

MICRO-CT EVALUATION OF THE MARGINAL FIT OF CAD/CAM ALL CERAMIC CROWNS

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ABSTRACT

Christian Brenes: CAD/CAM MATERIALS AND TECHNOLOGIES FOR ALL CERAMIC RESTORATIONS: A REVIEW OF THE LITERATURE
(Under the direction of Ibrahim Duqum)

Objectives: Evaluate the marginal fit of CAD/CAM all ceramic crowns made from lithium disilicate and zirconia using two different fabrication protocols (model and model-less). METHODS: Forty anterior all ceramic restorations (20 lithium disilicate, 20 zirconia) were fabricated using a CEREC Bluecam scanner. Two different fabrication methods were used: a full digital approach and a printed model. Completed crowns were cemented and marginal gap was evaluated using Micro-CT. Each specimen was analyzed in sagittal and trans-axial orientations, allowing a 360° evaluation of the vertical and horizontal fit. RESULTS: Vertical measurements in the lingual, distal and mesial views had an estimated marginal gap from 101.9 to 133.9 microns for E-max crowns and 126.4 to 165.4 microns for zirconia. No significant differences were found between model and model-less techniques. CONCLUSION: Lithium disilicate restorations exhibited a more accurate and consistent marginal adaptation when compared to zirconia crowns. No statistically significant differences were observed when comparing model or model-less approaches.

Keywords: CAD/CAM, Zirconia, Lithium Disilicate, Micro-CT.

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LIST OF ABBREVIATIONS

CAD:	Computer Aided Design
CAM:	Computer Aided Manufacturing
FDP:	Fixed Dental Prosthesis
OBJ:	Object
SEM:	Scanning Electronic Microscopy
STL:	STEREO LITHOGRAPHY
Y-TZP:	Yttria-Tetragonal Zirconia Polycrystal
ZLS:	Zirconia Reinforced Lithium Disilicate

CHAPTER 1: CAD/CAM MATERIALS AND SYSTEMS

INTRODUCTION

Dental crowns have been used for decades to restore compromised or heavily restored dentition, and for esthetic improvements. New CAD/CAM materials and systems have been developed and evolved in the last decade for fabrication of all-ceramic restorations.

Dental CAD/CAM technology is gaining popularity because of its benefits in terms of manufacturing time, material savings, standardization of the fabrication process, and predictability of the restorations. When the CAD/CAM manufacturing process is employed, the number of steps required for the fabrication of a restoration is less compared to traditional methods (Fig 1). Another benefit of CAD/CAM dentistry include the use of contemporary materials and data acquisition instruments; which represents a non-destructive method of saving impressions, restorations and information that are saved on a computer and constitute an extraordinary communication tool for evaluation. Cooper (2011) stated that: "CAD/CAM technology is an efficient and effective point for critical evaluation of the proposed restorations prior to its fabrication".

The incorporation of dental technology has not only brought a new range of manufacturing methods and material options but also some concerns about the processes involving restorations fit, quality, accuracy, short and long-term prognosis (Miyazaki, 2009).

The purpose of this review is to provide an overview of the literature regarding the different materials and systems available until June 2014. In addition marginal fit of CAD/CAM restorations is included for clinical considerations.

1. CAD/CAM MATERIALS

1.2 GLASS CERAMICS

The first in office ceramic material was Vitablock Mark I (Ivoclar Vivadent, Liechtenstein), it was a feldspathic-based ceramic compressed into a block that was milled into a dental restoration (Poticny, 2012). After the invention of the Mark I block the next generation of materials for CAD/CAM milling fabrication of all-ceramic restorations were Vita Mark II (Ivoclar Vivadent, Liechtenstein) and Celay (VITA, Bad Säckingen, Germany), which replaced the original Mark I in 1987 for fine feldspathic porcelains primarily composed of silica oxide and aluminum oxide (Fasbinder, 2002) (Pallesen, et al. 2000). Mark II blocks are fabricated from feldspathic porcelain particles embedded in a glass matrix and used for single unit restorations available in polychromatic blanks nowadays. On the other hand, Celay ceramic inlays have been considered clinically acceptable by traditional criteria for marginal fit evaluation (Sorensen, et al. 1994).

Dicor-MGC was a glass ceramic material composed of 70% tetrasilicic fluormica crystals precipitated in a glass matrix; but this material is no longer available in the market (Chang, et al. 2003). Studies from Isenberg, et al. (1992) suggested that inlays of this type of ceramics were judged as clinically successful in a range from 3 to 5 years of clinical service (Kelly, et al. 1996). In 1997, Paradigma MZ100 blocks (3M ESPE, Center St. Paul, MN) were introduced as a highly filled ultrafine silica ceramic particles embedded in a resin matrix; the main advantage of this material is that it can be use as a milled dense composite that was free of polymerization shrinkage but can not be sintered or glazed (Poticny, et al. 2010).

In early 1998 IPS ProCAD (Ivoclar Vivadent, Liechtenstein) was introduced as a leucite reinforced ceramic similar to IPS Empress but with a finer particle size; this material was designed to be use with the CEREC system (Sirona Dental, Charlotte, NC) and was available in different shades (Fasbinder, 2002). More recently the introduction of IPS Empress CAD (Ivoclar

Vivadent, Liechtenstein) and Paradigm C (3M ESPE, Center St. Paul, MN) that according to the manufacturer 3M ESPE it is a 30%-45% leucite reinforced glass ceramic with a fine particle size.

To overcome esthetic problems of most CAD/CAM blocks having a monochromatic restoration; a different version was developed as a multicolored ceramic block which was called Vita TriLuxe (Ivoclar Vivadent, Liechtenstein) and also IPS Empress CAD Multiblock; the base of the block is a dark opaque layer, while the outer layer is more translucent; the CAD software allows the clinician to position or align the restoration into the block for the desired outcome of the restoration (Kurbad, et al. 2006) (Fritzsche. 2004).

In 2014 the Enamic (VITA, Bad Säckingen, Germany) material was released as a ceramic network infiltrated with a reinforcing polymer network that has the benefits of a ceramic and resin in one material but no clinical data is available (McLaren, et al. 2013).

1.3 ALUMINA BASED CERAMICS

VITA (Bad Säckingen, Germany) alumina blocks are In-Ceram Alumina is available for milling with the CEREC system (Sirona Dental, Charlotte, NC) and now compatible with other milling machines as well. Due to the opacity of alumina based ceramic materials the In-Ceram Spinell (VITA, Bad Säckingen, Germany) blocks were developed as an alternative for anterior esthetic restorations; it is a mixture of alumina and magnesia. Its flexural strength is less than In-Ceram Alumina, but veneering with feldspathic porcelain for a more esthetic result could follow it after the milling process (Bindl, et al. 2004).

Nobel Biocare developed Procera material; for its fabrication high purity aluminum oxide is compacted into an enlarged die that is fabricated from the scanned data (Denissen, et al. 2000). The enlarged fabricated core shrinks to the dimensions of the working die when sintered at 1550° C; this material offers a very high strength core for all-ceramic restorations; the crown is finished with the application of feldspathic porcelian (Fradeani, et al. 2005) (Esquivel, et al.

2001). More recently In-Coris AL (Sirona Dental, Charlotte, NC) has been introduced as a high strength aluminum oxide block with similar mechanical properties as Procera (Nobel Biocare, Zürich-Flughafen Switzerland).

1.4 LITHIUM DISILICATE

Lithium disilicate is composed of quartz, lithium dioxide, phosphor oxide, alumina, potassium oxide and other components. According to Saint-Jean (2014) the crystallization of lithium disilicate is heterogenous and can be achieved through a two or three stage process depending if the glass ceramic is intended to be used as a mill block (E-max CAD) or as a press ingot (E-max press).

Lithium disilicate blocks (blue blocks) are partially sintered and relatively soft; they are easier to mill and form to the desired restoration compared to fully sintered blocks; after this process the material is usually heated to 850°C for 20-30 minutes to precipitate the final phase. This sintering step is usually associated with a 0.2% shrinkage accounted for by the designing software (Shen, et al. 2014). Nowadays, blocks of lithium disilicate with the commercial name E-Max (Ivoclar Vivadent, Liechtenstein) are available for both in-office and in-laboratory fabrication of all-ceramic restorations; monolithic blocks require layering or staining to achieve good esthetic results (Kelly, 2004). Different in vitro studies that evaluate marginal accuracy of milled lithium disilicate revealed that these restorations could be as accurate as 56-63 microns (May, Russell, Razzoog, & Lang, 1998).

According to the manufacturer specifications the designing principles for E-max (lithium disilicate) are produced by default in the designing software, but in full all-ceramic single crowns structures the minimum thickness must be applied in the preparation design (Table 1).

Table 1: Recommended dimensions for E-max CAD by Ivoclar Vivadent

Material thickness	Anterior	Premolar	Molar	Veneers
Staining Technique	1.2	1.5	1.5	0.6
Cut-back technique	1.2	1.5	1.5	0.6
Layering technique	0.8	0.8	-	-

Values are expressed in millimeters

During the crystallization process the ceramic is converted from a lithium metasilicate crystal phase to lithium disilicate. Some commercial types of ceramics are Empress CAD and IPS E-max (Ivoclar Vivadent, Liechtenstein). The first one is a leucite based glass ceramic with a composition similar to Empress ceramic. IPS E-max was introduced in 2006 as a material with a flexural strength of 360 to 400 MPa (two to three times stronger than glass ceramics); the blocks are blue in the partially crystallized state but it achieves the final shade after it is submitted to the firing process in a porcelain oven for 20 to 25 minutes to complete the crystallization; the final result is a glass-ceramic with a fine grain size of approximately 1.5 μm and 70% crystal volume incorporated in a glass matrix (McLaren, et al. 2013).

In 2013 Dentsply (York, PA) introduced Celtra Duo; and more recently VITA (Bad Säckingen, Germany) with Suprinity; were the first glass ceramics reinforced with zirconia. Suprinity is a zirconia reinforced lithium silicate ceramic (ZLS) available in a precrystallized or fully crystalized (Suprinity FC) state indicated for all kind of single all-ceramic restorations.

1.5 ZIRCONIA

Zirconia has been used in dentistry as a biomaterial for the fabrication of crowns and FPD's restoration since 2004; it has been especially useful in the most posterior areas of the mouth where high occlusal forces are applied and there is limited inter-occlusal space (Anusavice, 2014). Dental restorations are made as full contour monolithic structures or frameworks that can be overlaid with porcelain after a cutback for more esthetic results.

Zirconia is a polymorphic material that can have three different phases depending on the temperature: monoclinic at room temperature, tetragonal above 1170 °C, and cubic beyond 2370 °C. According to Piconi (1999) "the phase transitions are reversible and free crystals are associated with volume expansion". Different authors state that when zirconia is heated to a temperature between 1470°C and 2010°C and cooled a volume shrinkage of 25 to 35% can occur that could affect marginal fit or passiveness of the restorations (Anusavice, 2014). This feature limited the use of pure zirconia until 1970 when Rieth and Gupta developed the yttria-tetragonal zirconia polycrystal (Y-TZP) containing 2-3% mol-yttria in the intent to minimize this effect (Luthardt, et al. 1999).

One of the most interesting properties of zirconia is transformation toughening; Kelly (2008) describes it as: "A phenomenon that happens when a fracture takes place by the extension of an already existing defect in the material structure, with the tetragonal grain size and stabilizer, the stress concentration at the tip of the crack constitutes an energy source able to trigger the transformation of tetragonal lattice into the monoclinic phase." This process dissipates part of the elastic energy that promotes progression of cracks in the restoration; there is a localized expansion of around 3.5% that increases the energy that opposes the crack propagation (Kosmac, 1999).

Zirconia restorations can be fabricated from fully sintered zirconium oxide or partially sintered zirconium oxide blanks (green-state). Proponent of milling fully sintered zirconia claim that fitness of restorations is better because it avoids volumetric changes during the fabrication

process. On the other hand, the green state is easier and faster to mill and proponents of milling partially sintered blanks claim that micro cracks can be induced to the restoration during the milling process and it also requires more time and intensive milling processes; this micro defects or surface flaws can affect the final strength of the final restoration and could potentially chip the marginal areas; however further research is needed about this topic (Luthardt, 2004).

One of the first systems that used zirconia was In-Ceram Zirconia (VITA, Bad Säckingen, Germany), which is a modification of the In-Ceram Alumina but with the addition of partially stabilized zirconia oxide to the composition (Sundh, et al. 2004). Recently many companies have integrated zirconia into their CAD/CAM workflow due to its mechanical properties, which are attractive for restorative dentistry; some of this properties are: high mechanical strength, fracture toughness, radiopacity for marginal integrity evaluation, and relatively high esthetics (Raigrodski, 2004).

Different systems in the market are using zirconia as one of their main materials such as: Ceramill Zolid (Amann Girbach, Herrschaftswiesen, Austria), Prettau (Zirkonzahn, An der Ahr, Italy), Cercon (Dentsply, NY), BruxZir (Glidewell Laboratories, Newport Beach, CA), IPS ZirCAD (Ivoclar Vivadent, Liechtenstein), Zenostar(Ivoclar Vivadent, Liechtenstein), inCoris ZI (Sirona Dental, Charlotte, NC), VITA In-Ceram YZ (VITA, Bad Säckingen, Germany), among others. Companies have introduced materials that are in combination with zirconia to improve its properties in different clinical situations. Lava Plus (3M ESPE, Center St. Paul, MN) for example is a combination of Zirconia and a nano-ceramic. Table 2 describes some of the CAD/CAM materials used by dental clinicians and laboratories for all-ceramic restorations and its restorative indications by the manufacturers.

Table 2. Most used CAD/CAM materials for all ceramic restorations available for 2014.

Material	Composition	Company	Indications
ArgenZ	Zirconia	Argen	Crowns, abutments, onlays.
BruxZir	Zirconia	Glidwell	Copings, multiunit, crowns, inlays/onlays
Ceramill Zolid	Zirconia	Amann Girbach	Crowns, inlays, onlays, multiunit.
Cercon ht	Zirconia	Dentsply	Copings, multiunit, crowns, veneers.
DC Zirkon	Zirconia	DCS Dental/Vita	Crowns, copings.
Empress CAD	Leucite reinforced	Ivoclar	Crowns, inlays, onlays.
Enamic	Ceramic resin	Ivoclar Vivadent	Crowns, inlays/onlays.
InCoris AL	Alumina oxide	Sirona	Copings, multiunit.
InCoris ZI	Zirconia	Sirona	Multiunit, crowns, inlays/onlays.
IPS E-max	Lithium Disilicate	Ivoclar	Crowns, inlays, onlays.
IPS Zircad	Zirconia	Ivoclar	Copings, multiunits.
Lava Ultimate	Ceramic resin	3M ESPE	Crowns, inlays, onlays.
Paradigm C	Leucite reinforced glass ceramic	3M ESPE	Crowns, inlays, onlays.
Prettau	Full contour zirconia	Zirkonzahn	Copings, multiunit, crowns, inlays/onlays
VITA Alumina	Sintered Aluminum	Vident	Crowns, inlays, onlays,

	Oxide		veneers.
Vita InCeram YZ	Zirconia	Vident	Crowns, inlays, onlays, multiunit, veneers, abutments.
VITA Mark II	Feldspathic porcelain	Vident	Crowns, inlays, onlays, veneers.
VITA Spinell	Aluminum oxide glass infiltration	Vident	Anterior crowns, veneers.
Vita TriLux	Feldspathic ceramic	Vident	Crowns, veneers, onlays, inlays.
Zenostar	Zirconia	Ivoclar Vivadent	Copings, multiunit, crowns, veneers.

2. CAD/CAM SYSTEMS

A number of different manufacturers are providing CAD/CAM systems which generally consist of a scanner, design software and a milling machines or 3D printers. Laboratories are able to receive digital impression files from dentists or use a scanner to create digital models that are use for restorations designing or CAD. Dental scanners vary in speed and accuracy. Milling machines vary in size, speed, axes, and also in which restorative materials can be milled; in this category milling machines could be classified as wet or dry depending if the materials require irrigation.

The development of dental CAD/CAM systems occurred around 1980 with the introduction of the Sopha system developed by Dr. Duret. Few years after that event Dr. Mormann and the electrical engineer Marco Brandestini developed the CEREC-1 system in 1983, the first full digital dental system created to allow dentist to design and fabricate in office restorations. Since

then the continuous evolution of systems dedicated to this field has continue and has exponentially increased in the last decade (Mormann,W. 2006).

Cerec systems has evolved into CEREC Bluecam scanner; accuracies as close as 17 microns for a single tooth have been reported by authors using this system. Recently CEREC Omnicam was introduced offering true color digital impressions without the need of a contrast medium (Mehl, Ender, Mormann, & Attin, 2009). In a recent study by Neves, et al (2013) about marginal fit of CAD/CAM restorations fabricated with CEREC Bluecam; they compared lithium disilicate single unit restorations to heat-pressed restorations and 83.8% of the specimens had measurements of vertical gap with less or at least 75 microns.

The Cerec InLab CAD software was designed for dental laboratories for a wide range of dental capabilities that can be combined with third party systems. With this software the dental technician is able to scan their own models using Sirona inEos X5 scanner and design the restoration; once this process is completed the file can be send to a remote milling machine or a milling center for fabrication in a wide range of materials.

The Procera system (Nobel Biocare, Zürich-Flughafen Switzerland) introduced in 1994 was the first system to provide fabrication of a restoration using a network connection. According to research data the average ranges of marginal fit of this restorations are from 54 to 64 microns (May, et al. 1998). A computer integrated crown reconstruction system (CICERO) introduced by Denison et al. in 1999 included a rapid custom fabrication of high strength alumina coping and semi finished crowns to be delivered to dental laboratories for porcelain layering and finishing, but is no longer available (Vander, et al. 2001).

Another system that was developed years ago was the Celay system, which fabricated feldspathic restorations through a copy-milling process. The system duplicated an acrylic resin pattern replica of a restoration. Zirkonzahn company (An der Ahr, Italy) developed a similar system called the Zirkograph in 2003 which was able to copy-mill zirconia prosthesis and restorations out a replica of the restoration. Few years after the invention of this system the

Cercon system (Dentsply, York, PA) was able to design and mill zirconia restorations out of a wax pattern (Raigrodski, 2004).

Almost at the same time that these companies develop this first copy mill prototypes Lava (3M ESPE) introduced in 2002 the fabrication of yttria-tetragonal zirconia polycrystal (Y-TZP) cores and frameworks for all ceramic restorations. With the Lava system the die is scanned by a optical process, the CAD software designs and enlarge the restoration or framework that is milled from a pre-sintered blank (Piwowarczyk, et al. 2005). Studies on marginal adaptation suggest that Lava restorations have a marginal fit that can be as low as 21 microns (Hertlein, et al. 2003). Some other systems that were able to mill zirconia were DCS Zirkon(DCS Dental) and Denzir (Guazzato, 2004).

In the last decade companies have decided to differentiate their products by having a full CAD/CAM platform or by focusing on specific areas of expertise like CAD software and intraoral scanners; these companies claim to have an open platform because their systems allow exporting universal files such as Stereo Lithography (STL) or Object (OBJ) to be used with the majority of nesting software and milling machines in the market that are able to import them. Defenders of close platforms claim that the integration of different CAD and CAM systems does not allow for a good integration between parts and probably lead to the incorporation of fabrication errors; at this point no research about systems integration is available. Table 3 shows some of the systems used for dental CAD with their file output; Table 4 shows some of the most used CAM systems with their material recommendations and capabilities.

Table 3. Most used dental CAD systems available for 2014

CAD System	Manufacturer	File output
3Shape	3Shape	Proprietary/STL
ARTI / Modelliere	Zirkonzahn	STL

CeraMill	Amann Girbach	STL
Cercon Eye/Art	Dentsply	Proprietary
Cerec	Sirona	Proprietary
Delcam	Delcam	STL
Dental Wings	Dental Wings	STL
E4D	Planmeca	Proprietary/STL
Exocad	Exocad	STL
InLab	Sirona	Proprietary/STL
Procera	Nobel Biocare	Proprietary/STL

Table 4. Most used dental CAM systems available for 2014

CAM System	Manufacturer	Type	Milling materials
BruxZir Mill	Glidewell	Dry	Zirconia, wax, PMMA
CARES	Straumann	Wet/Dry	Zirconia, Glass ceramic, ceramic resins, Lithium Disilicate, Chrome Cobalt, PMMA, wax, titanium.
CeraMill Motion 2	Amann Girbach	Wet/Dry	Zirconia, Glass ceramic, ceramic resins, Lithium Disilicate, Chrome Cobalt, PMMA, wax, titanium.
Datron D5	Datron	Wet/Dry	Zirconia, Glass ceramic, ceramic resins, Lithium Disilicate, Chrome Cobalt, PMMA, wax, titanium.
Denzir	Ivoclar	Dry	Zirconia
E4D PlanMill 40	Planmeca	Wet	Lithium disilicate, ceramic resin
InLab MC XL	Sirona	Wet/Dry	Zirconia, Glass ceramic, ceramic

			resins, Lithium Disilicate, Chrome Cobalt, PMMA, wax, titanium.
LAVA	3M ESPE	Dry	Zirconia, wax, glass ceramic
M1/M5	Zirkonzahn	Wet/Dry	Zirconia, Glass ceramic, ceramic resins, Lithium Disilicate, Chrome Cobalt, PMMA, wax, titanium.
Procera	Nobel Biocare	Wet	Aluminum oxide
Zenotec	Ivoclar	Dry	Zirconia, Wax, PMMA.

3. MARGINAL FIT

Marginal fit evaluation is considered an essential factor for clinical success. Christensen (1966) reported that clinically detectable subgingival margins are in a range of 34-119 microns and 2-51 microns for supragingival margins. McLean (1971) suggested that 120 microns should be the limit for clinically acceptable marginal discrepancies.

Poor marginal adaptation can result in dissolution of cement; increase plaque accumulation, periodontal inflammation, and secondary caries (Bindl, et al. 2005). Holmes, et al. (1989) did a research study measuring the marginal fit of restorations and defined absolute marginal discrepancy for the first time. This concept states that marginal fit should be considered as the angular combination of the vertical and horizontal error.

Some of the main concerns from clinicians about all-ceramic CAD/CAM restorations accuracy of fit are: scanning resolution, software designing limitations, and milling hardware limitations of accuracy. Clinicians' and technicians' experience with the CAM/CAM system integration is also a key factor for fabricating good restoration; the computer software per se will not allow an inexperienced operator to create an excellent dental restoration from scratch (Martin, 2000).

The clinical evaluation is an evaluation method used to evaluate the marginal fit of restorations especially in clinical in vivo studies; this process is done routinely at delivery and is usually evaluated by the use of instruments like sharp dental explorers. In an article by Hickel (2007) different recommendations regarding clinical evaluation of restorations were proposed. The use of explorers with blunt tips of 150 and 250 microns are recommended as the development of secondary caries has only been correlated to gaps >250 microns. It has been stated in different studies evaluating restorations made with conventional or digital impressions that marginal gaps that are not clinically detectable represent a harmonious continuation of the junction tooth/restoration. According to Hickel (2007) “gaps that deviate from ideal but could be adjusted to ideal by polishing are between 50 and 150 microns; gaps with leakage and discoloration limited to the borders of the restorations are easily perceptible with explorers and are not considered to have a long-term negative impact if they are between 150 and 250; gaps larger than 250 microns should be replaced to prevent secondary caries or large fractures at the margins”.

Although in clinical practice the previous methods in addition to radiographs are used to determine marginal fit; several authors have reported the use of other methods to investigate or testing parameters to evaluate the fit of CAD/CAM restorations; this techniques vary in terms of accuracy, reliability and process of evaluation.

Direct view has been widely used in different studies; this method involves the evaluation of the gap between the crown and the die or tooth; but some of the disadvantages of this techniques is the difficulty of selection for the points that have to be measure and is very difficult to evaluate discrepancies because is harder to differentiate between the tooth and the cement.

Scanning Electronic Microscopy (SEM) imaging and light microscopy have been used to evaluate marginal gap of different restorations. Groten, et al. (1997) compared the fit of all

ceramic restorations using SEM and light microscopy and found no significant differences between the accuracy of the two techniques, although SEM provided more realistic observations in complex morphologies. Some authors have reported that other microscopes have been used such as digital microscopy and stereomicroscopy, but these ones show more standard deviations and some of the results are questionable (Nawafleh, et al. 2013).

The replica technique is done using light body silicone material as a cement substitute during the procedure and then the layer is carefully removed from the die; a heavy body material of a different color is used to hold the thin layer of light body. The material replica is sectioned and measured using a microscope. This technique has been widely used but it has been stated that its limitations involve possible alterations and distortions during the impression, difficulty on finding the margins and altered sectioning that could lead to distortions of the measurements. Different authors have performed a variation of the technique; for example Felton, et al. (1991) used a replica of impressions of the margins using low viscosity vinyl polysiloxane materials and then poured a model that can be used for observation with scanning electron microscope.

The cross-sectioning technique allows the direct measurements of the cement thickness and marginal gap, but is dependent on the plane of sectioning of the specimen which at the same time could lead to distortions and also the measurements are limited to the portion of the sample that was sectioned which may or may not represent the complete fit of the crown; it also doesn't allow for long term analysis and comparison of the results before and after different experimental stages using the same specimens (Shearer, et al. 1996).

The profilometry is a non-destructive technique, which allows for accurate focus, the sample can be analyzed in a focal plane; in case of sequential analysis, extreme care should be taken in repositioning the specimens or problems with re-measuring could occur.

On the other hand, 3D reconstruction uses a scanner with high accuracy that reconstructs the restoration, die and die spacer. This data can be analyzed separately using different software and measurements can be done in a circumferential manner. A similar technique can be done using a micro-CT in which a micro-CT scanner is used to scan the specimen and different software's can be used to evaluate the data; the specimens can be evaluated in a circumferential way and a 3D reconstruction of the data can be performed; more precise measurements of the samples can be done by analyzing different points on the different two-dimensional images provided by the data according to the plane in which the data is analyzed. The disadvantages of these techniques involve the technical difficulties of using multiple software's for the analysis of the data.

A literature review about the accuracy and reliability of methods to measure marginal adaptation of crowns and fixed partial dentures by Nawafleh, et al. (2013) showed that from 183 papers that met the inclusion criteria 47.5% used direct view techniques which was the most commonly used method; it was followed by 23.5% of cross-sectional technique and 20.2% of impression replica techniques; the marginal gap values reported from this methods varied among individual systems, sample sizes and measurements per specimens.

The following is a review of some of the most recent studies done on dental CAD/CAM systems for all-ceramic restorations:

Table 5. Summary of research studies including marginal adaptation of all-ceramic restorations.

Study	Material and System	Type of Study	Mean Marginal Gap
Att, et al.	Zirconia/DCS	In vitro	86
Baig, et al.	Cercon/Zirconia	In vitro	66.4
Bindl, et al.	In Ceram/CEREC	In vitro	43

	Procera		17
Boeining, et al.	Procera	In vivo	90-118
Colpani, et al.	In ceram/CEREC	In vitro	28.5
De Vico, et al.	Zirconia/3shape	In vitro	78.8
Denissen, et al.	Mark II/ CEREC 2	In vivo	85
	Procera		68
	CICERO		74
Grenade, et al.	Procera	In vitro	51
	Ceramill/zirconia		81
Hmaidouch et al.	In Ceram YZ/ CEREC	In vitro	81.6
In-sung, et al.	In Ceram/Celay	In vitro	83
Lee, et al.	Alumina/Procera	In vitro	89.5
	Mark II/CEREC		94.4
Martinez, et al.	In Ceram		12.3
	Cercon		13.1
	Procera		8.7
Matta, et al.	Zirconia/Lava	In vitro	51
	Zirconia/Zenotec		82
May, et al.	Procera	In vitro	56-63
Neves, et al.	Lithium disilicate/CEREC	In vitro	39.2
	Lithium disilicate/E4d		66.9
Pelekanos et al.	In ceram AI/CEREC	In vitro	55
Reich, et al.	In Ceram/CEREC	In vivo	77
	Lava		80

Souza, et al.	Leucite reinforced ceramic/ CEREC	In vitro	28-99
Syrek, et al.	Lava	In vitro	49

MATERIALS AND METHODS

Forty typodont specimens equally divided in 4 groups were prepared for all ceramic crowns by dental students enrolled in the preclinical fixed course at the School of Dentistry (University of North Carolina) using the following preparation guidelines for a maxillary left canine (tooth number 11):

- 2 mm incisal reduction
- 1.5-1.8 axial reduction with 1.3-1.5 heavy chamfer finish line (margin).
- Lingual fossa reduction 1.5 mm.
- All line angles and point angles were rounded to have a smooth rounded outline.

All the preparations were scanned using laser-based intraoral scanner (CEREC Blue Cam, Sirona) after coating the preparation, adjacent teeth and opposing teeth with scanning powder (CEREC Optispray, Sirona). Maxillo-mandibular relations were captured using a buccal scan for virtual articulation. The digital files were sent via Cerec-Connect to two different dental laboratories; samples were divided into materials and fabrication technique (Table 6).

Table 6. Sample distribution between dental laboratories.

Sample	Emax group (N.)	Zirconia group (N.)
Model-less	10	10
Model	10	10
Total	20	20

Abbreviation: N.; number of samples

For the Model-less group the files were downloaded and transferred to the CAD software for crown design (Cerec In Lab 4.2.3); the crowns were designed and then sent to the CAM nesting software for the milling process (Fig 1). One dental laboratory used a 5 axis Roland DWX-50 milling machine to mill crowns from ArgenZ high translucency zirconia discs (98mm). Milled crowns were sintered at 1530-1560°F degrees. The second laboratory fabricated lithium disilicate crowns (IPS E-max CAD, Ivoclar Vivadent, Vident) using an MC XL milling machine (Sirona) and crowns were crystallized at 1545°F for 7 minutes. All restorations were stained, glazed, and returned for seating and cementation.

The model group workflow began by creation of a printed model of the scanned area with the dies (Sirona Infinident, Charlotte, North Carolina). The dental laboratory received the models; and these were used to clinically confirm the fit and contacts of the restorations after being designed and milled. Upon verification on the printed models the restorations were then stained, glazed or modified and returned for seating and cementation.

A clinical protocol for seating and adjusting all ceramic crown restorations was done for each restoration and then cemented to the typodont tooth using a dual cure resin cement (Rely X Unicem, 3M ESPE). After all specimens were collected they were submitted for analysis using micro-computed tomography scanner.

All 40 specimens were scanned for fit analysis using a quantitative micro-computed tomography scanner (Scanco micro-CT 40 scanner; Scanco Medical AG, Zürich, Switzerland) at the Biomedical Research Imaging Center (BRIC) at the University of North Carolina. Digital Imaging and Communications in Medicine (DICOM) files were generated using a 70-kilovolt peak (kVp) with a resolution of 1024x1024 pixels; the pixel size for the slice width were 8 microns nominal isotropic with a scan time of approximately 40 minutos.

All the images were analyzed in the sagittal and transaxial views with the CTan processing software (Skyscan, Bruker Corporation, Kontich, Belgium). The analysis protocol consisted in a total of 26 images per sample within the 360-degree perimeter. Thus, 13 images per perspective (sagittal and transaxial) were evenly distributed around the cervical margin (Fig 2). Measurements were performed with the processing software using a digital measuring tool which allows for micrometer unit quantification; for each image two horizontal and two vertical measurements corresponding to the bucal and lingual or mesial and distal were taken at 400x magnification (Fig. 3). The vertical gap measurements were made from the external crown margin to the most external point of the tooth. For the horizontal gap, measurements are made from the most external point of the margin of the tooth to the crown margin (Fig. 4).

Precision and repeatability measurements were performed and all measurements were computed and organized in a Microsoft Excel document for statistical analysis. Descriptive statistics were performed comparing the medians for each group; there were 10 samples for each group with 13 correlated images each sample. Four continuous outcomes (Buccal, Lingual, Mesial and Distal) were measured on each image for horizontal and vertical marginal discrepancy. Logarithmic transformation was used for each outcome variable for easier visualization of the data and to improve interpretability. Each of the variables was normally distributed after transformation. Linear mixed models were used to assess the main effect of two explanatory variables, Model Type (model and model-less) and material (E-max and Zirconia), on each outcome variable. The analysis was conducted separately for each

direction. A compound symmetric variance-covariance structure was assumed. Level of significance was set at 0.05. Least square means for each outcome were calculated for the main effects from the linear mixed models. All analysis was performed with SAS 9.3 (SAS institute, Cary, NC).

A reliability analysis was performed by re-measuring 4 randomized selected images for each sample and performing intra-class correlations to determine any systematic bias in the measurements.

RESULTS

Table 7 shows the result of linear mixed models with compound symmetric covariance structure for each outcome by direction. For all outcomes, the marginal gap was larger for zirconia than for lithium disilicate. Table 8 shows the logarithmic transformations that were applied (log10) in the statistical analysis and the re-transformed raw values for easier visualization and interpretability of the data.

Table 7. Result of linear mixed models with compound symmetric covariance structure for each outcome by direction

Direction	Outcome	Effect	Num DF / Den DF	F	P value*
Sagittal	Vertical B	Model type	1 / 37	0.93	0.341
		Material	1 / 37	0.14	0.713
	Vertical L	Model type	1 / 37	0.38	0.543
		Material	1 / 37	8.56	0.006*
	Horizontal B	Model type	1 / 37	0.07	0.793
		Material	1 / 37	4.76	0.036*
	Horizontal L	Model type	1 / 37	17.48	<.001*
		Material	1 / 37	29.46	<.001*
	Vertical D	Model type	1 / 37	3.57	0.067
		Material	1 / 37	4.20	0.048*
Trans-axial	Vertical M	Model type	1 / 37	0.83	0.367
		Material	1 / 37	4.30	0.045*
	Horizontal D	Model type	1 / 37	1.51	0.227
		Material	1 / 37	2.92	0.096
	Horizontal M	Model type	1 / 37	0.30	0.585
		Material	1 / 37	0.83	0.367

*Statistically significant difference (p<0.05)

There was a statistically significant difference between the marginal misfit of zirconia and lithium disilicate in the following surfaces: horizontal buccal ($P=0.036$), and lingual ($P<0.001$) surfaces of the restorations; the vertical lingual ($P=0.006$), distal ($P=0.048$) and mesial ($P=0.045$) surfaces.

Table 8 shows the least square means from the linear mixed models surfaces according to the different directions and outcomes. The average marginal gap as determined by micro-CT analysis for the surfaces that showed statistically significant results were estimated as follows: the estimated horizontal marginal gap of the buccal view was 133.9 μm for E-max and 156.3 μm for zirconia; the horizontal marginal gap in the lingual surface was 122.7 μm and 165.4 μm for E-max and zirconia, respectively. On the other hand the vertical marginal gap in the lingual view was 101.9 μm for lithium disilicate and 140.2 μm for zirconia; the marginal gap in the distal surface was 104.6 μm for lithium disilicate and 126.4 μm for zirconia; the marginal gap in the mesial surface was 111.8 μm for lithium disilicate and 142.9 μm respectively. The percentage of restorations that were under 120 microns was 48% for E-max and 25% for Zirconia restorations.

Table 8. Least square means from the linear mixed models.

Direction	Outcome	Effect	Log10 transformed values		Re-transformed to raw values	
			Est	Dif.	Est	Ratio
Sagittal	Vertical B	Model Type	Model	-0.06	115.82	0.88
			Model-less		132.34	
		Material	E-max	-0.02	120.67	0.95
			Zirconia		127.03	
	Vertical L	Model Type	Model	0.03	123.65	1.07
			Model-less		115.64	
		Material	E-max	-0.14	101.95	0.73

Trans-axial	Horizontal B	Model Type	Zirconia	2.15		140.25	
			Model	2.16		146.05	
			Model-less	2.16	0.01	143.35	1.02
		Material	E-max	2.13		133.91	
			Zirconia	2.19	-0.07	156.35	0.86
	Horizontal L	Model Type	Model	2.20		159.85	
			Model-less	2.10	0.10	127.06	1.26
			E-max	2.09		122.77	
		Material	Zirconia	2.22	-0.13	165.42	0.74
	Vertical D	Model Type	Model	2.10		125.55	
			Model-less	2.02	0.08	105.39	1.19
			E-max	2.02		104.62	
		Material	Zirconia	2.10	-0.08	126.47	0.83
	Vertical M	Model Type	Model	2.08		119.78	
			Model-less	2.13	-0.05	133.44	0.90
			E-max	2.05		111.84	
		Material	Zirconia	2.16	-0.11	142.92	0.78
	Horizontal D	Model Type	Model	2.19		153.57	
			Model-less	2.15	0.04	141.22	1.09
			E-max	2.14		138.90	
		Material	Zirconia	2.19	-0.05	156.13	0.89
	Horizontal M	Model Type	Model	2.12		132.31	
			Model-less	2.14	-0.02	137.25	0.96
			E-max	2.14		138.90	
		Material	Zirconia	2.12	0.03	130.74	1.06

Abbreviations: B, buccal; L, lingual, D, distal; M, mesial.

In regards to the fabrication technique, the two model types differed significantly only for horizontal lingual measures ($p < 0.001$) in the sagittal direction being the model-less technique better than the model technique.

Table 9 shows the mean difference and paired t-test from the reliability analysis. The intraclass correlation coefficients results were 0.99 indicating high concordance between measurements beyond that expected by chance and there is no statically significant values from the paired tests indicating that there is no systematic bias and high consistency between measurements.

Table 9. Mean difference and paired t-test.

Direction	Variable	Original (matched to Reassessment)		Reassessment		Paired t-test		
		Mean	Std Dev	Mean	Std Dev	t	DF	P
Sagittal	VBD	147.55	95.47	148.29	92.87	-0.66	39	0.51
	VLM	142.87	97.19	141.97	98.17	0.51	39	0.62
	HBD	151.30	48.55	153.32	47.95	-2.03	39	0.05
	HLM	156.32	78.47	156.68	77.04	-0.27	39	0.79
Trans-axial	VBD	136.37	79.38	137.62	77.73	-1.00	39	0.33
	VLM	139.51	94.39	138.78	94.12	0.63	39	0.53
	HBD	157.19	61.92	154.89	60.68	1.30	39	0.20
	HLM	141.72	57.47	141.19	57.30	0.38	39	0.71

DISCUSSION

This research consisted in the in vitro evaluation of lithium disilicate and zirconia all-ceramic restorations because these materials represent two of the most used ceramic materials in dentistry. It also evaluated the effect of using a printed model versus a fully digital approach for crown fabrication. The null hypothesis stating that the difference between materials would not be statistically significant in regards to the marginal fit of the restorations was rejected.

Data from this study revealed statistically significant differences in marginal adaptation when restorations were fabricated with zirconia or lithium disilicate. The results indicated that compared to zirconia, lithium disilicate crowns fabricated using a CAD/CAM approach presented less marginal gap (better adaptation). Thus, it was expected that lithium disilicate would have a superior fit compared to zirconia because the last one exhibits more shrinking compensation when its sintered; in addition to the fact that lithium disilicate restorations were fabricated thru the complete Cerec workflow in contrast to the system integration of Cerec and Roland DWX 50 milling machine used for the fabrication of zirconia crowns which has not yet being studied and for which no previous research has been reported.

It is important to note that the crown marginal fit is a culmination of an entire digital workflow. The materials per se do not represent the only variable in the process and other factors related to the digital methodology may be responsible of the results obtained in this research study.

One possible explanation may reside in the fact that the level of expertise of the operators using the Cerec intraoral scanner and CAD system was not high and they did not have plenty of experience. There was no standardization of the digital impression process technique or margin marking during the clinical procedure other than following the manufactures recommendations. The quality of acquisition and processing of the scanned data in conjunction with the clinical and technical experience with the CAM/CAM system and its integration is a key factor for restoration success when using CAD/CAM technology (Martin, 2000).

In this study an axial reduction with heavy chamfer finish line was chosen because according to most studies there is no significant difference in the marginal gap when a chamfer and shoulder margin configurations are used (Baig, et al. 2010). In a study by Cerutti, et al. (2014) the comparison of the marginal fit of CAD/CAM crown copings using chamfer and shoulder preparations showed no significant differences regarding the dimension of the gap and both are able to help clinicians obtaining acceptable marginal fit with zirconia copings. In contrast to this results Bindl, et al. (2007) observed better marginal adaptation when using rounded shoulder configurations than with chamfer finish lines preparations, however, they also noticed a smaller internal gap with chamfer designs and this findings could suggest that the preparation form could have influence the results.

The fabrication process when milling zirconia versus lithium disilicate restorations is a factor that could lead to a different marginal adaptation. The milling process of zirconia is done in a dry environment in contrast to lithium disilicate, which is milled in a wet environment. According to the manufactures recommendations zirconia should not be milled in a wet environment because this could lead to larger milling times and possible burs damage, the slurry clogs the filters of most milling machines and that increases operation costs.

The potential differences between the different milling machines during the CAM fabrication phase is a variable that has to be considered. The use of different nesting programs, tool path determination, integral dimensional constraints and calibration effects of the individual mills could lead to different marginal adaptation results. According to the scientific guidelines of several manufactures different milling systems could lead to different marginal adaptation that can vary as a result of differences in the dimension on the milling tools, the number of axis, and the selected milling strategy. According to the manufacture Ivoclar Vivadent, “highly aggressive milling strategies can induce surface flaws that can potentially chip marginal areas, although the proper milling strategy is integrated into the software of the approved milling machines, users can try to speed the process by “fooling” the software into thinking that a different material is being milled.” Faster milling strategies are almost always detrimental and should be avoided.

Furthermore, the milling process and the preparation design may also affect the internal adaptation of the crown; the narrowest possible diameter of the preparation is determined by the smallest diameter of the bur used for milling the internal surface; as a consequence in structures that are smaller than the narrowest bur diameter, more internal material may be removed than necessary affecting the fit of the restoration and resulting in larger internal gaps. The same phenomenon could happen when selecting between a detailed or regular milling processes, as the path of the burs will determine how detailed the restoration is going to fit (Reich, et al. 2005).

The dimensional inaccuracies associated with shrinking during the sintering process and individual handlings are factors that may have impacted the fabrication process. As previously stated, the sintering process of lithium disilicate is associated with a 0.2% shrinkage accounted for the CAD software; while in zirconia a volume shrinkage of 25% to 35% can occur without additives like yttria. This process affects the marginal fit and passiveness of the restorations (Anusavice, 2014) (Shen, et al. 2014).

The restoration parameters during the design also influence the marginal adaptation of CAD/CAM all ceramic restorations; for example, the virtual configuration of the die spacer between the tooth and the restorations is essential for the accuracy of the marginal adaptation. Weittstein et al. (2009) demonstrated that the difference of fit between CAD/CAM restorations is directly related to the gap parameters from the computer design and also related to the intrinsic properties of the CAD/CAM system; the die spacer should be uniform and facilitate seating; several studies have looked at the effect of die spacer on the retention and physical properties of crowns (Campbell, 1990). In this study both laboratories used the default internal parameters of 40 microns for crown fabrication proposed by the In-Lab software. Previous studies have stated that chair-side milling has demonstrated the ability to produce marginal and internal adaptations within 50 to 100 microns (Mörmann, 2006) when using the same parameters that are proposed in the software. In a study by Nakamura, et al (2003), the marginal and internal fit of all ceramic crowns was examined using three different luting space settings (10, 30 and 50 microns); marginal gaps of a luting space of 10 microns tend to show greater marginal gaps than when it was set at 30 or 50 microns; crowns with a luting space of 30 and 50 microns showed a good fit regardless of the occlusal convergence angle of the abutments.

In this study all the restorations were cemented to each preparation adding another possible factor that could affect the marginal adaptation of the restorations. As stated in previous studies when restorations are cemented the cement space should be uniform and facilitate seating without compromising the marginal adaptation (May, et al. 1998). The specimens could potentially lose the precision of the primary marginal adaptation due to the influence of factors like cement type, viscosity, and cementation technique. Shearer, et al. (1995) showed that the use of cement or cement analogues could give different results. Martinez-Ruz, et al. (2012) analyzed the effect of cement selection on the marginal adaptation of different CAD/CAM systems; there was a significant increase in the marginal gap caused by the luting cement in all

the different zirconia systems they used, having the resin cement the larger marginal discrepancies when compared to glass-ionomer cement. Experimental in-vitro studies should evaluate the restorations before and after cementation to be able to discard the fact that the cement type, viscosity or technique could make a difference during marginal adaptation.

In vitro results should be viewed cautiously because the testing methods does not completely represent what happens in a clinical environment. The approach employed in the present study was to somehow recreate a more realistic environment to evaluate restorations made by clinicians in a daily basis using different samples; for each sample a different scan and computerized design was performed. The majority of the investigations focus primarily in achieving the best possible accuracy that can be obtained from the systems under ideal conditions eliminating the influence of common clinical errors. On the other hand, both groups had broad standard deviations values and the data was difficult to interpret without logarithmic transformations. Future studies should include and correlate the materials and systems used in this study in more standardized environments that could help correlate the results.

Evaluation methods such as 3D reconstruction, direct viewing and Micro-CT evaluation provide non-destructive methods. Previous research studies have been done using techniques that could represent measurement of distorted processed samples, which have incorporated errors. The angular measurement as proposed by Holmes, et al. (1989) was selected because marginal misfit can result in vertical and/or horizontal gaps or a combination of them. When comparing the data with previous studies that used CEREC, most investigators assessed inlay and onlay restorations on previous CEREC models before CEREC Bluecam. Recent standardized in vitro studies from Lee et al. (2008) reported a mean marginal discrepancy of 89.5 microns using Mark II milling blocks for single restorations. More recently, Neves et al. (2014) reported a marginal discrepancy of 39.2 microns for lithium disilicate crowns in a standardized in vitro study. In regards to the use of the Roland DWX-50 milling machine as a

milling machine in combination with CEREC or any other digital impression system no research was found. The different techniques that have been used to analyze marginal adaptation present a variety of results even when similar experimental methods are used, different methods including micro-CT avoid distortions and offer very high resolution; as a consequence the methods used for specimen evaluation could play a major role on the data obtained and not only the accuracy of the marginal adaptation. The results obtained for the model and model-less technique showed that there were no significant differences. During the fabrication process dental laboratories use stone or printed models as a traditional method to check proximal contacts, occlusal contacts and contours. The digital workflow and fabrication process is very standardized and predictable; most digital design programs can be learned in days and most design softwares have tools that facilitate the design process (Fasbinder, 2012). When comparing digital versus traditional impressions the time required to take impressions can be reduced because rescans of the missing areas can be acquired in 1 to 2 minutes in comparison to retaking traditional impressions with rubber base materials which usually takes around 5-7 minutes for each impression using polyvinyl siloxane impression materials (Lee, et al. 2013). It is important to mention that according to different studies is not uncommon to find different distortions like drags, voids or tears in traditional impressions (Wassell, et al. 2002).

In addition, digital dentistry represents a great tool in oral health education for evaluation of restorations during the fabrication process as it provides ways view restoration in big screens and also quantifies proximal and occlusal contacts. Using digital impressions could also reduce waste, there are no concerns about manipulation or distortion of materials and avoid the need for disinfection materials; it also has the advantage that the data can be stored in a computer and no duplicates are needed. Different studies have shown that the accuracy of digital workflows is similar to conventional methods for fixed prosthetic restorations showing that virtual casts are accurate (Hwang, et al. 2013).

CONCLUSION

Within the limitations of this study, lithium disilicate restorations exhibit more accurate and standardized marginal adaptation results than zirconia crowns under these circumstances. No statistically significant difference was found between the use of a fully digital approach and the use of a printed model for crown fabrication. Data should be interpreted carefully because due to the different variables incorporated into dental digital technology workflow. Further research about CAD/CAM materials and systems is needed.

FIGURES

Figure 1. Digital and conventional workflow for all-ceramic crown fabrication.

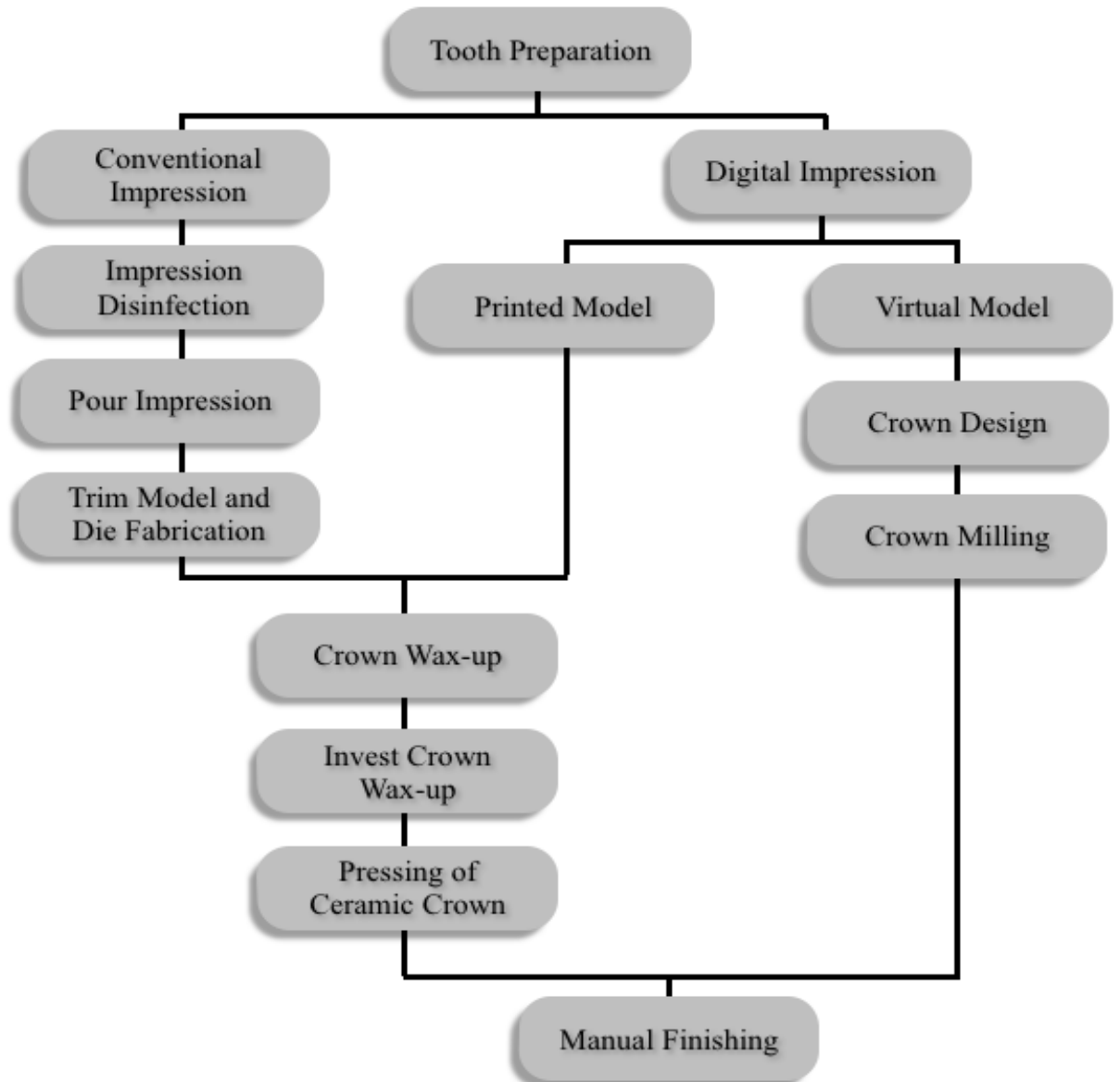


Figure 2. Crown design using the In-Lab software (Sirona Dental)

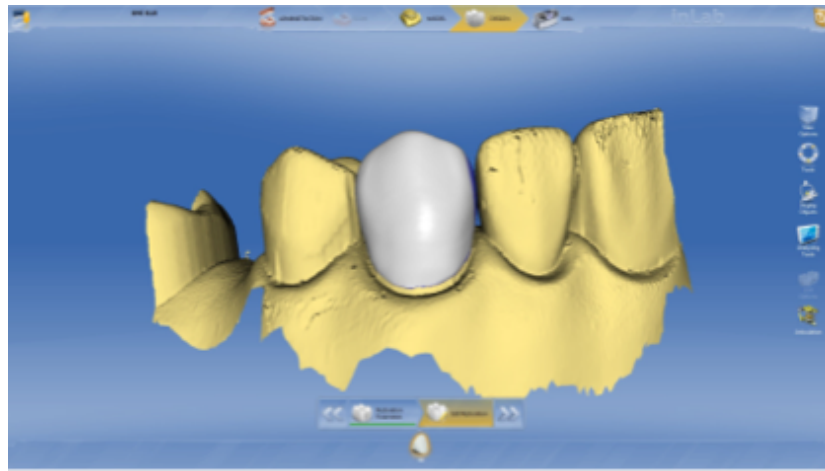


Figure 3. Squematic representation of the 26 images selected for analysis in the micro-CT coronal view of the specimen.

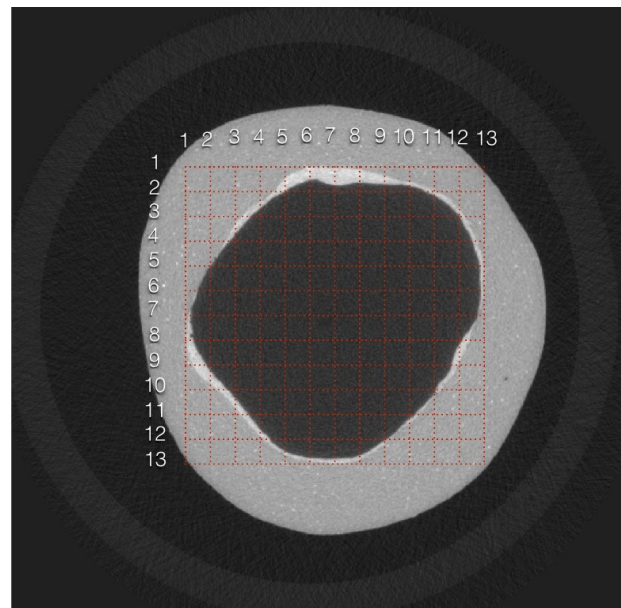


Figure 4. Micro computed tomography, sagittal image of crown at 100x magnification.

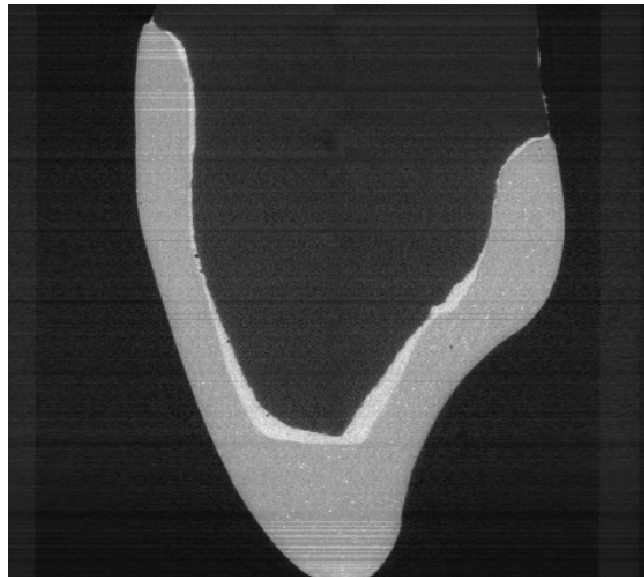
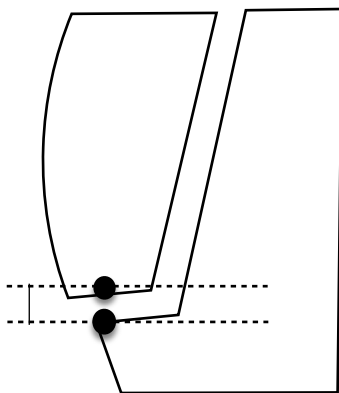
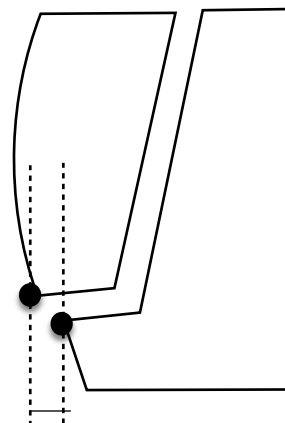


Figure 5. A) Schematic representation of the vertical misfit to be evaluated in the micro-CT. B) Horizontal misfit.



A)



B)

Figure 6. Graphic representation of the specimen medians for E-max model group.

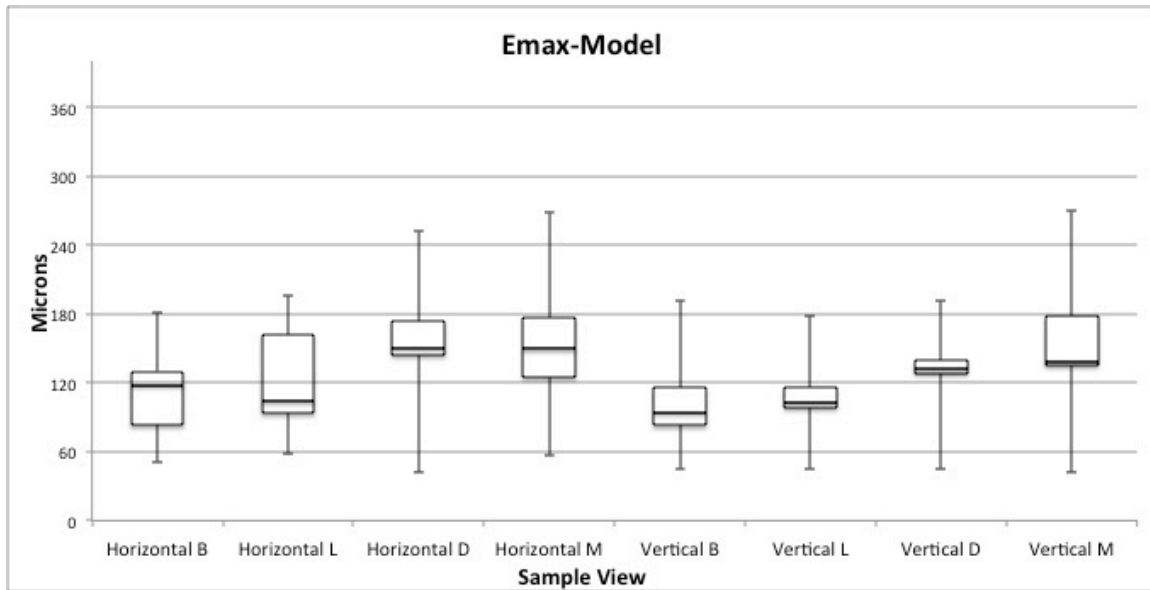


Figure 7. Graphic representation of the specimen medians for E-max model-less group.

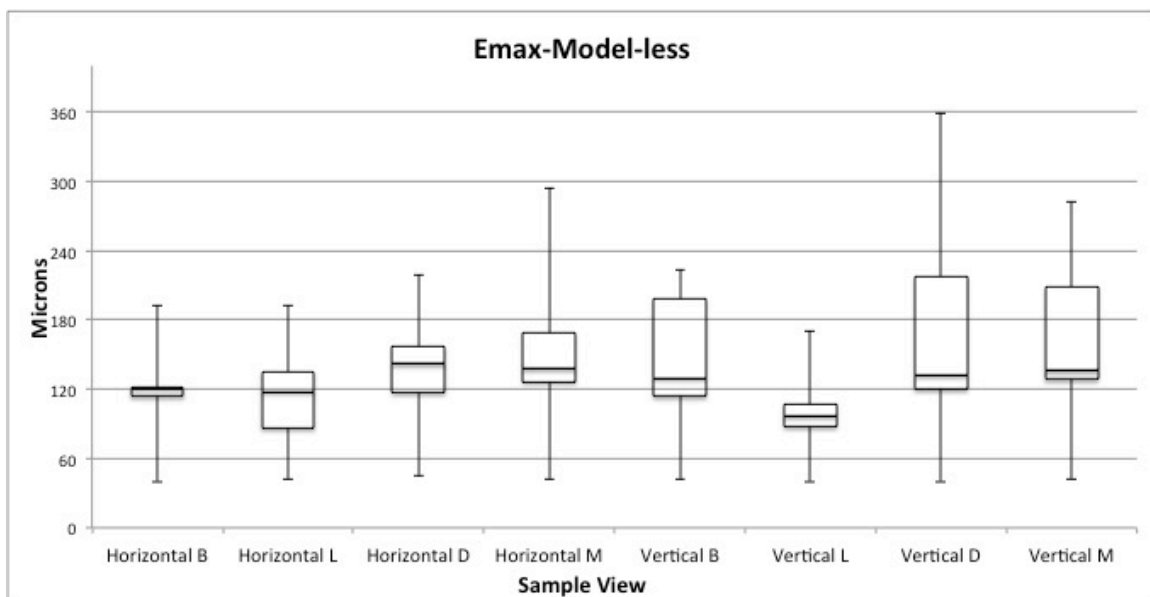


Figure 8. Graphic representation of the specimen medians for zirconia model group.

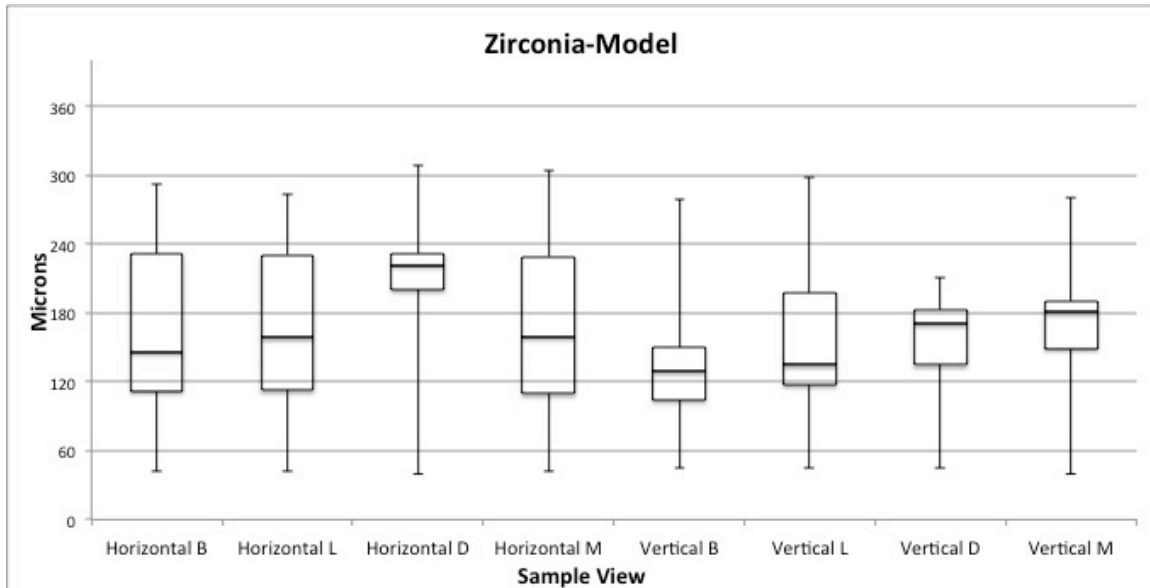
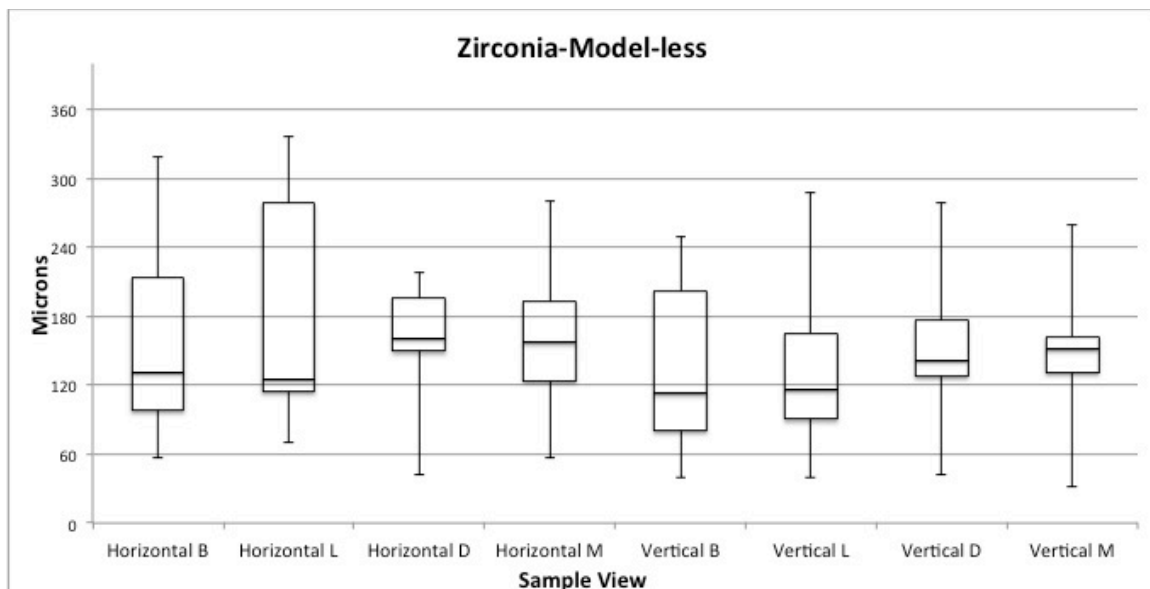


Figure 9. Graphic representation of the specimen medians for zirconia model-less group.



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