MARGINAL ADAPTATION & INTERNAL FIT OF DIGITALLY DESIGNED LITHIUM DISILICATE CROWNS MANUFACTURED BY CAD/CAM AND THE CONVENTIONAL HEAT-PRESS TECHNIQUE

A Thesis

by

DRUTHIL BELUR

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	William W. Nagy
Committee Members,	Elias Kontogiorgos
	John T. Goodman
	David F. Murchison
Head of Department,	Larry L. Bellinger

May 2018

Major Subject: Oral Biology

ABSTRACT

The purpose of the *in vitro* study was to evaluate and compare marginal fit & internal fit of digitally designed lithium disilicate crowns manufactured by the computer-aided design/computer-aided manufacturing (CAD/CAM) technique and the conventional lost-wax heat-pressed technique. The method used for analyzing the crowns was based on 3D metrology using advanced hardware and software. A high resolution industrial non-contact scanner with an accuracy of 4 microns was used to generate point cloud data which was converted to a polygonal mesh as a 3D surface representation. This data was subsequently analyzed using engineering software with over 145,000 points of measurement for each sample in both groups.

A Master Die was scanned with a 3Shape D900 Laboratory Scanner and a 'Standard Tesselation Language' (STL) crown file was generated using Amann Girrbach's Ceramill Mind design software (Ver 3.6.1). From this crown STL, two groups were milled with Amann Girrbach's Ceramill Motion 2 (5-axis) milling machine: one group consisting of 15 crowns using Ivoclar Vivadent's ProArt CAD Wax Pucks; and the second group consisting of 15 crowns with Ivoclar Vivadent's IPS e.max© CAD blocks. The ProArt CAD Wax crowns were subsequently pressed with IPS e.max© Press Ingots and the IPS e.max© CAD block crowns were crystallized per Ivoclar Vivadent's specifications.

The crowns from the two groups were evaluated using a 'triple-scan protocol' described by Holst et al. Each sample was scanned 12-13 times with the ATOS III Scanner (GOM, Germany), generating 8 million data points per scan. Using an in-built software (ATOS

Professional, Germany), macros were designed to separately analyze the marginal fit and internal fit. The marginal zone comprised of 63,960 points of measurements, and the remaining internal fit comprised of 82,263 points of measurement.

After calculating the means for each area of each sample, a paired t-test was used to determine the differences between the two groups ($P<0.05$). For the conventional heat-pressed technique, the mean values were 93.07 µm (± SD 9.58 mm) for marginal adaptation and 127.20 µm (± SD 10.44 mm) for the internal fit. For the CAD/CAM milled technique, the mean values were 83.13 µm (± SD 7.50 µm) for marginal adaptation and 103.00 µm (± SD 7.45 µm) for the internal fit. The results indicated that the marginal adaptation and internal fit were statistically significant with the CAD/CAM manufacturing technique when compared to the conventional lost-wax heat-press technique. The average measurements with the 'CAD/CAM' group were smaller than those with the 'Pressed' Group. The results are consistent with recent publications showing that CAD/CAM milling is of greater accuracy.

ACKNOWLEDGEMENTS

I would like to thank my Thesis Committee Members: Dr. William Nagy, Dr. John T. Goodman, Dr. Elias Kontogiorgos, and Dr. David F. Murchison. I thank each of them for their time, dedication and input into my research. To my former director and mentor, Dr. William Nagy, I sincerely thank him for investing his time and energy into my education. His genuine passion for teaching was inspiring and I wouldn't have made it this far if it wasn't for him. I'd also like to thank my current Director, Dr. Aaron Cho for his support.

I would like to acknowledge Texas A&M University for providing me the facilities to complete this project.

I'd also like to thank Ivoclar for providing the lithium disilicate CAD blocks, lithium disilicate ingots and other materials used for my research. A thank you to Wendell McMcall, owner of the dental laboratory for milling my samples with the Amann Girrbach milling unit at cost price.

A special thank you to my co-residents, past and present. A thank you to my department staff and other faculty for making my time at Texas A&M University College of Dentistry a wonderful experience.

Finally, a thank you to my family who have always been there to support me and inspire me to be a better person and succeed both professionally, and personally.

CONTRIBUTORS AND FUNDING SOURCES

This work was supervised by a thesis committee consisting of Professor William W. Nagy, Committee Chair of the Department of Restorative Sciences; Clinical Associate Professor John T. Goodman, Committee Member of the Department of Restorative Sciences; Associate Professor Elias Kontogiorgos, Committee Member of the Department of Restorative Sciences; and Clinical Professor David F. Murchison, Committee Member of the Department of Biological Sciences. All work for the thesis was completed independently by the student.

Graduate study was supported by a $1,500 contribution from Texas A&M University College of Dentistry. The remaining costs for the study were out of pocket by the resident.

Ivoclar Vivadent was generous to support this study and donated the following materials: Resin Epoxy Master Die, ProArt CAD Wax Discs, IPS e.max© CAD blocks, IPS e.max© Press ingots, IPS PressVest Premium liquid and powder, IPS Investment Ring System, and IPS e.max© Press Invex Liquid.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION AND LITERATURE REVIEW

Lithium disilicate has gained wide acceptance in its use for indirect crown restorations. This trend is driven by numerous factors ranging from the materials' excellent optical properties, [1] flexural strength, and relatively decreased material costs when compared to high noble alloys. Lithium disilicate restorations have become a popular choice for inlays, onlays and full coverage crown restorations.

Computer-aided design and computer-aided manufacturing (CAD/CAM) processes are available in many dental practices, dental laboratories, and production centers.[2] For laboratory CAD/CAM milling, there are several companies around the world which manufacture various models based on intended use. Amann Girrbach (AG) is a manufacturer based out of Austria. They have partners in over 90 countries, and are considered one of the leaders in innovation in digital dental prosthetics. AG manufactures 4-axis and 5-axis milling machines. The model used in the study is an Amann Girrbach (AG) Ceramill Motion 2 milling unit. It is a 5-axis operation design that has a dry and wet drilling mode, enabling a wide array of dental materials to be milled within a single unit. The conventional wet drilling is used for IPS e.max©, Titanium, and Cr-CO alloys. The dry milling feature enables the use of acrylic resin, model resin, polyurethane, and wax.

In the manufacture of indirect restorations, fabricating the wax pattern is usually a time consuming step which relies on the experience, knowledge, and skill of the dental technician.

Thermal sensitivity, elastic memory, and a high coefficient of thermal expansion of waxes[3] contribute to inaccuracies. Fabricating CAD/CAM wax patterns with modern equipment can reduce or eliminate the inaccuracies of the conventional waxing technique.[4,5] It is said to be faster, more economical, predictable, consistent, and accurate. Ivoclar's ProArt CAD Wax discs are made from a synthetic wax reinforced with a dimensionally stable polyurethane material which are specifically designed to suit the lithium disilicate glass ceramic IPS e.max© Press. The material does not leave a residue during burnout.

Although dental CAD/CAM technology has improved significantly over the years, studies reveal that the accuracy of these restorations remains questionable. Controversies still exist on the effect of a milling procedure for a prosthesis. When comparing CAD/CAM restorations to pressed restorations, results vary from a better fit,[6,7] to no difference,[8,9] to a greater misfit.[10,11,12,13,14,15] Accuracy is affected by many factors including the type of material, properties of the material, design of the preparation, scanning device, software design, spacer thickness, and accuracy of the milling machine.

Crown adaptation may be determined by measuring marginal gaps and internal gaps of the restorations. The fit of many full coverage restorative materials have been extensively studied in the dental literature and remains a topic of significant interest due to its high clinical relevance. [16,17,18,19] Holmes et al characterized the internal gap as the perpendicular distance from the internal surface of the restoration to the axial wall of the preparation, whereas the marginal gap is the perpendicular distance from the internal surface of the restoration to the finish line of the preparation.[20] Holmes also stated that the marginal fit of any dental restoration is vital to its long-term success.[21] Schwartz et al evaluated unserviceable crowns and fixed partial dentures to determine causes of restoration failures and determined that 11.3% of the restorations failing are the result of defective margins.[22] Behrend claims a ring of cement is inevitable at the margin and the presence of this cement line must be accepted, contributing to marginal discrepancies.[23]

A range of 39 to 180 µm[24,25,26,27] has been proposed in the literature as a clinically acceptable value for marginal gap depending on the restoration. However, no consensus has been reached regarding a currently acceptable value for all. Several in vitro studies have reported the marginal gap of CAD/CAM generated ceramic single tooth restorations to be between 64 and 83 µm.[28,29,30,31] May et al reported that the marginal fit of the Procera CAD/CAM system ranged between 54 and 64 µm.[32]

Ivoclar Vivadent, recommends a software mill setting that includes a 20 micron cement spacer from the margin up to 1mm and then 60 microns from that line up. Nakamura et al. reported on the marginal and internal fit of CAD/CAM Vita Mark II ceramic crowns. In this study, luting space settings of 10, 30, and 50 µm were tested. It was determined that for crowns milled with 30 or 50 µm of luting space, better marginal fit was obtained. [33] In a similar in vitro study, Iwai et al. examined the influence of cement space on the adaptation of zirconium dioxide ceramic copings. Results indicated that the 60 µm cement space group exhibited statistically smaller marginal discrepancies compared to the other tested groups of 10 and 30 μm of die spacer. [34]

Many methods have been used to evaluate the marginal and internal adaptation of crowns. Assif et al compared the tactile method (with the explorer) to the use of radiographs and to a technique using an impression material replica.[35] The results supported that the impression technique was most accurate of the three. The replica technique has been validated in the past[36] and is a popular method,[37,38,39,40] however, it is technique sensitive and possibly inaccurate since the impression material used could be easily distorted or damaged.[41, 42, 43] Scanning electron microscopy is a popular technique in the analysis of specimens, with methods that involve a non-destructive method,[44,45] while other methods involve sectioning of the samples being analyzed. [46,47] However, the obvious limitations of this technique are the destruction of the samples which creates the need for duplicates, the limited area that is evaluated since the sections have a minimum thickness and the additional steps required to embed in the resin and section. Another powerful tool in dental research is the computerized x-ray micro-tomography (micro-CT),[48,49] which produces high-resolution images that can be quantitatively analyzed with appropriate software. The disadvantages of this method are the low capacity the CT can discriminate in comparison with optical or electron microscopy, possible artifacts from refractive radiation, and the compulsory radio-opacity of the material being tested. [50]

A significant drawback of the majority of published studies is the limitation of two dimensional analyses. Recent technology, and the use of sophisticated professional engineering software have gained popularity.[51,52,53,54] Most have been based on non-contact scanners and other hardware to capture point data, which are processed by algorithms in the software to process this data into useful forms. Thousands of point cloud data are converted in to a polygonal mesh as a 3D surface representation which are subsequently analyzed. However, best-fit registration algorithms are used for virtual alignment. The principle of this technique is adopted from industrial quality control protocols, where the software attempts to align the greatest possible contact area of the selected samples, which could skew the results, as areas of greater misfit are virtually approximated and not accurately represent the true discrepancy.

Holst et al. developed a triple-scan protocol using a non-contact scanner (ATOS III, GOM, Germany) for 3D fit assessment of dental restorations.[55] The sensitivity of the non-contact scanner used was 4 microns. Three scans were performed: a) the die; b) the coping; c) the coping on the die. The 3 separate scans of the objects were digitized to surface tessellation/triangulation language (STL's). Surfaces were generated from point clouds with the scanner software (ATOS system, GOM). Through a combination of best-fit algorithms and a subtractive method in the software, the fit assessment was verified by intra-class correlation coefficients that revealed an almost perfect coefficient for repeatability ($r=0.981$, $p<.001$). The same main investigator used this protocol in another study to assess the precision of fit of CAD/CAM dental implant superstructures.[56] The statistical analysis, again similar to the previous study, resulted in an intra-class correlation of 0.991 and thereby a statistically significant repeatability of measurements.

This triple-scan protocol represents a highly reliable method for analyzing marginal adaptation and internal fit three dimensionally. The disadvantages of 2D measurements are eliminated. This platform delivers the power to streamline the process, allow a non-destructive approach, reduce human interaction in measurements and recording, decrease measuring time, and enhance results to make this method a superior alternative. Groten et all suggested that 50 points of measurement are needed for best accuracy.[57] With the ATOS scanner and the software used, more than 100,000 points of measurements were used.

The purpose of this in vitro study was to evaluate marginal adaptation & internal fit of digitally designed lithium disilicate crowns manufactured by computer-aided design/computer-aided manufacturing (CAD/CAM), and the conventional heat-press technique using Amann Girrbach's Ceramill Motion 2 milling unit using the triple-scan protocol. The null hypothesis was that there would be no difference in marginal adaptation and internal fit of the digitally designed lithium disilicate crowns manufactured by computer-aided design/computer-aided manufacturing (CAD/CAM) and the conventional heat-press technique

2. MATERIALS AND METHODS

A Master Die was scanned with a 3Shape D900 Scanner and a 'Standard Tesselation Language' (STL) Crown File was designed and generated using Amann Girrbach's Ceramill Mind design software (Ver 3.6.1). From this STL Crown, two groups were milled: one group consisting of 15 samples with Ivoclar Vivadent's ProArt CAD Wax (Yellow), specifically designed to suit the lithium disilicate glass ceramic IPS e.max© Press; and the second group consisting of 15 samples with Ivoclar Vivadent's IPS e.max© CAD blocks. The ProArt CAD Wax crown samples were subsequently pressed and the IPS e.max© CAD block samples were crystallized.

A total of 30 samples were analyzed using a triple-scan protocol with a non-contact scanner (ATOS III, GOM, Germany). The scanner generated thousands of point cloud data which were converted into a polygonal mesh as a 3D surface representation that was analyzed. An in-built macro in the software analyzed the marginal adaptation & internal fit of the samples.

2.1 Master Die Fabrication

A milled epoxy resin 'Master Die' of a maxillary 1st molar for a full coverage restoration/crown was provided by Ivoclar Vivadent. Modifications were made using a high-speed handpiece with a round-end tapered diamond bur (5856, Brassler USA, Savanah, GA) according to Ivoclar Vivadent's guidelines for IPS e.max© for posterior crowns (Figure 1).

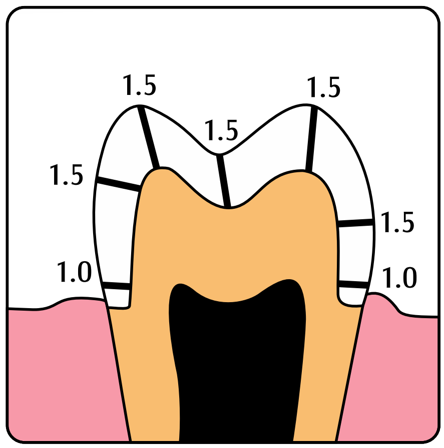

Figure 1. Ivoclar Vivadent's guidelines for IPS e.max© posterior crowns (Units = mm).

The margins were prepared to have a deep chamfer with a width of at least 1 mm with rounded internal line angles; occlusal reduction of at least 1.5 mm; buccal and palatal axial reduction of at least 1.5mm. There was a minimum preparation height of 4 mm and total occlusal convergence of (TOC) of 4-6 degrees (Figure 2).

Figure 2. Milled epoxy resin ‘Master Die’.

2.2 Crown Fabrication

The Master Die was scanned using a 3Shape (Copenhagen, Denmark) D900 Scanner (Figure 3) generating a ‘Standard Tessellation Language’ (STL) file of the die. A single unit maxillary first molar crown was designed (Figure 4) using Amann Girrbach’s Ceramill Mind design software (Ver 3.6.1), ensuring the minimum thickness per Ivoclar Vivadent’s guidelines for IPS e.max© were maintained. An STL file of the crown was generated.

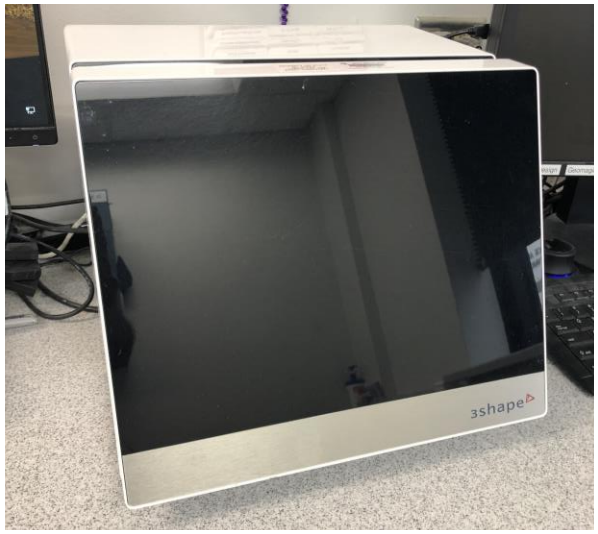

Figure 3. 3Shape D900 lab scanner.

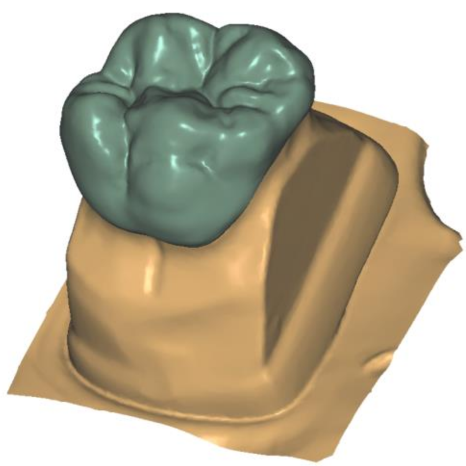

Figure 4. Crown STL using Amann Girrbach Ceramill Mind design software.

2.3 Milling of Samples

Using Amann Girrbach's Ceramill Motion 2 (Figure 5), a 5-axis milling unit, two groups of crowns were milled from the crown STL file. The first group ('WaxMill') utilized the milling machines' 'Dry Mode' and consisted of 15 crowns using two Ivoclar Vivadent's ProArt CAD Wax 20mm Yellow Discs (Figure 6)(Appendix A). The second group ('CAMMill') utilized the milling machines' 'Wet Mode' and consisted of 15 crowns using Ivoclar Vivadent's IPS e.max© CAD blocks (Figure 7). 4 boxes of the CAD blocks were ordered. They were all Medium Opacity #3 (MO3) Blocks having size C14 which corresponded to the size of the crown's dimensions to be milled (Appendix A). New milling burs were used at start. Per Ivoclar Vivadent, the software mill settings involved a 20 micron spacer from the margin up to 1mm and then 60 microns from that line up.

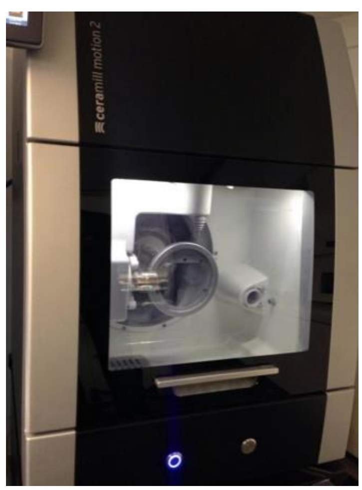

Figure 5. Amann Girrbach Ceramill Motion 2 5-axis milling unit.

Figure 6. Ivoclar Vivadent ProArt CAD Wax disc.

Figure 7. Ivoclar Vivadent’s IPS e.max© CAD blocks.

2.4 Preparation of Samples

The ‘WaxMill’ group (Figure 8) and ‘CAMMill’ group (Figure 9) were visually inspected for any voids or gross defects. The milled crowns from Ivoclar Vivadent’s ProArt CAD Wax Discs were to be pressed, and the milled Ivoclar Vivadent’s IPS e.max© CAD blocks being in the pre-crystalline ‘blue state’ were to be fired.

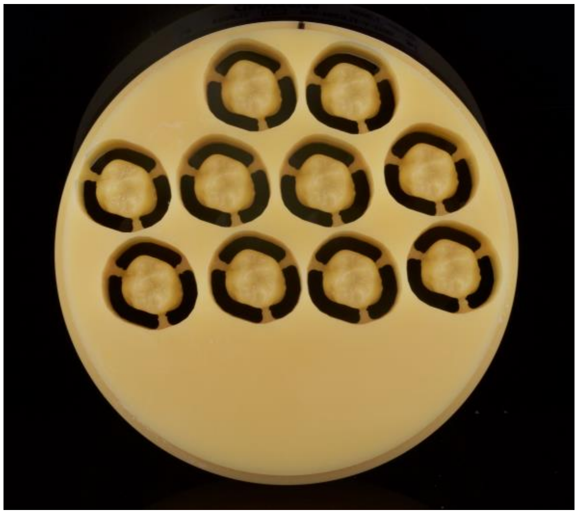

Figure 8. Ivoclar Vivadent ProArt CAD Wax milled crowns.

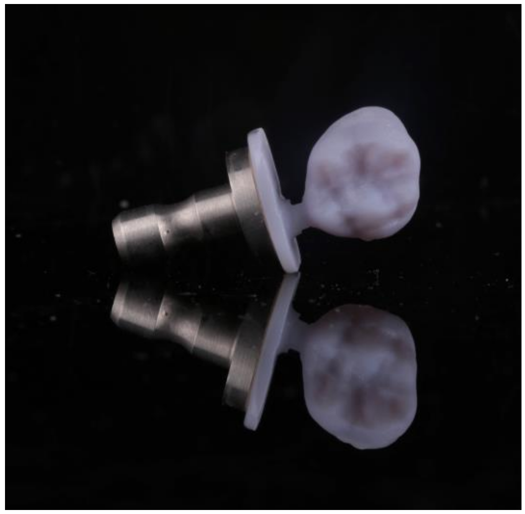

Figure 9. Ivoclar Vivadent's IPS e.max© CAD milled crown.

2.4.1 Fabrication of Pressed Samples

Each of the 15 'WaxMill' crowns were seated onto the master die and 2.5x magnification was used to visually inspect that the margins were closed circumferentially. It was confirmed that all crowns seated completely and no adjustments were necessary. Ivoclar Vivadent's instructions were followed for each step. Each crown was sprued with a 3mm long, 12-gauge sprue wax (2.77mm in diameter) with a 45-60 degree sprue angle to the ring base. Care was taken to ensure that each sprue was attached in the direction of flow of the ceramic and at the thickest part of the wax so that smooth flowing of the viscous ceramic during pressing is enabled. The 200g IPS Investment Ring System (Appendix A) was used, hence two crowns were sprued with each ring base (Figure 10). A minimum distance of 3mm between objects was maintained along with a minimum distance of 10mm from the waxed-up objects and silicone ring (Figure 11). A maximum height of the wax objects with sprue did not exceed 16 mm.

Figure 10. Two Ivoclar Vivadent ProArt CAD Wax milled crowns sprued to a ring base.

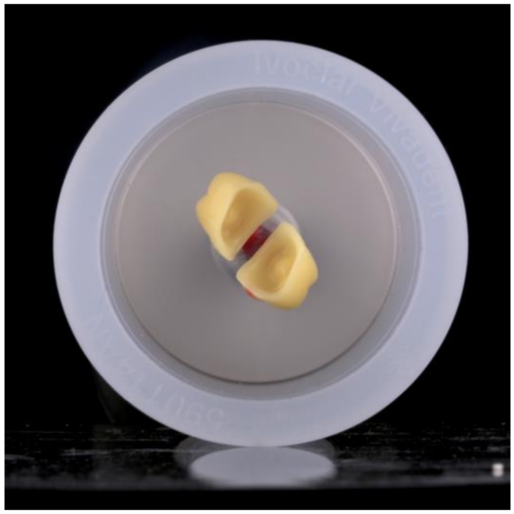

Figure 11. Clearance between and around wax objects per Ivoclar Vivadent instructions.

The sprued crowns were invested with a phosphate-bonded investment (IPS PressVEST Premium, Ivoclar Vivadent) per the manufacturer's instructions. The IPS PressVEST Premium Powder was used (Appendix A) along with the IPS PressVEST Premium Liquid (Appendix A). Since the 200g IPS Investment Ring System was used, the mixing ratio of 36ml of IPS PressVEST Premium Liquid was mixed with 16ml of distilled water. 200g of the IPS PressVEST Premium Powder was premixed by hand for 20-30 seconds using a spatula until all the powder was mixed with the liquid. A vacuum mixing device (VPM2, Whipmix Corp.) was subsequently used for 90 seconds at 350 rpm. The investing was then carried out on a vibrator unit under gentle vibration (Figure 12).

Figure 12. Investing the milled wax crowns with IPS PressVEST Premium.

A speed heating procedure (set investment ring placed directly into a furnace which has been preheated to the final temperature and then transferred to the press furnace after a defined time) was used, and a minimum setting time of 30 minutes was observed. After a maximum 45 minute setting time, the set investment was removed from the silicone ring and placed in a preheating furnace (Apollo II Whip Mix, Louisville, KY)(Figure 13) for a minimum of 60 minutes at a temperature of 1562°F.

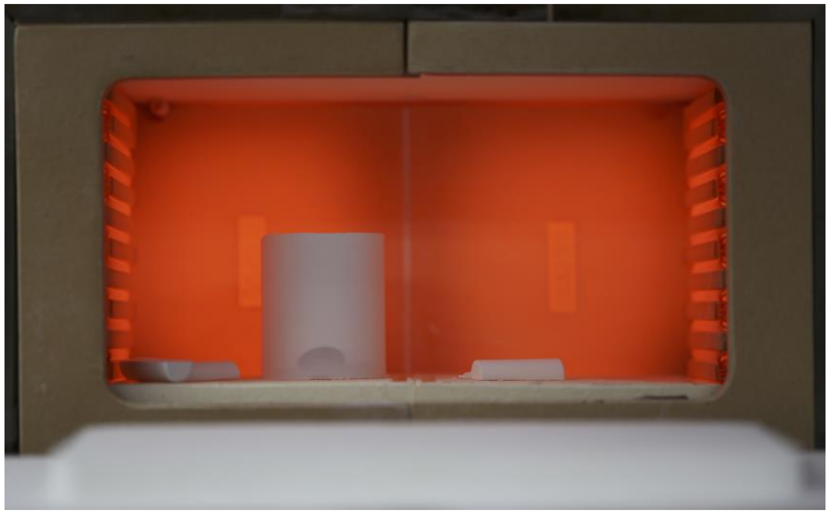

Figure 13. Preheating furnace (Apollo II Whip Mix, Louisville, KY) at 1562°F.

A Vario Press 300 (Zubler USA Inc., Irving, TX)(Figure 14) furnace was used for pressing. While the investment was preheating, the warm up cycle was executed. The firing parameters used were per Ivoclar Vivadent's recommendations for the 200g IPS Investment Ring System and the MO IPS e.max© Press ingots.

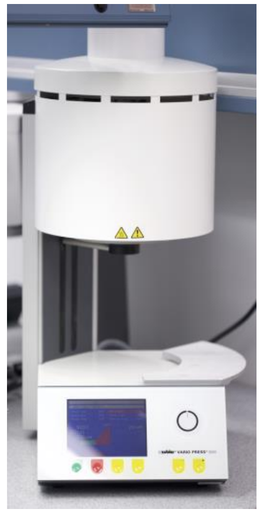

Figure 14. Vario Press 300 (Zubler USA Inc., Irving, TX).

A Medium Opacity (MO3) Ivoclar Vivadent IPS e.max© CAD block was selected, with the same opacity (MO3) as the IPS e.max© Press ingots. During the investing procedures, the weight difference between the ring base: with and without the sprued objects was determined. This difference was less than 2g and the corresponding ingot size for use with the 200g IPS Investment Ring System was determined to be a large (L) sized ingot (Figure 15).

	Small Ingot	**Large Ingot (L)**
Wax Weight	up to max. 0.75 g	up to max. 2 g
Investment Ring System	100 g or 200 g	only 200 g

Figure 15. Ivoclar Vivadent recommendations for selecting ingot size. [58]

The IPS e.max© Press ingots having medium opacity #3 (MO 3 L) are shown in Figure 16 (Appendix A).

Figure 16. IPS e.max© Press ingots (MO 3 L).

After completing the preheating cycle for a minimum of 60 minutes, the investment ring was removed from the preheating furnace. The IPS e.max Press (MO 3 L) ingot was inserted in to the investment ring with the non-imprinted side facing down (Figure 17).

Figure 17. Investment ring with ingot inserted.

A single-use plunger (13mm, Zubler USA Inc., Irving, TX) was subsequently placed into the investment ring over the ingot, all within a maximum of 30 seconds of removing the investment ring from the preheating furnace to prevent it from cooling down too much. The loaded investment ring was then immediately placed in the center of the hot press furnace (Vario Press 300 Zubler USA Inc., Irving, TX) and the press program was initiated as recommended by Ivoclar Vivadent (Figure 18).

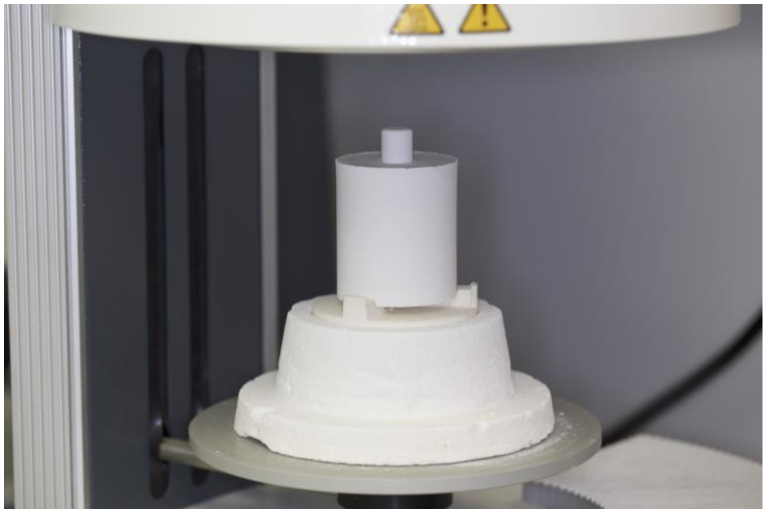

Figure 18. Investment ring with ingot and plunger in center of press furnace.

Following the pressing cycle, the investment was allowed to cool for at least 60 minutes. The length of the plunger was measured on the cooled investment ring (Figure 19) and sectioned off with a separating disc and plaster knife.

Figure 19. Single use plunger used to mark investment ring.

The crowns were divested using polishing beads at 60 psi for gross removal of investment material (Figure 20) and 30 psi for fine removal of investment material (Figure 21).

Figure 20. Gross removal of investment material at 60 psi with polishing beads.

Figure 21. Fine removal of investment material at 30 psi with polishing beads.

Sprues were removed with an aluminum-oxide separating disc (Keystone Industries, Gibbstown, NJ) with irrigation. The reaction layer formed during the press procedure was removed using IPS e.max Press Invex Liquid (Appendix A). The liquid was poured in to a cup, and the crowns were immersed in it and placed in an ultrasonic cleaner for 10 minutes. The samples were removed from the liquid and cleaned under running water. The reaction layer was carefully removed with Type 100 Aluminium oxide at 15 psi pressure (Figure 22). Complete seating of the restorations onto the master die was confirmed visually with 2.5x magnification and with an explorer tip (EXPL-5/6, Brasseler USA, Savannah, GA). The samples were cleaned with a steam jet (Touchsteam, Kerr Corp USA) and then packaged individually and labelled as the “Pressed Group” for shipping (Figure 23).

Figure 22. Pressed crowns with reaction layer removed.

Figure 23. “Pressed Group” of crowns packaged for shipping.

2.4.2 Firing/crystallization of Milled Samples

After milling the 15 'CAMMill' crowns, they were cleaned with a steam jet (Touchsteam, Kerr Corp USA). The pre-crystallized crowns were secured with IPS Object Fix Putty (Ivoclar Vivadent) on pegs (Figure 24). 3 crowns were fired at a time, centered on the crystallization tray of A Vario Press 300 (Zubler USA Inc., Irving, TX). The firing parameters used were per Ivoclar Vivadent's specifications for the medium opacity (MO) ingots.

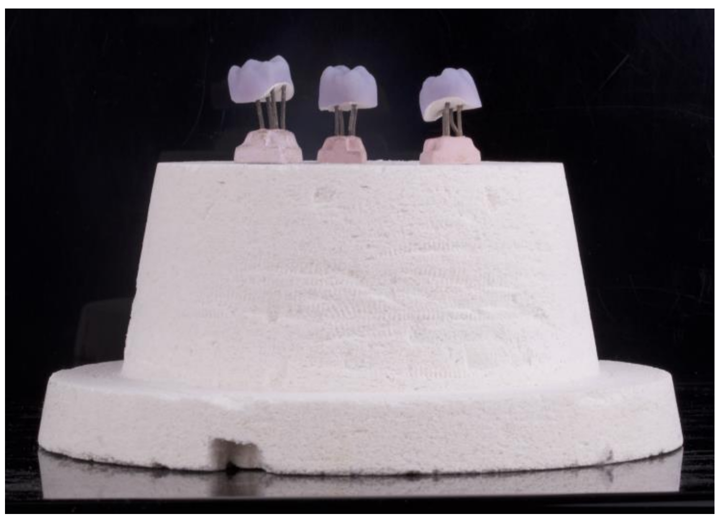

Figure 24. Pre-crystallized crowns secured with IPS Object Fix Putty (Ivoclar Vivadent) on pegs.

After the firing cycle (Figure 25), the cooled CAD restorations were separated from the IPS Object Fix Putty and cleaned with a steam jet (Touchsteam, Kerr Corp USA). Complete seating of the restorations onto the master die was confirmed visually with 2.5x magnification and with an explorer tip (EXPL-5/6, Brasseler USA, Savannah, GA). The samples were cleaned again with a steam jet (Touchsteam, Kerr Corp USA) and then packaged individually and labelled as the "Milled Group" for shipping (Figure 26).

Figure 25. Cooled CAD crowns after the firing cycle.

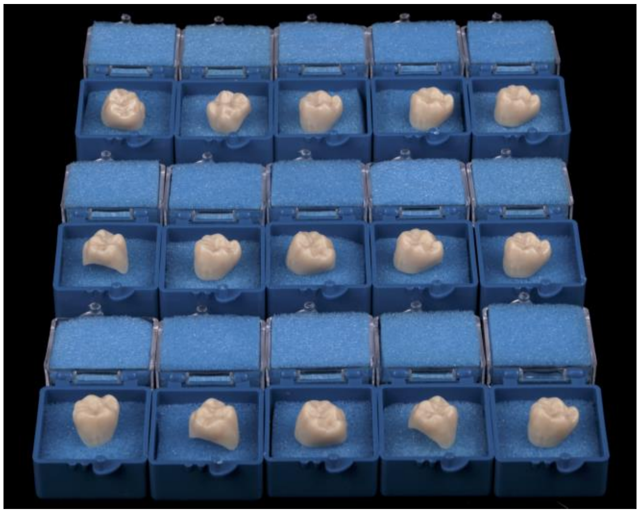

Figure 26. "Milled Group" of crowns packaged for shipping.

2.5 Scanning and Measuring Data

The scanning was performed at Capture 3D Inc. (Michigan, USA) where the non-contact ATOS III (GOM, Germany) scanner was located. Headquartered in Costa Mesa, California, the company was founded in 1997 as the exclusive North American partner for GOM Germany. They have an Automated Metrology Solutions Center in Farmington Hills, Michigan, where their high quality industrial 3D metrology systems are engineered incorporating the latest advanced hardware technologies integrated with intelligent software algorithms. The scanner used is the ATOS III (GOM, Germany). GOM develops and distributes optical measuring systems with it's main focus on applications like 3D digitizing, 3D coordinate measurements, deformation measurements and quality control. GOM systems are used for product development and for quality assurance, material and component testing. All over the world GOM systems are used in the automotive industry, aerospace industry and consumer goods industry as well as by their suppliers. This also includes numerous research centers and universities.

The packaged crowns, totaling 30 units were shipped to Capture 3D, Inc (Michigan, USA). The model of the scanner used was the ATOS III (GOM, Germany), which is a high resolution, optical digitizer that delivers rapid and precise three dimensional measuring data (Figure 27). The protocol used was based on Holst et al. [55] The ATOS III scanner is based on blue light technology (Figure 28).

Figure 27. (used with permission from [88]) ATOS III scanner (GOM, Germany).

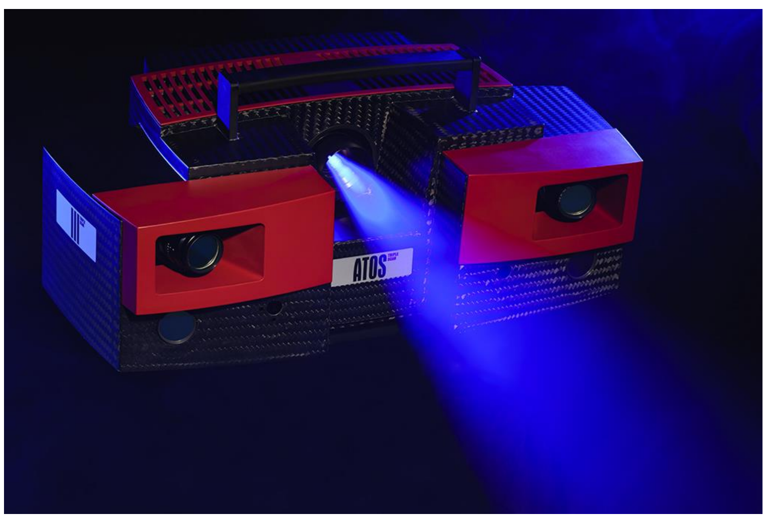

Figure 28. (used with permission from [88]) Blue light technology with the ATOS III scanner (GOM, Germany).

Print polyester reference markers (Oracal 352, Oralfol, Germany) were used on the exterior of the crowns and master die. About 6-7 markers were used for each sample, and were 50 microns in thickness with a diameter of 0.4mm (Figure 29). These markers were meant to facilitate efficient virtual alignment of the samples with ease during post-processing with the software.

Figure 29. Reference markers.

A “Fringe Pattern” of light is projected onto the surface of the crowns during the scanning process, which looks similar to the stripes on a Zebra. The ATOS sensor has two sensing cameras that are both watching the striped pattern during the scanning process, and valuing 3D data points along the edges of the contrast stripes (Figure 30).

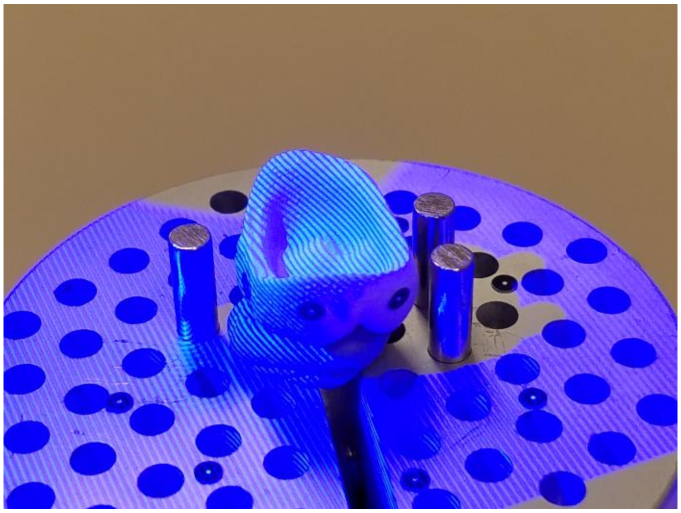

Figure 30. (used with permission from [88]) “Fringe Pattern” on scanning object.

Each sensor is capable of collecting up to 8 million data points each time a ‘shot’ of scan data is acquired. Further, the ATOS sensor was fitted with a 60mm field of view (patch size of each shot of data). The estimated level of accuracy for this configuration of the ATOS III scanner fitted with a 60mm telescopic field of view is approximately 0.004mm (0.00015”), and is tested and certified in accordance with the VDI/VDE 2634 Part 3 standard. This standard was defined in December 2008 by a committee of VDI experts as the standard method for evaluating multiple view, optical 3D-measuring systems based upon scanning area.

The scanner was used to digitize the ‘Master Die’ and the crowns in each group (‘Pressed’ and ‘Milled’) generating STL’s using the ATOS Software (ATOS Professional, GOM). Three different categories of scans were performed: Master Die (D), Crown (C), and Crown on Die (CoD). Prior to scanning each ‘CoD’ setup, in order ensure adequate seating of the crowns, the occlusal surface was first scanned, and a reversion of this was generated from which a printed jig was manufactured. This printed jig was secured over the 'CoD' setup with a metal arm applying 1 lb of force, allowing even pressure on the crown through the printed jig (Figure 31).

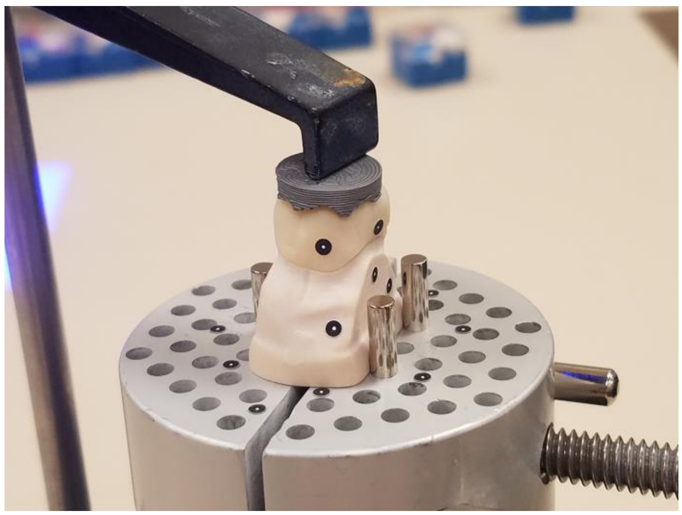

Figure 31. (used with permission from [88]) Crown on Die (CoD) setup with a printed jig and metal stabilizing arm.

Each sample was scanned 12-13 times and the data was stitched by the ATOS software (ATOD Professional, GOM, Germany). Per the triple scan protocol, the STL's generated from each sample were subsequently aligned by using the 'reference markers' (Figure 32). In the first step, using the reference markers on the Master Die STL and the Crown on Die STL, they were registered by manual alignment at the reference markers followed by a best fit algorithm in the software. The 'reference markers' form a 'constellation' that is the basis for the triple scan protocol (Figure 33).

Figure 32. (used with permission from [88]) STL's of Die (D), Crown (C), and Crown on Die (CoD).

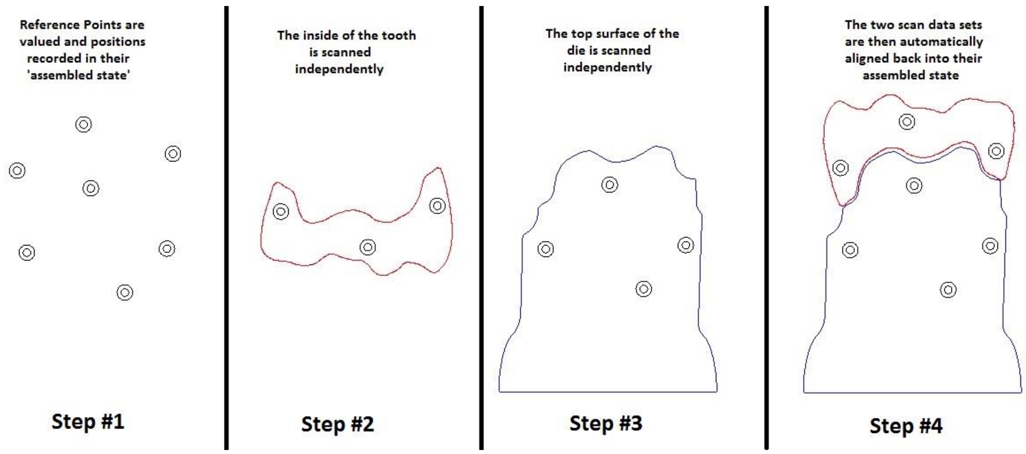

Figure 33. (used with permission from [88]) 'Constellation' formed from the 'reference markers' that was used for the software's virtual 'best fit algorithm'.

In the second step, the same protocol was used to match the Crown (C) STL with the Crown od Die (CoD) STL. The final step was to delete the CoD STL and maintain the remaining two STL's ('D' and 'C') for fit assessment.

To measure the space between the Crown and Master Die, the outer surface of the crown was deleted, followed by reversion of the surface of the intaglio of the crown (C) and calculation of points of deviations from the Master Die (D). The ATOS software (ATOS Professional, GOM) converts the various deviations in the form of a colored histogram based on actual measurements (Figure 34). The range varied from 0.000 mm (green) to 0.200 mm (red) (Figure 35).

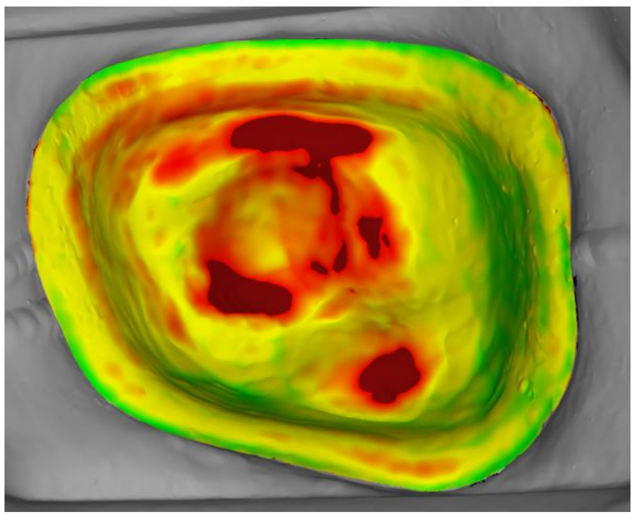

Figure 34. Data points represented as a colored histogram.

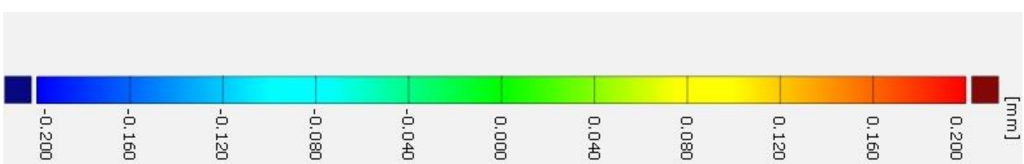

Figure 35. Histogram bar representing range of values.

Using the ATOS Software (ATOS Professional, GOM), two areas were highlighted for assessment: a) margins: determined from the outer edge of the scan and then inward for a distance of 1mm (Figure 36); and b) internal fit: for the remainder of the data (Figure 37). Highlighting the internal fit was a simple inversion option in the software. Thousand's of points of measurement were determined for each sample from each group. Since the scanning area and mapping were standardized for each sample using the ATOS Software (ATOS Professional, GOM), the total number of points of measurement for the marginal adaptation was 63,960, and for the internal fit was 82,263. The software had an in-built macro to calculate the mean for all the thousand's of data points for each of the areas selected within the samples.

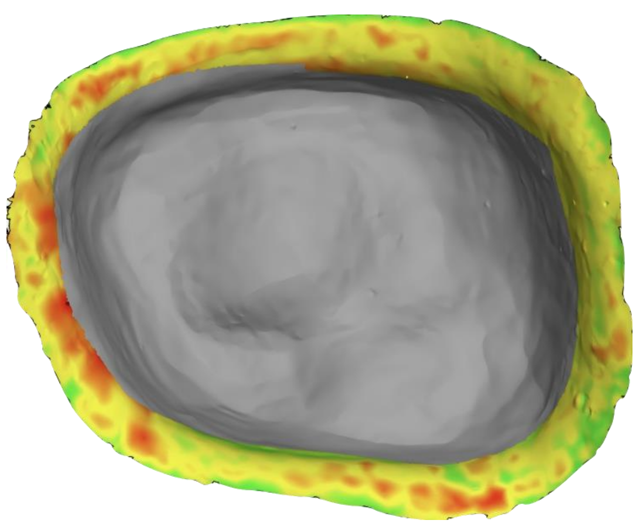

Figure 36. Data map of samples for 'Marginal Adaptation'.

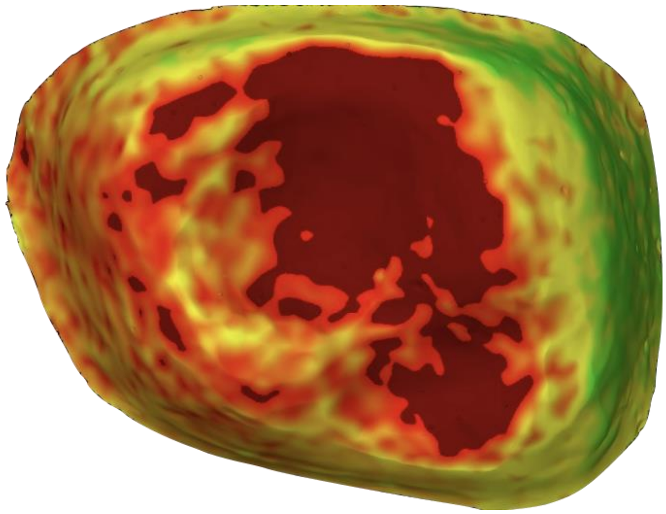

Figure 37. Data map of samples for ‘Internal Fit’.

Medium opacity (MO) CAD blocks and Ingots were used during manufacture of the samples. When scanning was first performed on the crowns, the high intensity of the blue light was absorbed through the translucency of the material, versus being reflected for the sensors to evaluate. As a result, several dozen additional scans were performed at different angles to compensate for this lack of reflectivity. The multiple scans per sample required stitching by the software, allowing for potential error. Per the recommendation of the Application Engineers, a reflective titanium dioxide spray was used. A 400 grain rutile white titanium oxide spray was used (Figure 38). The crowns were sprayed in a booth using an in-house setup pointing the nozzle 10” away from the samples with a single pass (Figure 39).

Figure 38. (used with permission from [88]) 400 grain rutile white titanium oxide spray.

Figure 39. (used with permission from [88]) In-house booth for reflective spray.

This technique was previously validated by Capture 3D (MI, USA) for a potential error of 0.001 mm. An in-house study on a smooth granite surface using 4 different sprays (Figure

40) revealed the least error of 1 micron with the 400 grain rutile white titanium oxide spray ("airbrush referenz") (Figure 41).

Figure 40. (used with permission from [88]) Testing of sprays on a granite slab.

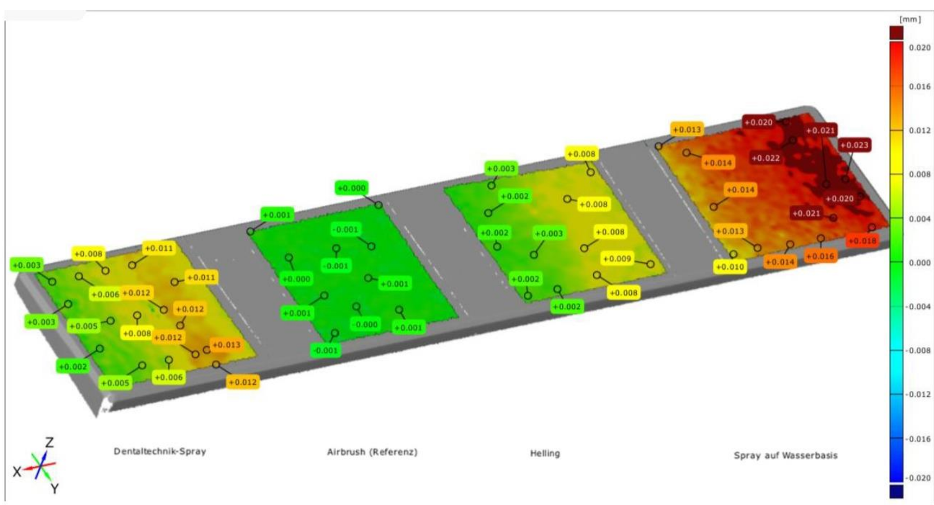

Figure 41. (used with permission from [88]) Validated study for various sprays.

2.6 Statistical Analysis

Two areas of measurement were considered: 1. Marginal Adaptation, which were the areas of the margins of all the samples, exactly 1mm from the outer boundary inwards for comparing the 'Pressed Group' and the 'Milled Group' (Table 1); 2. Internal Fit, for comparing the remainder of the internal surface area for the 'Pressed' Group and the 'Milled' Group (Table 2). Each value in the table represents the mean from 63,960 points of measurement for marginal adaptation; and 82,263 points of measurement for the internal fit. The mean for each of the areas measured for both groups was determined by the in-built macro in the software (ATOS Professional, GOM, Germany). Hence, the values listed in each cell in Table 1 are the mean for 63,960 points of measurement for marginal adaptation, and the values listed in each cell in Table 2 are the mean for 82,263 points of measurement for the internal fit. This data was then analyzed using a statistical software (SPSS 19.0, SPSS Inc., Chicago, IL). A paired t-test was used for comparing the marginal adaptation and internal fit of the two groups of samples. The significance level was set at $P \leq 0.05$.

Sample	Pressed Group	Milled Group
1	93	80
2	87	85
3	95	72
4	107	80
5	86	95
6	96	82
7	97	98
8	91	81
9	100	82
10	85	79
11	80	75
12	93	73
13	81	87
14	116	88
15	89	90

Table 1. Marginal Adaptation for "Pressed Group" and "Milled Group" of Crowns (Microns).

Sample	Pressed Group	Milled Group
1	135	104
2	119	106
3	128	93
4	147	103
5	120	115
6	136	101
7	131	121
8	123	98
9	135	100
10	120	101
11	118	94
12	123	95
13	111	103
14	144	105
15	118	106

Table 2. Internal Fit for "Pressed Group" and "Milled Group" of Crowns (Microns).

Descriptive statistics for marginal adaptation of the "Pressed Group" is shown in Table 3, and for the "Milled Group" in Table 4.

Mean	93.07
Standard Error	2.47
Median	93.00
Mode	93.00
Standard Deviation	9.58
Sample Variance	91.78
Kurtosis	1.13
Skewness	0.94
Range	36.00
Minimum	80.00
Maximum	116.00
Sum	1396.00
Count	15.00

Table 3. Descriptive Statistics for Marginal Adaptation of the “Pressed Group”.

Mean	83.13
Standard Error	1.94
Median	82.00
Mode	80.00
Standard Deviation	7.50
Sample Variance	56.27
Kurtosis	-0.21
Skewness	0.46
Range	26.00
Minimum	72.00
Maximum	98.00
Sum	1247.00
Count	15.00

Table 4. Descriptive Statistics for Marginal Adaptation of the “Milled Group”.

Descriptive statistics for internal fit of the “Pressed Group” is shown in Table 5, and for the “Milled Group” in Table 6.

Mean	127.20
Standard Error	2.70
Median	123.00
Mode	135.00
Standard Deviation	10.44
Sample Variance	109.03
Kurtosis	-0.62
Skewness	0.50
Range	36.00
Minimum	111.00
Maximum	147.00
Sum	1908.00
Count	15

Table 5. Descriptive Statistics for Internal Fit of the "Pressed Group".

Mean	103.00
Standard Error	1.92
Median	103.00
Mode	106.00
Standard Deviation	7.45
Sample Variance	55.57
Kurtosis	1.47
Skewness	1.04
Range	28.00
Minimum	93.00
Maximum	121.00
Sum	1545.00
Count	15

Table 6. Descriptive Statistics for Internal Fit of the "Milled Group".

3. RESULTS

The mean values for marginal adaptation were 93.07 µm (± SD 9.58 mm) for the ‘Pressed’ group, and 83.13 µm (± SD 7.50 µm) for the ‘Milled’ group. The mean values for the internal fit were 127.20 µm (± SD 10.44 mm) for the ‘Pressed’ group and 103.00 µm (± SD 7.45 µm) for the ‘Milled’ group. Statistical significance ($P<.05$) was found for the marginal adaptation as well as internal fit between the two groups. A more statistically significant difference in fit was found in the CAD/CAM group than with conventional manufacturing for both, the marginal adaptation ($P\leq0.004$) as well as the internal fit ($P\leq0.001$).

A bar graph comparing the marginal adaptation of both groups (in microns, including SD) is shown in Figure 42, and a bar graph comparing the internal fit of both groups (in microns, including SD) is shown in Figure 43.

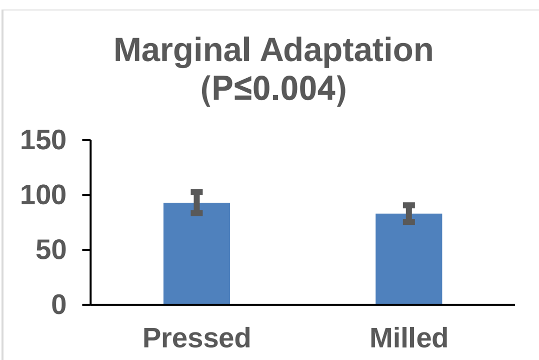

Figure 42. Bar graph comparing marginal adaptation of “Pressed Group” and “Milled Group” (microns).

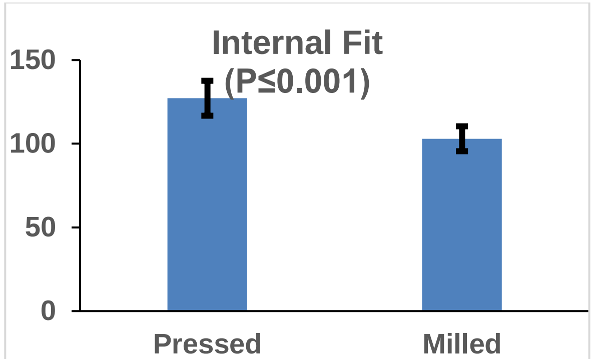

Figure 43. Bar graph comparing internal fit of “Pressed Group” and “Milled Group” (microns).

4. DISCUSSION

The aim of this study was to evaluate marginal adaptation & internal fit of digitally designed lithium disilicate crowns manufactured by the CAD/CAM milling technique and the conventional lost wax heat-press technique. Marginal fit and intimate adaption of the crown to the tooth is of significant importance with regards to the success and survival of indirect restorations. In the present study, CAD was used to generate the STL of a crown, which was the starting point for both groups of samples. Using the same milling machine for the fabrication of samples for both groups, their accuracy from a technology/manufacturing standpoint, is considered identical. After firing one group and pressing the other, the samples were scanned and analyzed with a unique technique to potentially overcome the drawbacks of previously used methods.

The results of this study show that marginal adaptation and internal fit of lithium disilicate crowns manufactured by the CAD/CAM milling technique were better than the conventional lost wax heat-press manufacturing technique. The null hypothesis was rejected. These findings provide useful information regarding the applications of CAD/CAM technology and the active role that the practitioner or technician needs to assume in the digital design and milling of restorations. After analyzing thousands of points for measurement, the CAD/CAM group had a mean of 83.13 µm for marginal adaptation and a mean 103.00 µm for internal fit. The conventional lost wax heat-press group had a mean of 93.07 µm for marginal adaptation and mean of 127.20 µm for internal fit. CAD/CAM manufacturing of lithium disilicate crowns significantly decreased the marginal gap and internal fit when compared with the conventional heat-pressed lost wax method of manufacturing. These results also support the findings of other authors who have compared digital and traditional workflows for the manufacture of crowns and found that the digital workflow allows for the fabrication of restorations of equal or superior fit to those fabricated by traditional methods (Table 7).

Author	Measurements (microns)	Focus	CAD/CAM Fit
Pimenta et al[60]	35 (CAD/CAM) vs. 76 (Pressed)	M	Better
Anadioti et al[61]	145 (CAD/CAM) vs. 211 (Pressed)	IF	Better
Alfaro et al[62]	160 (CAD/CAM) vs. 210 (Pressed)	IF	Better
Freire et al[63]	27 (CAD/CAM) vs. (Not publ.)(Pressed)	M	Better
Homsy et al[64]	24 (CAD/CAM) vs. 33 (Pressed)	M	Better
Mostafa et al[65]	33 (CAD/CAM) vs. 51 (Pressed)	M	Better
Real-Voltas et al[66]	20 (CAD/CAM) vs 109 (Cast)	M	Better
Neves et al[67]	39 (CAD/CAM) vs. 36 (Pressed)	M	No difference
Kim et al[68]	200 (CAD/CAM) vs. 176 (Pressed)	M	No difference
Dahl et al[69]	within 100 for CAD/CAM & Pressed	IF	No difference
Zeltner et al[70]	83.6 (CAD/CAM) vs 90.4 (Pressed)	M	No difference

*M = Marginal adaptation; IF = Internal Fit

Table 7. Publications (2014-2017) comparing CAD/CAM Milling to Conventional Manufacturing Methods.

The marginal and internal gap have been well documented for complete coverage single restorations in pressed glass ceramic, however, from manually fabricated wax patterns (Table 8). In the manufacture of indirect restorations, fabricating the wax pattern is usually a time consuming step which relies on the experience, knowledge, and skill of the dental technician. Thermal sensitivity, elastic memory, and a high coefficient of thermal expansion of waxes[3] contribute to inaccuracies. In this study, the starting point for the "Pressed Group" and "Milled Group" were from the same crown STL. The 'WaxMill' crowns and the pre-sintered 'CAMMill' crowns were both milled by the same milling unit, from the same STL. Shamseddine et al showed that CAD/CAM waxing techniques resulted in an improved fit of a pressed lithium disilicate crowns when compared to a traditional manual waxing technique. Hence, this workflow is perceived to eliminate the limitations of using a manual waxing technique. In addition, the material used for the 'WaxMill' group was Ivoclar Vivadent's ProArt CAD Wax. This material burns without leaving a residue. It has a dropping point of 77-86 °C and a flash point greater than 180 °C, and is also stable at room temperature with a range of 36-82 °F.

A drawback of the majority of published studies involving the analysis of marginal adaptation and internal fit of crowns is the limitation to two dimensional analyses (Table 9). This study used a non-destructive method based on 3D metrology with a non-contact scanner using sophisticated professional engineering hardware and software. Groten et al suggested that 50 points of measurement are needed for best accuracy.[57] In this study, point cloud data were converted in to a polygonal mesh as a 3D surface representation which were subsequently analyzed to produce over 145,000 points of measurement for each sample.

Authors (Year)	Manual Waxup
Zeltner et al (2017) [70]	✔
Mostafa et al (2017) [65]	✔
Kim et al (2016) [68]	✔
Alfaro et al (2015) [62]	✔
Anadioti et al. (2015) [61]	✔
Pimenta et al. (2015) [60]	✔
Demir et al. (2015) [71]	✔
Ng et al. (2014) [6]	✔
Beyari et al. (2014) [72]	✔
Mously et al. (2014) [73]	✔
Neves et al. (2014) [67]	✔
Asavapanumas et al. (2013) [74]	✔
Martinez-Rus et al. (2013) [13]	✔
Yucel et al. (2013) [13]	✔
Cho et al. (2012) [76]	✔
Farid et al. (2012) [77]	✔
Subasi et al. (2012) [78]	✔
Borges et al. (2012) [79]	✔
Yüksel et al. (2011) [80]	✔
Baig et al. (2010) [14]	✔
Holden et al. (2009) [81]	✔
Good et al. (2009) [82]	✔
Al-Rabab'ah et al. (2008) [7]	✔
Bindl et al. (2005) [47]	✔

Goldin et al. (2005) [83]	✔

Table 8. Peer-Reviewed Studies on Single Crown Marginal and Internal Fit of Pressed Glass Ceramics involving a Traditional Manual Waxing Technique.

Authors (Year)	Measurements Method
Zeltner et al (2017) [70]	Optical Microscope
Mostafa et al (2017) [65]	Micro-CT
Kim et al (2016) [68]	Micro-CT
Alfaro et al (2015) [62]	Micro-CT
Anadioti et al. (2015) [61]	Triple scan
Pimenta et al. (2015) [60]	X-ray micro-CT
Demir et al. (2015) [71]	Micro-CT
Ng et al. (2014) [6]	Stereomicroscope
Beyari et al. (2014) [72]	Stereomicroscope
Mously et al. (2014) [73]	Micro-CT
Neves et al. (2014) [67]	Micro-CT
Asavapanumas et al. (2013) [74]	Stereomicroscope
Martinez-Rus et al. (2013) [13]	SEM
Yucel et al. (2013) [13]	Stereomicroscope
Cho et al. (2012) [76]	Optical Microscope
Farid et al. (2012) [77]	Stereomicroscope
Subasi et al. (2012) [78]	Stereomicroscope
Borges et al. (2012) [79]	Optical Microscope
Yüksel et al. (2011) [80]	Stereomicroscope
Baig et al. (2010) [14]	Computerized image analysis
Holden et al. (2009) [81]	Optical Microscope
Good et al. (2009) [82]	Profilometry
Al-Rabab‘ah et al. (2008) [7]	Stereomicroscope
Bindl et al. (2005) [47]	SEM
Goldin et al. (2005) [83]	Optical Microscope

Table 9. Peer-Reviewed Studies on Single Crown Marginal and Internal Fit of Pressed Glass Ceramics involving Traditional Techniques for Analyzing Samples.

Professional engineering software with non-contact scanning have been used in the recent past,[51, 52, 53, 54] however, have used a best-fit registration algorithm for virtual alignment. The principle of this technique was also adopted from industrial quality control protocols, where the software attempts to align the greatest possible contact area of the selected samples. This could skew the results, as areas of greater misfit are virtually approximated and do not accurately represent the true discrepancy. This study used the triple-scan protocol developed by Holst et al.[55] Through a combination of best-fit algorithms and a subtractive method in the software, the fit assessment was verified by intra-class correlation coefficients that revealed an almost perfect coefficient for repeatability ($r=0.981$, $p<.001$). The same main investigator used this protocol in another study to assess the precision of fit of CAD/CAM dental implant superstructures.[56] The statistical analysis, again similar to the previous study, resulted in an intra-class correlation of 0.991 and thereby a statistically significant repeatability of measurements.

Holmes et al described the considerations in the measurement of marginal fit.[20] There are many different locations between the restoration and the tooth where the measurements can be made. This study did not measure a horizontal marginal discrepancy, but measured the marginal gap and internal gap (Figure 44).

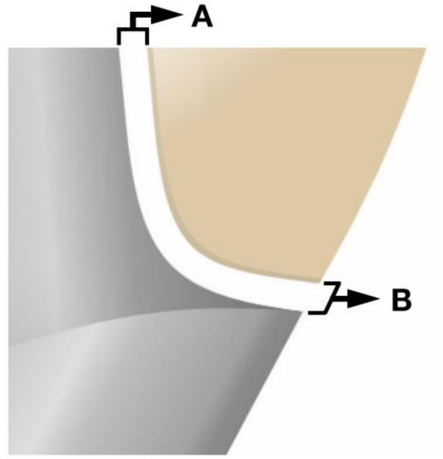

Figure 44. Marginal gap (A) and internal Gap (B)

In this study, the measurements ranged from 1 micron at the margin to 414 microns at the occlusal surface of the samples. This finding may be attributed to limitations in the milling accuracies due to the dimensions of the burs.[83] The mean of both groups used in this study do fall within the range of more recent studies (Table 7).

One of the limitations of this study was the opacity of the material used. Li et al showed when using powder free intra-oral scanner, a higher translucency resulted in lower accuracy and morphological changes. Although medium opacity #3 (MO 3) CAD blocks and Press Ingots were used, during initial scanning of the samples, there were empty spaces in the digitized crowns due to the intensity of blue light used in the ATOS III scanner (GOM, Germany). To overcome this problem, a reflective titanium oxide spray was used. Although the spraying technique was standardized and the in-house study showed a deviation of 1 micron, variation in the distance of the spray from the object in addition to total duration of spraying could influence variations in the data. High Opacity (HO) CAD blocks or Press Ingots could have avoided the need for the reflective spray.

Another limitation of the study is the reaction layer formed during the pressing of the lost wax heat-press crowns. Longer holding temperatures are thought to have an effect on the reaction layer. The reaction layer formed with the conventional lost wax heat-press group of crowns could have influenced the higher average of measurements for the samples. Although the recommendations used were per Ivoclar Vivadent, other manufacturer's have suggested alternative durations. Further studies are needed to explore this variation.

Although the results indicate a closer fit with the CAD/CAM group of crowns in the marginal area and internal fit, the clinical relevance could be limited. Both manufacturing techniques are within an acceptable range of fit. Future studies are needed to evaluate variations in firing ovens. The technique described above for analyzing samples could be used to evaluate the accuracy of other CAD/CAM milling systems. In addition to lithium disilicate used in this study, other materials used in the manufacture of full coverage crowns could be evaluated as well. This study has a broad range of applications and could also be used to evaluate other restorations and abutments manufactured by CAD/CAM and conventional methods.

5. CONCLUSION

Within the limitations of this in vitro study, the following conclusions can be drawn:

1. The CAD/CAM milling technique decreased the marginal gap of lithium disilicate crowns when compared with the conventional heat-pressed lost wax method of manufacturing.
2. The CAD/CAM milling technique decreased the internal fit of lithium disilicate crowns when compared with the conventional heat-pressed lost wax method of manufacturing.

REFERENCES

1. Alemi, A., Khademinia, S., Joo, S.W., Dolatyari M., Bakhtiari A. Lithium metasilicate and lithium disilicate nanomaterials: optical properties and density functional theory calculations. Int Nano Lett 2013;3:14.
2. Beuer F, Edelhoff D, Gernet W, Naumann M. Effect of preparation angles on the precision of zirconia crown copings fabricated by CAD/CAM system. Dent Mater J 2008;27:814-20.
3. Abduo J, Lyons K, Swain M. Fit of zirconia fixed partial denture: a systematic review. J Oral Rehabil 2010;37:866-76.
4. Shamseddine, L., et al. Marginal and internal fit of pressed ceramic crowns made from conventional and computer-aided design and computer-aided manufacturing wax patterns: An in vitro comparison. J Prosthet Dent, 2016;116(2):242-8
5. Miyazaki T, Hotta Y. CAD/CAM systems available for the fabrication of crown and bridge restorations. Aust Dent J 2011;56:97-106.
6. Ng J, Ruse D, Wyatt C. A Comparison of the marginal fit of crowns fabricated with digital and conventional methods. J Prosthet Dent 2014;112:555-60.
7. Al-Rabab‘ah MA, Macfarlane TV, McCord JF. Vertical marginal and internal adaptation of all-ceramic copings made by CAD/CAM technology. Eur J Prosthodont Restor Dent 2008;16:109-15.
8. Yüksel E, Zaimog!lu A. Influence of marginal fit and cement types on microleakage of all-ceramic crown systems. Braz Oral Res 2011;25:261-6.

9. Guess PC, Vagkopoulou T, Zhang Y, Wolkewitz M, Strub JR. Marginal and internal fit of heat pressed versus CAD/CAM fabricated all ceramic onlays after exposure to thermo-mechanical fatigue. J Dent 2014;42:199-209.
10. Vojdani M, Torabi K, Farjood E, Khaledi A. Comparison the marginal and internal fit of metal copings cast from wax patterns fabricated by CAD/CAM and conventional wax up techniques. J Dent 2013;14:118-29.
11. Tan PL, Gratton DG, Diaz-Arnold AM, Holmes DC. An in vitro comparison of vertical marginal gaps of CAD/CAM titanium and conventional cast res- torations. J Prosthodont 2008;17:378-83.
12. Anadioti E, Aquilino SA, Gratton DG, Holloway JA, Denry I, Thomas GW, et al. 3D and 2D marginal fit of pressed and CAD/CAM lithium disilicate crowns made from digital and conventional impressions. J Prosthodont 2014;23:610-7.
13. Martinez-Rus F, Ferreiroa A, Ozcan M, Pradies G. Marginal discrepancy of monolithic and veneered all-ceramic crowns on titanium and zirconia implant abutments before and after adhesive cementation: a scanning elec- tron microscopy analysis. Int J Oral Maxillofac Implants 2013;28:480-7.
14. Baig MR, Tan KB, Nicholls JI. Evaluation of the marginal fit of a zirconia ceramic computer-aided machined (CAM) crown system. J Prosthet Dent 2010;104:216-27.
15. Stappert CF, Chitmongkolsuk S, Silva NR, Att W, Strub JR. Effect of mouth- motion fatigue and thermal cycling on the marginal accuracy of partial coverage restorations made of various dental materials. Dent Mater 2008;24:1248-57.

16. Hunter AJ, Hunter AR. Gingival crown margin configurations: a review and discussion. Part I: Terminology and widths. J Prosthet Dent. 1990 Nov;64(5):548-52.

17. Hunter AJ, Hunter AR. Gingival margins for crowns: a review and discussion. Part II: Discrepancies and configurations. J Prosthet Dent. 1990 Dec;64(6):636-42.

18. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: a systematic review. J Prosthet Dent. 2013 Dec;110(6):447-454.

19. Tsirogiannis P, Reissmann DR, Heydecke G. Evaluation of the marginal fit of single-unit, complete-coverage ceramic restorations fabricated after digital and conventional impressions: A systematic review and meta-analysis. J Prosthet Dent. 2016 Sep;116(3):328-335.

20. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent 1989;62(4):405-408.

21. Holmes JR, Bayne SC. Marginal fit of castable ceramic crowns. J Prosthet Dent, 1992. 67(5):594-9.

22. Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent, 1989;62(4):405-8

23. Schwartz NL, Whitsett LD, Berry TD, Stewart JL. Unserviceable crowns and fixed partial dentures. JADA, Dec 1970;81:1395-1401.

24. Behrend DB. Crown margins and gingival health. Ann R Aust Co11 Dent Surg 1984;8:138-45.

25. Felton DA, Kanoy BE, Bayne SC, Wirthman GP. Effect of in vivo crown margin discrepancies on periodontal health. J Prosthet Dent 1991;65:357-64.

26. Tan PL, Gratton DG, Diaz-Arnold AM, Holmes DC. An in vitro comparison of vertical marginal gaps of CAD/CAM titanium and conventional cast restorations. J Prosthodont 2008;17:378-83.

27. Coli P, Karlsson S. Fit of a new pressure-sintered zirconium dioxide coping. Int J Prosthodont 2004;17:59-64.

28. Chan C, Haraszthy G, Geis-Gerstorfer J, Weber H, Huettemann H. Scanning electron microscopic studies of the marginal fit of three esthetic crowns. Quintessence Int 1989;20:189-93.

29. Reich S, Wichmann M, Nkenke E, Proeschel P. Clinical fit of all-ceramic three-unit fixed partial dentures, generated with three different CAD/CAM systems. Eur J Oral Sci 2005;113:174-9.

30. Bindl A, Windisch S, Mormann WH. Full- ceramic CAD/CAM anterior crowns and copings. Int J Comput Dent 1999;2:97-111.

31. Lin MT, Sy-Munoz J, Munoz CA, Goodacre CJ, Naylor WP. The effect of tooth preparation form on the fit of Procera cop- ings. Int J Prosthodont 1998;11:580-90.

32. Sulaiman F, Chai J, Jameson LM, Wozniak WT. A comparison of the marginal fit of In-Ceram, IPS Empress, and Procera crowns. Int J Prosthodont 1997;10:478-84.

33. May KB, Russell MM, Razzoog ME, Lang BR. Precision of fit: the Procera AllCeram crown. J Prosthet Dent 1998;80:394-404.

34. Nakamura T, Dei N, Kojima T, Wakabayashi K. Marginal and internal fit of Cerec 3 CAD/CAM all-ceramic crowns. Int J Prosthodont 2003;16(3):244-8.

35. Iwai T, Komine F, Kobayashi K, Saito A, Matsumara H. Influence of convergence angle and cement space on adaptation of zirconium dioxide ceramic copings. Acta Odontol Scand 2008;66(4):214-8.

36. Assif D, Antopolski B, Helft M, Kaffe I. Comparison of methods of clinical evaluation of the marginal fit of complete cast gold crowns. J Prosthet Dent. 1985;54(1):20-24.

37. Rahme HY, Tehini GE, Adib SM, Ardo AS, Rifai KT. In vitro evaluation of the "replica technique" in the measurement of the fit of procera crowns. J Contemp Dent Pract 2008;9(2):25-32.

38. Pelekanos S, Koumanou M, Koutayas SO, Zinelis S, Eliades G. Micro-CT evaluation of the marginal fit of different In-Ceram alumina copings. Eur J Esthet Dent 2009;4:278-92.

39. Boening KW, Wolf BH, Schmidt AE,Kastner K, Walter MH. Clinical fit of Procera AllCeram crowns. J Prosthet Dent 2000;84:419-24.

40. Reich S, Wichmann M, Nkenke E, Proeschel P. Clinical fit of all-ceramic three-unit fixed partial dentures, generated with three different CAD/CAM systems. Eur J Oral Sci 2005;113:174-9.

41. Kokubo Y, Ohkubo C, Tsumita M, Miyashita A, Vult von Steyern P, Fukushima S. Clinical marginal and internal gaps of Procera AllCeram crowns. J Oral Rehabil 2005;32:526-30.

42. Luthardt RG, Bornemann G, Lemelson S, Walter MH, Huls A. An innovative method for evaluation of the 3-D internal fit of CAD/CAM crowns fabricated after direct optical versus indirect laser scan digitizing. Int J Prosthodont 2004;17:680-5.

43. Luthardt RG, Bornemann G, Lemelson S, Walter MH, Huls A. An innovative method for evaluation of the 3-D internal fit of CAD/CAM crowns fabricated after direct optical versus indirect laser scan digitizing. Int J Prosthodont 2004;17:680-5.
44. Lee DH. Digital approach to assessing the 3-dimensional misfit of fixed dental prostheses. J Prosthet Dent 2016 Dec;116(6):836-839.
45. Belser UC, MacEntee MI, Richter WA. Fit of three porcelain-fused-to-metal marginal designs in vivo: a scanning electron microscope study. J Prosthet Dent 1985;53(1):24-9.
46. Chan C, Haraszthy G, Geis-Gerstorfer J, Weber H, Huettemann H. Scanning electron microscopic studies of the marginal fit of three esthetic crowns. Quintessence Int 1989;20(3):189-93.
47. Hamaguchi H, Cacciatore A, Tueller VM. Marginal distortion of the porcelain- bonded-to-metal complete crown: an SEM study. J Prosthet Dent 1982;47(2):146-53.
48. Bindl A, Mormann WH. Marginal and internal fit of all-ceramic CAD/CAM crown-copings on chamfer preparations. J Oral Rehabil 2005;32:441-7.
49. Swain MV, Xue J. State of the art of Micro-CT applications in dental research. Int J Oral Sci 2009;1:177-88.
50. Krasanaki ME, Pelekanos S, Andreiotelli M, Koutayas SO, Eliades G. X-ray microtomographic evaluation of the influence of two preparation types on marginal fit of CAD/ CAM alumina copings: a pilot study. Int J Prosthodont 2012;25:170-2.
51. Shahmoradi M, Lashgari M, Rabbani H, Qin J, Swain M. A comparative study of new and current methods for dental micro-CT image denoising. Dentomaxillofac Radiol 2016;45(3):20150302.

52. Zandparsa R, El Huni RM, Hirayama H, Johnson MI. Effect of different dental ceramic systems on the wear of human enamel: An in vitro study. J Prosthet Dent 2016;115(2):230-7.

53. Dindaroğlu F, Duran GS, Görgülü S. Reproducibility of the lip position at rest: A 3-dimensional perspective. Am J Orthod Dentofacial Orthop 2016;149(5):757-65.

54. Tahmaseb A1, van de Weijden JJ, Mercelis P, De Clerck R, Wismeijer D. Parameters of passive fit using a new technique to mill implant-supported superstructures: an in vitro study of a novel three-dimensional force measurement-misfit method. Int J Oral Maxillofac Implants 2010;25(2):247-57.

55. Drago C1, Saldarriaga RL, Domagala D, Almasri R. Volumetric determination of the amount of misfit in CAD/CAM and cast implant frameworks: a multicenter laboratory study. Int J Oral Maxillofac Implants 2010;25(5):920-9.

56. Holst S, Karl M, Wichmann M, Matta RE. A new triple-scan protocol for 3D fit assessment of dental restorations. Quintessence Int 2011;42(8):651-7.

57. Holst S, Karl M, Wichmann M, Matta RE. A technique for in vitro fit assessment of multi-unit screw-retained implant restorations: Application of a triple-scan protocol. J Dent Biomech. 2012;3:1758736012452181

58. Reprinted from Ivoclar Vivadent IPS e.max© Press Instructions for use. 2009. Pg 22. Ivoclar Vivadent, Schaan, Lichtenstein.

59. Groten M, Axmann D, Pröbster L, Weber H. Determination of the minimum number of marginal gap measurements required for practical in-vitro testing. J Prosthet Dent. 2000;83:40–49.

60. Pimenta MA, Frasca LC, Lopes R, Rivaldo E. Evaluation of marginal and internal fit of ceramic and metallic crown copings using x-ray microtomography (micro-CT) technology. J Prosthet Dent 2015;114(2):223-8.

61. Anadioti E, Aquilino SA, Gratton DG, Holloway JA, Denry IL, Thomas GW, Qian F. J Internal fit of pressed and computer-aided design/computer-aided manufacturing ceramic crowns made from digital and conventional impressions. Prosthet Dent 2015;113(4):304-9.

62. Alfaro DP, Ruse ND, Carvalho RM, Wyatt CC. Assessment of the Internal Fit of Lithium Disilicate Crowns Using Micro-CT. J Prosthodont 2015;24(5):381-6.

63. Freire Y, Gonzalo E, Lopez-Suarez C, Suarez MJ. The Marginal Fit of CAD/CAM Monolithic Ceramic and Metal-Ceramic Crowns. J Prosthodont 2017 Feb 2.

64. Homsy FR, Özcan M, Khoury M, Majzoub ZAK. Marginal and internal fit of pressed lithium disilicate inlays fabricated with milling, 3D printing, and conventional technologies. J Prosthet Dent. 2017 Sep 29. pii: S0022-3913(17)30518-8.

65. Mostafa NZ, Ruse ND, Ford NL, Carvalho RM, Wyatt CC. Marginal Fit of Lithium Disilicate Crowns Fabricated Using Conventional and Digital Methodology: A Three-Dimensional Analysis. J Prosthodont. 2017 Aug 21. doi: 10.1111/jopr.12656.

66. Real-Voltas F, Romano-Cardozo E, Figueras-Alvarez O, Brufau-de Barbera M, Cabratosa-Termes J. Comparison of the Marginal Fit of Cobalt-Chromium Metal Ceramic Crowns Fabricated by CAD/CAM Techniques and Conventional Methods at Three Production Stages. Int J Prosthodont 2017;30(3):304–305.

67. Neves FD, Prado CJ, Prudente MS, Carneiro TA, Zancopé K, Davi LR, Mendonça G, Cooper LF, Soares CJ. Micro-computed tomography evaluation of marginal fit of lithium disilicate crowns fabricated by using chairside CAD/CAM systems or the heat-pressing technique. J Prosthet Dent 2014;112(5):1134-40.
68. Kim JH, Jeong JH, Lee JH, Cho HW. Fit of lithium disilicate crowns fabricated from conventional and digital impressions assessed with micro-CT. J Prosthet Dent 2016;116(4):551-557.
69. Dahl BE, Dahl JE, Rønold HJ. Internal fit of three-unit fixed dental prostheses produced by computer-aided design/computer-aided manufacturing and the lost-wax metal casting technique assessed using the triple-scan protocol. Eur J Oral Sci. 2017 Nov 24.
70. Zeltner M, Sailer I, Mühlemann S, Özcan M, Hämmerle CH, Benic GI. Randomized controlled within-subject evaluation of digital and conventional workflows for the fabrication of lithium disilicate single crowns. Part III: marginal and internal fit. J Prosthet Dent. 2017;117(3):354-362.
71. Demir N, Ozturk AN, Malkoc MA. Evaluation of the marginal fit of full ceramic crowns by the microcomputed tomography (micro-CT) technique. Eur J Dent 2014;8:437-44.
72. Beyari MM. Marginal and internal crown fit evaluation of CAD/CAM versus press-laboratory all-ceramic crown. Clinical Medicine and Diagnostics 2014;4:21-6.
73. Mously HA, Finkelman M, Zandparsa R, Hirayama H. Marginal and internal adaptation of ceramic crown restorations fabricated with CAD/CAM technology and the heat-press technique. J Prosthet Dent 2014;112:249-56.

74. Asavapanumas C, Leevailoj C. The influence of finish line curvature on the marginal gap width of ceramic copings. J Prosthet Dent 2013;109:227-33.

75. Yucel MT, Aykent F, Avunduk MC. In vitro evaluation of the marginal fit of different all-ceramic crowns. J Dent Sci 2013;8:225-30.

76. Cho SH, Nagy WW, Goodman JT, Solomon E, Koike M. The effect of multiple firings on the marginal integrity of pressable ceramic single crowns. J Prosthet Dent 2012;107:17-23.

77. Farid F, Hajimiragha H, Jelodar R, Mostafavi AS, Nokhbatolfoghahaie H. In vitro evaluation of the effect of core thickness and fabrication stages on the marginal accuracy of an all-ceramic system. J Dent 2012;9:188-94.

78. Subasi G, Ozturk N, Inan O, Bozogullari N. Evaluation of marginal fit of two all-ceramic copings with two finish lines. Eur J Dent 2012;6:163-8.

79. Borges GA, Faria JS, Agarwal P, Spohr AM, Correr-Sobrinho L, Miranzi BA. In vitro marginal fit of three all-ceramic crown systems before and after cementation. Oper Dent 2012;37:641-9.

80. Yüksel E, Zaimo!glu A. Influence of marginal fit and cement types on microleakage of all-ceramic crown systems. Braz Oral Res 2011;25:261-6.

81. Holden JE, Goldstein GR, Hittelman EL, Clark EA. Comparison of the marginal fit of pressable ceramic to metal ceramic restorations. J Prosthodont 2009;18:645-8.

82. Good ML, Mitchell CA, Pintado MR, Douglas WH. Quantification of all-ceramic crown margin surface profile from try-in to 1-week post-cementation. J Dent 2009;37:65-75.

83. Goldin EB, Boyd NW 3rd, Goldstein GR, Hittelman EL, Thompson VP. Marginal fit of leucite-glass pressable ceramic restorations and ceramic pressed-to-metal restorations. J Prosthet Dent 2005;93:143-7.

84. Reprinted from Ivoclar Vivadent IPS e.max© CAD Instructions for use. 2009. Pg 62. Ivoclar Vivadent, Schaan, Lichtenstein.

85. Reprinted from Vario Press 300. Operation Instruction. 2004/Rev. 2. Pg 40. Zubler USA Inc., Irving, TX.

86. Reprinted from Ivoclar Vivadent IPS e.max© Press Instructions for use. 2009. Pg 60. Ivoclar Vivadent, Schaan, Lichtenstein.

87. Reprinted from Vario Press 300. Operation Instruction. 2004/Rev. 2. Pg 35. Zubler USA Inc., Irving, TX.

88. Used with permission from Capture 3D Inc. Michigan, USA

APPENDIX A

Material	Manufacturer	Details
ProArt CAD Wax 20mm Yellow Discs	Ivoclar Vivadent	Ref#:673964; Lot#: TL6394, Exp:6/30/2019
IPS e.max© CAD blocks	Ivoclar Vivadent	MO 3, Ref #596800, Lot #L03488
IPS e.max© Press ingots	Ivoclar Vivadent	MO 3 L, Ref# 596765;Lot# KM0090
200g IPS Investment Ring System	Ivoclar Vivadent	Ref# 597061, Lot# W33445
The IPS PressVEST Premium Powder	Ivoclar Vivadent	5kg box, Ref#:685586AN; Lot #WL1768; Exp:5/31/2019
IPS PressVEST Premium Liquid	Ivoclar Vivadent	1 Liter, Lot#: 685588; Lot#: WL1832; Exp:8/31/2019
IPS e.max Press Invex Liquid	Ivoclar Vivadent	1 Liter, Ref#:597064; Lot#:VL0251; Exp:12/31/2021

Specifications of Materials used.

IPS e.max® CAD –

CRYSTALLIZATION PARAMETERS / KRISTALLISATIONSPARAMETER

ivoclar vivadent

Ivoclar Vivadent furnaces / *Öfen* (110 + 220 V)

Crystallization parameters / *Kristallisationsparameter* IPS e.max CAD MO/LT/HT

Furnace *Ofen*	Closing time *Schliesszeit* S min	Stand-by temperature *Bereitschafts-temperatur* B °C / °F	Heating rate *Heizrate* t_1 °C/min / °F/min	Firing temperature *Brenn-temperatur* T_1 °C / °F	Holding time *Haltezeit* H_1 min	Heating rate *Heizrate* t_2 °C/min / °F/min	Firing temperature *Brenn-temperatur* T_2 ° C / °F	Holding time *Haltezeit* H_2 min	Longterm cooling *Langzeitabkühlung* L °C/min / °F/min	Cooling rate *Kühlrate* t_l °C/min / °F/min	Vacuum 1 *Vakuum 1* 1_1 1_2 °C / °F	Vacuum 2 *Vakuum 2* 2_1 2_2 °C / °F
P80	6:00	403 / 757	–	–	–	30 / 54	850 / 1562	10:00	700 / 1292	–	–	550 / 1022 850 / 1562
P100, P200	6:00	403 / 757	60 / 108	770 / 1418	0:10	30 / 54	850 / 1562	10:00	700 / 1292	–	550 / 1022 770 / 1418	770 / 1418 850 / 1562
P300, P500, P700	6:00	403 / 757	60 / 108	770 / 1418	0:10	30 / 54	850 / 1562	10:00	700 / 1292	0	550 / 1022 770 / 1418	770 / 1418 850 / 1562
PX1	6:00	403 / 757	60 / 108	770 / 1418	0:10	30 / 54	850 / 1562	10:00	775 / 1427 1:30 min 700 / 1292 0:20 min	–	550 / 1022 770 / 1418	770 / 1418 850 / 1562
EP 600	6:00	403 / 757	60 / 108	770 / 1418	0:10	30 / 54	850 / 1562	10:00	700 / 1292	–	550 / 1022 770 / 1418	770 / 1418 850 / 1562
EP 5000	6:00	403 / 757	60 / 108	770 / 1418	0:10	30 / 54	850 / 1562	10:00	700 / 1292	0	550 / 1022 770 / 1418	770 / 1418 850 / 1562

With the Programat P100, only programs 65–69 can be used!

Crystallization Parameters for e.max CAD, per Ivoclar Vivadent (Schaan, Lichtenstein).[84]

5.2 Firing Programs* Ivoclar e-max® CAD Crystallization
Special Mode

	Start temperature [°C]	Pre dry	Pre drying time [min]	Closing time [min]	Soak temperature [°C]	Soak time [min]	Heat rate 1 [°C/min]	Final temperature 1 [°C]	Hold time 1 [min]	Heat rate 2 [°C/min]	Final temperature 2 [°C]	Hold time 2 [min]	Opening temperature [°C]	Vacuum	Release vacuum	Vacuum end [°C]
Crystalliz. HT / LT	403	no	–	6:00	550	0:00	90	820	0:10	30	840	7:00	700	yes	Hold time	7:00
Crystalliz. MO	403	no	–	6:00	550	0:00	60	770	0:10	30	850	10:00	700	yes	Hold time	10:00
Correction	403	no	–	6:00	550	0:00	90	820	0:10	30	840	3:00	700	yes	Hold time	3:00

*All firing programs are only recommendations of the ceramic producer and can be modified individually

Crystallization Parameters for e.max CAD per Zubler USA Inc. (Irving, TX).[85]

IPS e.max® Press
Press and Firing Parameters

Press Parameters for IPS e.max Press
The press furnace, investment ring size and the selected IPS e.max Press ingot must be considered.

Press Furnace	IPS e.max Press Ingots	IPS Investment Ring System	B °C/°F	t↗ °C/°F/min	T °C/°F	H min	V_1 °C/°F	V_2 °C/°F	
EP 500	 HO, MO, LT	100 g	700/1292	60/108	925/1697	15	500/932	925/1697	Program 11-20 Software 2.9
		200 g	700/1292	60/108	930/1706	25	500/932	930/1706	Program 11-20 Software 2.9
	 HT	100 g	700/1292	60/108	920/1688	15	500/932	920/1688	Program 11-20 Software 2.9
		200 g	700/1292	60/108	925/1697	25	500/932	925/1697	Program 11-20 Software 2.9

Press and Firing Parameters for e.max Press per Ivoclar Vivadent (Schaan, Lichtenstein).[86]

5.1 Press Programs* *I-Press Program*

Pressceramic	Ring size	Start temperature [°C]	Heat rate [°C/min]	Final temperature [°C]	Hold time [min]	Extra press time [min]	Maximum press time [min]	Pressure	Vacuum level	Opening time [min]
IPS e.max Press MO	**200g**	700	60	920	25:00	0:00	8:00	low	710mm	0:00

Press and Firing Parameters for e.max Press per Zubler USA Inc. (Irving, TX).[87]