the study were to examine gingival response to crown restorations, marginal discrepancy values, and restoration quality using modified United States Public Health Service (USPHS) criteria.

Chapter 2 MATERIALS AND METHODS

2.1 Study Design

This was a prospective clinical study that included patients aged 18 – 70 who required restoration of one or two posterior teeth. Approval was given by an Institutional Review Board under the Office of Human Ethics at the University of North Carolina at Chapel Hill (IRB 11-2099.) Patients were screened and included based on the criteria listed in Appendix A. During the screening appointment, medical history was reviewed, and all patients had a bitewing and periapical radiograph exposed. For individuals meeting the selection criteria for treatment IRB approved consent documents were signed. Qualifying teeth were randomized into three restorative groups using computerized software prior to treatment. All individuals followed an approved written protocol for treatment. Patients were asked to be available for up to two years for recall appointments.

2.2. Visit 1 - Crown Preparation Treatment

Prior to any treatment performed baseline data measurements were made for tooth shade, gingival crevicular fluid (GCF) volume and bleeding on probing (BOP). Tooth shade was chosen using a Vita-Lumin Classic shade guide. GCF was collected using Periopaper Strips and a calibrated Periotron 8000 (Oraflow, Smithtown, NY)

was used for measuring volume following manufacturer's directions for use. BOP was measured using a UNC-15 periodontal probe (Hu-Friedy, Chicago, IL). GCF and BOP measurements were collected for each tooth assigned and a control tooth on the contralateral side. For patients receiving two crowns on similar contralateral teeth (e.g. mandibular first molars), a separate adjacent or opposing tooth was used as the control tooth for measurements. Periopaper strips were inserted on buccal and lingual sides of both treated and control teeth and values were recorded for each area. BOP was recorded as either present or not present. Patients were anesthetized using a local anesthetic (Lidocaine 2% w/ 1:100k epinephrine). A polyvinylsiloxane (Regisil, Dentsply-Caulk, Milford, DE) quadrant impression was made encompassing the tooth to be prepared. This was later used for fabrication of a provisional restoration from a bis-acryl provisional material (Integrity Temporary Crown and Bridge Material, Dentsply-Caulk). All crown preparations were prepared by one of three calibrated operators. Teeth requiring a build-up for appropriate resistance or retention form were treated with either an amalgam core (Sybralloy, Kerr Dental, Orange, CA) or composite core (Comp-Core, Premier Dental, Plymouth Meeting, PA) prior to crown preparation. All teeth were prepared using standard recommended preparation guidelines and water-cooled diamond burs (Premier Dental). Teeth were reduced 1.5-2.0mm occlusally, and 1.0-1.5mm axially with a deep chamfer margin circumferentially. A total occlusal convergence angle of 10-16 degrees was attempted for each preparation. Gingival cord (Ultrapak, Ultradent, South Jordan, Utah) was placed prior to final margination and scanning. When necessary a hemostatic liquid (Hemodent, Premier Dental) was used to control

sulcular fluid or bleeding prior to intraoral scanning. Following tooth preparation a second gingival retraction cord was placed and allowed to sit for 10 minutes. Following removal of the second gingival retraction cord teeth were scanned according to the type of restoration assigned; PFM and Zr restorations were assigned to the iTero scanner (Align Technology, Inc, San Jose, CA) and eMax crowns were assigned to the E4D scanner (D4D Technologies, Richardson, TX). Prior to scanning, one cord was removed. Scans were obtained according to manufactures directions for each intraoral scanner. Once scanning was complete, preparations were reviewed chairside using the scanned image, and if necessary, adjustments were made and the tooth was rescanned. An intraocclusal record was made using Virtual CADbite Registration material (Ivoclar Vivadent, Amherst, NY) for teeth assigned to the eMax group. PFM and Zr crown intraocclusal scans were made as directed by the iTero scanner. Once scanning was complete, all cords were removed, and a provisional restoration was fabricated, polished, and cemented using Temp-Bond (Kerr Dental). Patients were given post-operative instructions and oral hygiene instructions prior to being dismissed.

2.3. Crown Fabrication

Figure 1 demonstrates the workflow once scans were obtained of prepared teeth. PFM and Zr crown preparations scanned by the iTero scanner were sent electronically to the imaging center for Align Technology, Inc., in San Jose, Costa Rica. Prior to sending the scanned preparations, marginal areas were marked

electronically when significant deviations were noted from the default margin. Once the scanned images were cleaned and the marginal areas were trimmed by use of computer software, images and Cadent models were sent to Microdental Laboratories (Dublin, CA). Two dental laboratory technicians fabricated all PFM and Zr crowns. Both PFM and Zr crowns were designed using 3Shape software (3Shape, Copenhagen, Denmark). Die-space allowance was set at .030mm for Zr crowns, and .040mm for PFM crowns. PFM copings were produced by Rapid-Prototype printing using the Envisiontec Ultra ^{2} 3-D printer (EnvisionTEC, Dearborn, MI). Printed copings were invested and cast using a high noble alloy followed by application of porcelain (IPS d.Sign, In-Line Porcelain, Ivoclar-Vivadent, Schaan, Lichtenstein). The Cadent models were used for porcelain application and to verify interproximal contacts and marginal adaptation. Zr restorations were fabricated using milling technology (Wieland Mini, Wieland Dental, Pforzheim, Germany). Intrinsically colored monolithic Zr blocks were milled in the “green-state” and then sintered following manufacturers recommendations. If necessary, extrinsic stains were added for characterization (Empress stains, Ivoclar-Vivadent).

eMax CAD crowns were fabricated within the Graduate Prosthodontics Clinic at the University of North Carolina using design software within the E4D scanner. Restorations were sent electronically to the E4D mill and eMax CAD blocks were milled according to the selected shade. Default cement spacing settings of 0.10 mm were used. Following milling, sintering was completed following manufacturer’s directions. Staining and glazing was completed using eMax stains (Ivoclar-Vivadent).

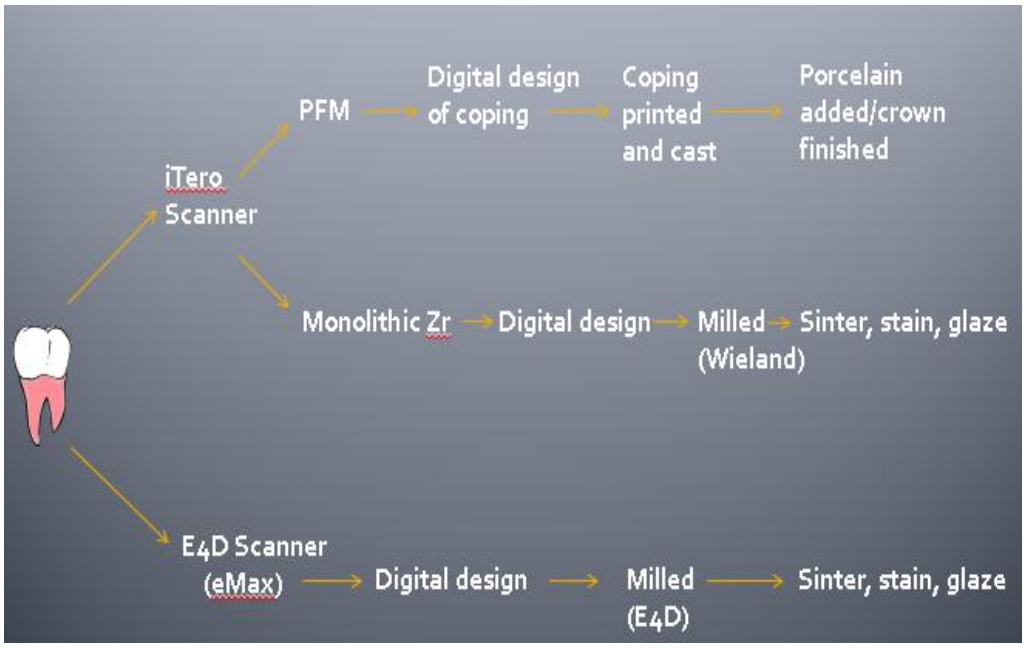

Figure 1. Flow of Restoration Fabrication

2.4 Visit 2 - Crown Insertion

Prior to crown insertion, one operator was calibrated for use of the modified USPHS crown quality criteria as listed in Table 2.1. USPHS ratings were recorded during the crown insertion appointment. Appendix A details specific characteristics for each criteria graded.

Table 2.1 Modified USPHS criteria for crown evaluation

	Marginal Adaptation	Crown Contour	Shade	Occlusion
R – Excellent	Ideal	Ideal	Ideal	Ideal
S – Acceptable	Less than ideal but acceptable	Less than ideal but minimal or no changes required	Less than ideal but no changes required	Less than ideal but no changes required/minimal adjustments necessary
T – Acceptable/ Modifications needed	Less than ideal, adjust or remake	Additions/ reductions necessary	Staining/other shade modifications required	Adjustments necessary
V – Unacceptable	Remake	Remake	Remake	Remake

Provisional crowns were removed, and excess provisional cement was cleaned from the treated tooth and gingiva. All crowns were fitted first by verifying interproximal contacts. If necessary, excess contacts were adjusted using Dialite porcelain polishing wheels (Brasseler, Savannah, GA). For crowns requiring addition of an interproximal contact, all other fit parameters were verified first prior to adding porcelain. For Zr and eMax crowns, black addition silicone was used to verify the fit of the intaglio surface (Fit-Checker, GC America, Alsip, IL). White addition silicone was used for PFM crowns (Fit-Checker, GC America). If necessary, internal adjustments were made for PFM crowns using a carbide bur. Zr and eMax crowns were adjusted by using a water-cooled fine diamond (Premier Dental). Margins were verified by using explorer feel. Following internal fitting of the crowns, occlusion was checked using occlusal indicating paper (Accufilm, Parkell Dental, Edgewood, NY). If adjustments were necessary Dialite polishing wheels (Brasseler) were used. If extensive adjustment was necessary, the crown was reglazed. Once seated, the shade of the crown was verified with the patient. All crowns were cemented using a

glass-ionomer cement (Ketac-Cem, 3M ESPE, St. Paul, MN). All excess cement was cleaned, and post-operative instructions were given to patients.

2.5 Visit 3 - One-month recall visit

Patients were recalled at one-month post-cementation for GCF and BOP measurements, and a polyvinylsiloxane impression of the cemented crown was made for micro-CT analysis of crown contour. A small gingival retraction cord (Ultrapak, Ultradent) was placed along the buccal margin prior to a light-body impression material being placed and then covered with a heavy-body material in a quadrant tray (Imprint 3, 3M ESPE). Photographs were made, and patients were given instructions for oral hygiene.

2.6. Micro-CT analysis

Following the one-month recall visit, the quadrant PVS impressions were sectioned through the buccal and occlusal surfaces of the impression as to include only the buccal section of the treated tooth. Samples were sent to the Biomedical Research Imaging Center (University of North Carolina, Chapel Hill, NC) for scanning. All samples were scanned using a Scanco µCT 40 scanner (Scanco Medical, Brüttisellen, Switzerland). Dicom files were created, and slices were approximately 20 microns in width with approximately 6 microns of resolution. Images were then analyzed using Image J software (U.S. National Institutes of

Health, Bethesda, Maryland). Measurements of each crown were made at six locations along the buccal margin, approximately 0.5-1.0 mm apart. Measurements were made from the prepared crown margin of the tooth to closest horizontal point of the crown restoration. Measurements were recorded as absolute values representing overextended or underextended crown margins.

2.7 Statistical analysis

Statistical analysis was performed using computerized software (SAS, Cary, North Carolina, USA). The Mantel Haenszel row mean score statistic was used to assess an association between crown system and the modified USPHS criteria for acceptable, thus the R, S and T values were combined for this analysis. Linear mixed models were used for assessment of crown system and GCF volumes. Generalized Estimated Equations (GEE) method was used for BOP analysis. One-way ANOVA was used to determine significance with horizontal marginal discrepancies between crown systems. For those showing significance pairwise comparisons were used between crown systems and scanners. Bonferoni's method was used to obtain adjusted P values, with statistical significance set at $\alpha<.05$.

Chapter 3 Results

A total of 32 crowns were fabricated for 22 patients. One patient received three crowns (protocol deviation), seven patients received two crowns, and the remaining 14 patients received one crown. Six crowns were rejected for unacceptable marginal adaptation and required refabrication. The remake rate due to unacceptable marginal adaptation was 18.8%. Two of the remade restorations were done by conventional techniques due to technical problems with the intraoral scanner used. These crowns were left out of the micro-CT marginal analysis since CAD/CAM techniques were not a part of the remake process. One eMax crown was fabricated using a PVS impression due to technical complications with the E4D scanner. This crown was fabricated using the same protocol for a Zr crown once the cast was scanned using 3Shape software, and this is included in analysis for gingival measurements and micro-CT analysis. Three patients did not return for the one-month follow-up, and were excluded from statistical analysis for gingival measurements, and horizontal marginal discrepancy values. One eMax crown was cemented using Variolink II composite cement (Ivoclar-Vivadent) due to concerns with thinness of the final restoration (approximately 1mm thick on occlusal portion).

There was no statistically significant association between crown type and marginal adaptation, shade or contour, however there was a statistically significant

association between occlusion and Zr crowns (P=.0005). Tables 3.1 - 3.4 show the distribution of USHPS criteria by crown system.

Table 3.1 Modified USPHS Criteria – Shade

Crown System	Modified USPHS Criteria – Shade				
	Unacceptable/ Rejected	Acceptable with modifications	Acceptable	Excellent	Total
PFM	0	2	6	4	12
Zr	0	6	3	1	10
eMax	0	1	9	0	10
Total	0	9	18	5	32

Table 3.2 Modified USPHS Criteria – Contour

Crown System	Modified USPHS Criteria – Contour				
	Unacceptable/ Rejected	Acceptable with modifications	Acceptable	Excellent	Total
PFM	0	2	7	3	12
Zr	0	0	9	1	10
eMax	0	3	7	0	10
Total	0	5	23	4	32

Table 3.3 Modified USPHS Criteria – Marginal Adaptation

Crown System	Modified USPHS Criteria - Marginal Adaptation				
	Unacceptable/ Rejected	Acceptable with modifications	Acceptable	Excellent	Total
PFM	3	0	8	1	12
Zr	1	0	5	4	10
eMax	2	1	7	0	10
Total	6	1	20	5	32

Table 3.4 Modified USPHS Criteria – Occlusion

Crown System	Modified USPHS Criteria - Occlusion				
	Unacceptable/ Rejected	Acceptable with modifications	Acceptable	Excellent	Total
PFM	0	0	7	5	12
Zr*	0	0	2	8	10
eMax	0	3	7	0	10
Total	0	3	16	13	32

(* denotes statistically significant values, Mantel Haenszel row mean score statistic)

There were no statistically significant differences among the three crown systems for GCF volumes or BOP. Tables 3.5, 3.6 and Figure 2 represent gingival parameter measurements.

Table 3.5 Linear Mixed Models Test for Significance of GCF Volumes– P values

	Buccal Surface	**Lingual Surface**
Crown System	0.2235	0.3810
Time of measure	0.4725	0.2136
Treated vs. Control	0.5836	0.0663

Figure 2. Bleeding on Probing (%)

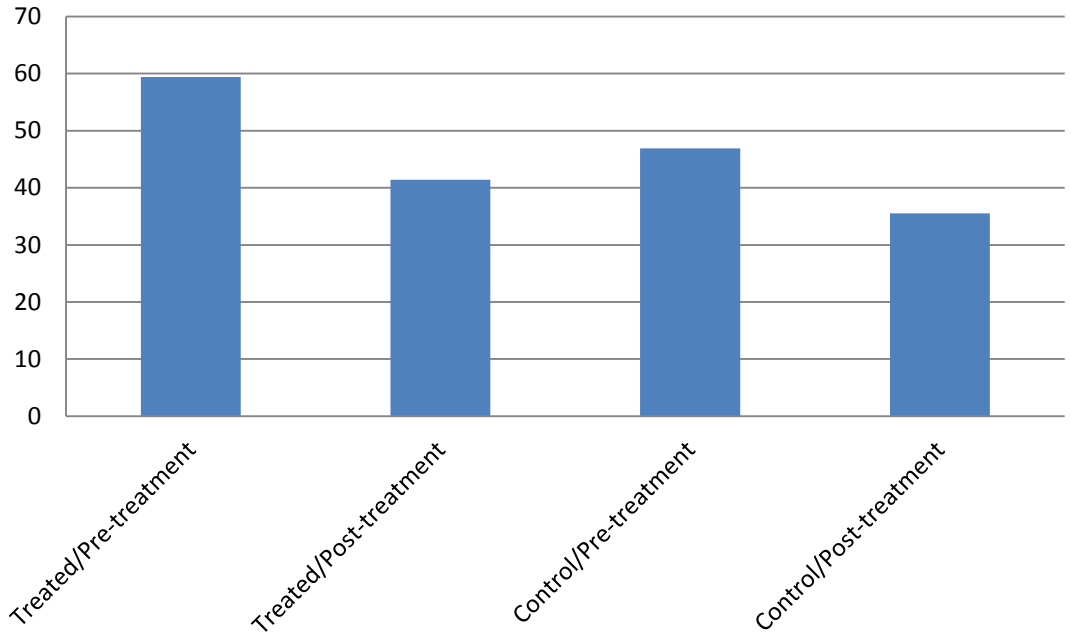

Table 3.6 Generalized Estimating Equations (GEE) Method for significance between variables for BOP

Variable	p-value
Crown System	0.9143
Time of Measure	0.0697
Tooth Status	0.1006

Since significance was shown (P=.003) using ANOVA, pairwise comparisons were used to determine which systems were significant in regards to horizontal discrepancy values. Only eMax vs. Zr showed statistical significance (P=.027). Figure 3 and Tables 3.7 and 3.8 show descriptive statistics as well as pairwise comparisons for horizontal discrepancy values.

Figure 3. Horizontal Discrepancy Findings

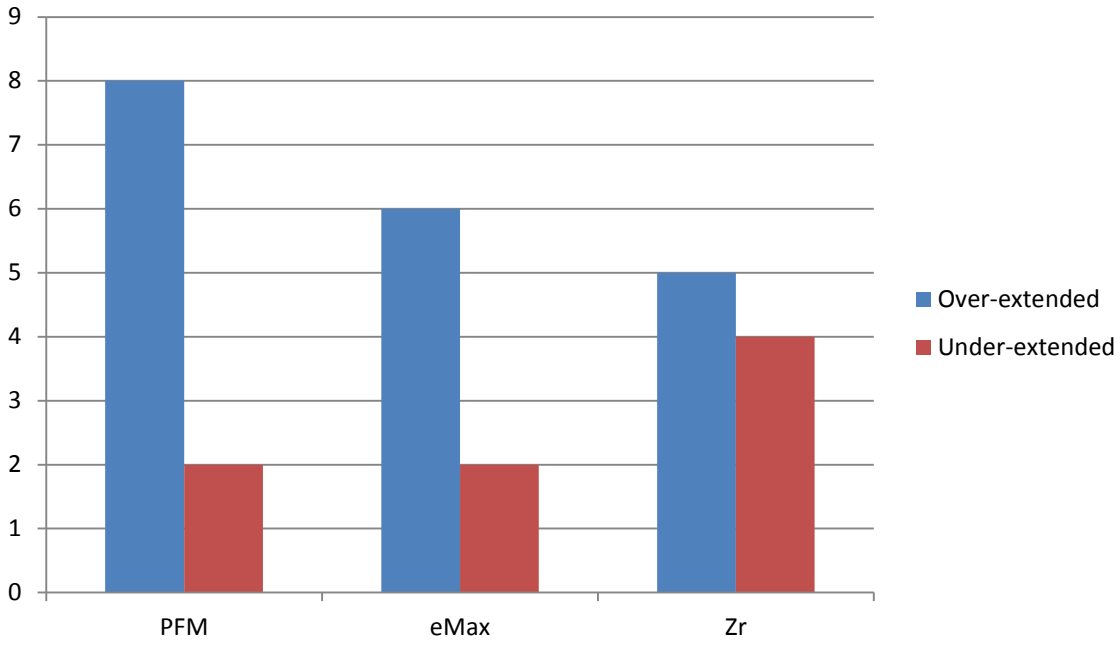

Table 3.7 Descriptive Statistics for Horizontal Marginal Discrepancy

	Mean Horizontal Marginal Discrepancy (μ)	S.D.	Range (μ)
eMax	113.8	43.2	11.0-260.0
Zr	68.5	33.4	15.0-190.0
PFM	92.4	20.6	23.0-210.0

Table 3.8 Pairwise Comparisons between crown systems

Group 1	Group 2	F	DF	Adj P
eMax	Zr	8.07	1	0.0270
eMax	PFM	1.89	1	0.5445
Zr	PFM	2.50	1	0.3798

Chapter 4 Discussion

4.1 Gingival Parameters

Many studies have indicated that the presence of a restoration near or below the gingival margin may induce localized inflammation, and potentially lead to future periodontal complications.[15,31, 32] Gemalmez[33] et al found significantly higher BOP readings for all-ceramic crowns with subgingival margins as compared to supra- or equigingival margins. Al-Wahadni[34] et al reported similar findings for 82 teeth that had received IPS Empress restorations. An increase in plaque index, gingival index and pocket depths were found for restored teeth compared to a control teeth. Although the data is short-term for this study, the analysis for GCF volume and the presence of BOP in this study indicate there were no statistically significant associations for any of the gingival parameters measured in regards to crown system, time of measurement, or for the treated or control tooth. The null hypothesis was accepted for this primary aim. Although there was an overall slight increase in GCF volume for the lingual surfaces of treated teeth, it was not statistically significant. It is worth noting that the frequency of BOP was less for both control and treated teeth at the one-month reevaluation. This may be due to the Hawthorn effect for study subjects. Six-month and one-year may reveal changes within subjects.

4.2 Modified USPHS Criteria

The null hypothesis was rejected for modified USPHS criteria since Zr crowns showed statistical significance in regards to crown occlusion. Very few Zr crowns required intraoral adjustment, which lends credibility to the accuracy of the intraoral scan, the method of obtaining an intraocclusal record, and the digital design and fabrication of the Zr restorations. The method of obtaining an intraocclusal record differed for the iTero and E4D scanners. The iTero scanner allowed for direct intraoral capture of the interarch relationship, while a PVS bite registration was made and then scanned intraorally for the E4D system. There is a possibility for the bite registration material to be inaccurate or move during the scan, as well as the digital alignment of the bite registration to be mismatched by the clinician. Although not statistically significant for any crown system, contour also reflects scan accuracy as the detail of adjacent dentition needs to be replicated accurately for interproximal contacts and overall crown contour to be correct. The majority of crowns (71.9%) were acceptable with either minimal adjustments or no adjustments. Although models were fabricated for crowns using the iTero scanner, only the PFMs required the use of the model for actual design. Interestingly, only Zr and PFM crowns received an excellent rating for the contour category while none of the eMax crowns were rated excellent. This could be explained by the use of a model to verify interproximal and occlusal contacts prior to crown seating. It could also be attributed to the clinician's design of the eMax crowns as compared to the experienced laboratory technicians' fabrication of Zr and PFM crowns.

Shade did not show statistical significance in any crown system, but deserves mention, as three times as many Zr crowns required custom staining as did PFMs. This was necessary despite the different shades of 3Y-TZP blocks available for the Zenostar system. Overall the eMax crowns showed the greatest shade acceptance without changes being required. This has been noted in the literature, as Zr restorations lack translucency and the ability to mimic a natural tooth shade and often require veneering porcelain to obtain esthetic results.[35]

Marginal adaptation for the majority of crowns was satisfactory. There were two PFM and one Zr crowns rejected early in the study prior to the operator marking the margins with the iTero scanner before sending for electronic processing. Once this process was done, there was only one other PFM rejected from the iTero category. The technique used to determine whether marginal adaptation was acceptable was by explorer feel. A bitewing radiograph was made for those restorations showing questionable interproximal adaptation. Although it was not specified what area of the margin deemed a crown unacceptable for statistical analysis, it was noted clinically that five of the six crowns requiring refabrication had discrepancies in an interproximal region. The interproximal regions and margins that lie close to the gingival sulcus remain challenging for scanners to capture, and for technicians to mark digitally. This is a limitation of using an intraoral scanning system that does not allow for the clinician to perform the actual digital die-trim, but instead relies upon a dental laboratory technician to read the scan and determine margin placement. Additionally, limitations with explorer feel could have resulted in potentially more crowns being unacceptable. It was shown by Hayazaki et al[36] that

horizontal discrepancies were more easily detected than vertical discrepancies for clinicians using different diameter explorer tips. Moreover, Leknius et al[37] showed different ranges of acceptability for dental students and experienced faculty members during crown seating, with median threshold values ranging from 95-113 microns. It is possible that more crowns could have been considered unacceptable if a new explorer of verified dimensions was used during crown evaluation and if more than one examiner was used to verify crown adaptation.

4.3 Horizontal marginal discrepancy values.

The micro-CT data was somewhat difficult to manipulate in order to visualize a vertical “gap” for the majority of samples. It is theorized that due to the short time (one-month) between cementation and impression, it is likely that many of the vertical discrepancies were not detected because of cement within these regions. However, differences in the overall horizontal contour of each crown system could be measured consistently, and there was a significant difference between crowns fabricated using the E4D system versus the iTero scanning system. Thus, the null hypothesis was rejected for this aim. The use of a model for PFM and Zr crowns is a possible explanation for this difference. eMax crowns were fabricated purely by digital design and milling, thus there was no model involved. Likewise, Zr crowns were digitally designed and milled, but finished on a solid model to verify contours. It is possible that Zr crowns could be milled, and then adjusted or rejected if marginal contour is inadequate. Another explanation lies with the type of mill that fabricated the restorations. The E4D mill is a 3-axis mill, with three variations of milling

diamonds to complete cutting of the eMax block. The Wieland mini-mill is a 4-axis mill with five different milling tools in varying diameters, so it is possible the mill could better accommodate marginal areas that were less than a deep chamfer's width, or had uneven architecture. The type of cement for all of the restorations was the same however the die spacing included in each crown type differed, so this could have affected the fit of some restorations. In addition, the type of preparation design deserves mention, as a deep chamfer margin was chosen. Other published literature has mentioned the use of a modified or rounded shoulder as a better type of margin design for all-ceramic restorations that will be of a milled-variety. Souza et al[38] found statistically significant differences in vertical marginal discrepancies between three margin designs using the CEREC system. The rounded shoulder design had a mean value of 29.24 microns, while the titled chamfer had a mean value of 99.92 microns. Baig et al[18] showed higher marginal discrepancy values for milled restorations with both a deep chamfer and rounded shoulder margin design.

4.4 Limitations of the Study

Blinding of the practitioners could have been incorporated into this study to ensure lack of bias with use of the intraoral scanners. In addition, a silicon replica of the fitted crown prior to cementation could have enabled analysis of marginal discrepancy values. Scanning electron microscopy might have been used to visualize and measure marginal discrepancies or "gaps" in a two-dimensional manner. A single independent clinician to evaluate crowns at the time of insertion could have strengthened the study as well. For comparison of marginal discrepancy

values a control group of crowns that were fabricated using traditional methods could have been incorporated. The type of cement used is not the manufacturer's recommended cement for eMax crowns, but was chosen for consistency. This could have affected marginal adaptation, as eMax crowns are recommended to be cemented using a resin cement. The small sample size of this study may be difficult to draw definitive conclusions, as well as the short time-span in which crowns were evaluated. Long-term follow-up of subjects will help determine if there are differences in gingival response to crowns systems, as well as the longevity of each type of restoration.

Chapter 5 Conclusion

Within the confines of this study, posterior single tooth restorations can be fabricated using CAD/CAM technology in various fashions. There are multiple pathways that can lead to the end result, and all or some of them can involve the use of CAD/CAM technology. CAD/CAM designed restorations show similar ranges of acceptance using modified USPHS criteria for marginal adaptation, shade, contour, and occlusion. In this study it was shown that occlusion for the Zr crowns was significantly better than the other crown types, and required less adjustments overall. In addition, crowns fabricated from a scan that allows production and use of a solid model showed statistically significant differences in regards to horizontal marginal discrepancy values. Intraoral scanning devices and digital design workflow that eliminates the use of a working model deserves further investigation.

APPENDIX A

Inclusion Criteria	Exclusion Criteria
a. Provision of written informed consent	a. Untreated rampant caries and uncontrolled periodontal disease
b. Age 18-70 years	b. Absence of opposing dentition
c. Good physical and mental health	c. Known pregnancy at time of inclusion
d. In need of one or two crowns to repair damaged or carious teeth	d. Present alcohol or drug abuse
e. A minimum of 20 teeth with stable intraocclusal contacts	e. Any systemic/local disease or condition that would prevent standard dental therapy using local anesthetic
f. Willing to return for 6 and 12 month recall visits	f. Known allergy to any restorative materials used in this study
g. Available contra-lateral, minimally restored or non-restored tooth to serve as control	g. History of presence of disease that could affect outcome of study
h. Mesial and/or distal tooth with proximal contact, and opposing tooth with occlusal contact	h. Study tooth may not serve as abutment for a removable partial denture
	i. Presence of periodontal or pulpal disease for the study tooth or control tooth
	j. Unlikely to be able to comply with study procedures according to Investigators
	k. Unable or unwilling to return for follow-up visits for a period of 2 years
	l. Unrealistic esthetic expectations of the patient

APPENDIX B

Modified USPHS/CDA criteria – Marginal Adaptation

R – Excellent/Ideal – Explorer does not catch; continuous adaptation and indistinguishable margins

S - Acceptable – Explorer detects but cannot penetrate marginal area

T – Acceptable w/ modifications – Explorer detectable and penetrates marginal area

V – Unacceptable – Explorer detectable, gross marginal discrepancies upon explorer examination

Modified USPHS/CDA criteria – Crown Contour

R – Excellent/Ideal – contour follows normal physiologic tooth contour with no adjustments needed

S – Acceptable – slightly under/overcontoured; no modifications needed

T – Acceptable w/ modifications – restoration requires significant addition or removal of structure for function (contact addition or contact reduction, recontouring)

V – Unacceptable – restoration is undercontoured/overcontoured such that remake is necessary

Modified USPHS/CDA criteria – Color/Surface

R – Excellent/Ideal – restoration matches and complements existing dentition harmoniously

S – Acceptable – restoration closely matches surrounding dentition, slight shade difference

T – Acceptable w/ modifications– restoration requires addition of surface staining to meet acceptable shade match

V – Unacceptable – restoration requires remake in order to meet esthetic requirements

Modified USPHS/CDA criteria – Occlusion

R – Excellent/Ideal – restoration demonstrates ideal, harmonious relationship with existing occlusal scheme

S – Acceptable – restoration demonstrates adequate occlusal anatomy and function, but less than ideal; minor adjustments may be necessary

T – Acceptable w/ modifications– restoration requires addition or elimination of occlusal contacts

V – Unacceptable – restoration lacks any occlusal contacts, or excessive contact and requires remake

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