Micro-CT Measurement of the Internal Fit of Lithium Disilicate Crowns

by

David Alfaro

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Abstract

The introduction of digital impressions into the field of dentistry has begun the era of entirely computer assisted crown fabrication. The aim of this study was to assess the internal fit of lithium disilicate crowns fabricated using this novel impression technology and to compare their fit to the fit of crowns obtained by traditional elastomeric impressions. Thus, 15 lithium disilicate crowns were fabricated using an entirely digital workflow (impression and fabrication), 15 lithium disilicate crowns were fabricated manually from digital impressions, and 15 lithium disilicate crowns were fabricated using a "traditional" manual process. For the fabrication of the crowns, tooth #15 was prepared for an all-ceramic restoration on an ivorine typodont, which in turn was digitized and a replica milled in zirconia. This master zirconia model and die were then utilized for the impression procedures. Duplicate dies of the master zirconia die were made in polyurethane, enabling the internal fit of each crown to be evaluated via micro CT analysis, due to the contrast in radioopacity between the ceramic, die and internal space. The total volume of the internal space (gap), the mean and maximum thickness of the gap, and the percentage of the gap that was at or below 120um thickness were calculated and evaluated statistically via one-way ANOVA, with post-hoc Scheffé analysis. The results demonstrated that the lithium disilicate crowns fabricated from digital impressions resulted in a smaller internal space, and therefore more intimate fit, in comparison to the lithium disilicate crowns fabricated via the traditional manual approach. Three-dimensional renderings of the internal space were also created, allowing for a descriptive analysis of the distribution of this internal space.

Preface

This project was a collaboration with a parallel Master of Science project at UBC Prosthodontics (Student: Dr. Jonathan Ng; Supervisor: Dr. Chris Wyatt). Both studies required the fabrication of a master zirconia cast replica of an ivorine typodont with #15 prepared for an all-ceramic crown. The preparation of the ivorine typodont was performed by Dr. Ng and the digitization and fabrication of the zirconia model was completed by Aurum Ceramics in Calgary. 15 pressed lithium disilicate crowns fabricated from polyvinyl siloxane (PVS) impressions and type IV dental stone casts, and 15 milled lithium disilicate crowns fabricated from LAVA COS digital impressions were required and fabricated for use in both projects. As part of the fabrication process of these 30 crowns, I was responsible for the fabrication of custom trays, and for the PVS and digital impressions, in co-operation with Dr. Ng. Independently from the other study I obtained 15 pressed lithium disilicate crowns from the digital impressions, resulting in a total of 45 crowns for this project. I also obtained duplicate dies and performed the Micro CT analysis on all 45 specimens. This project did not require ethics board approval.

Table of Contents

List of Tables

List of Figures

Acknowledgements

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A special thanks goes to Dr. Ng for the countless hours we spent working on our projects.

Most importantly, I want to thank my family for all of their support throughout these years of education.

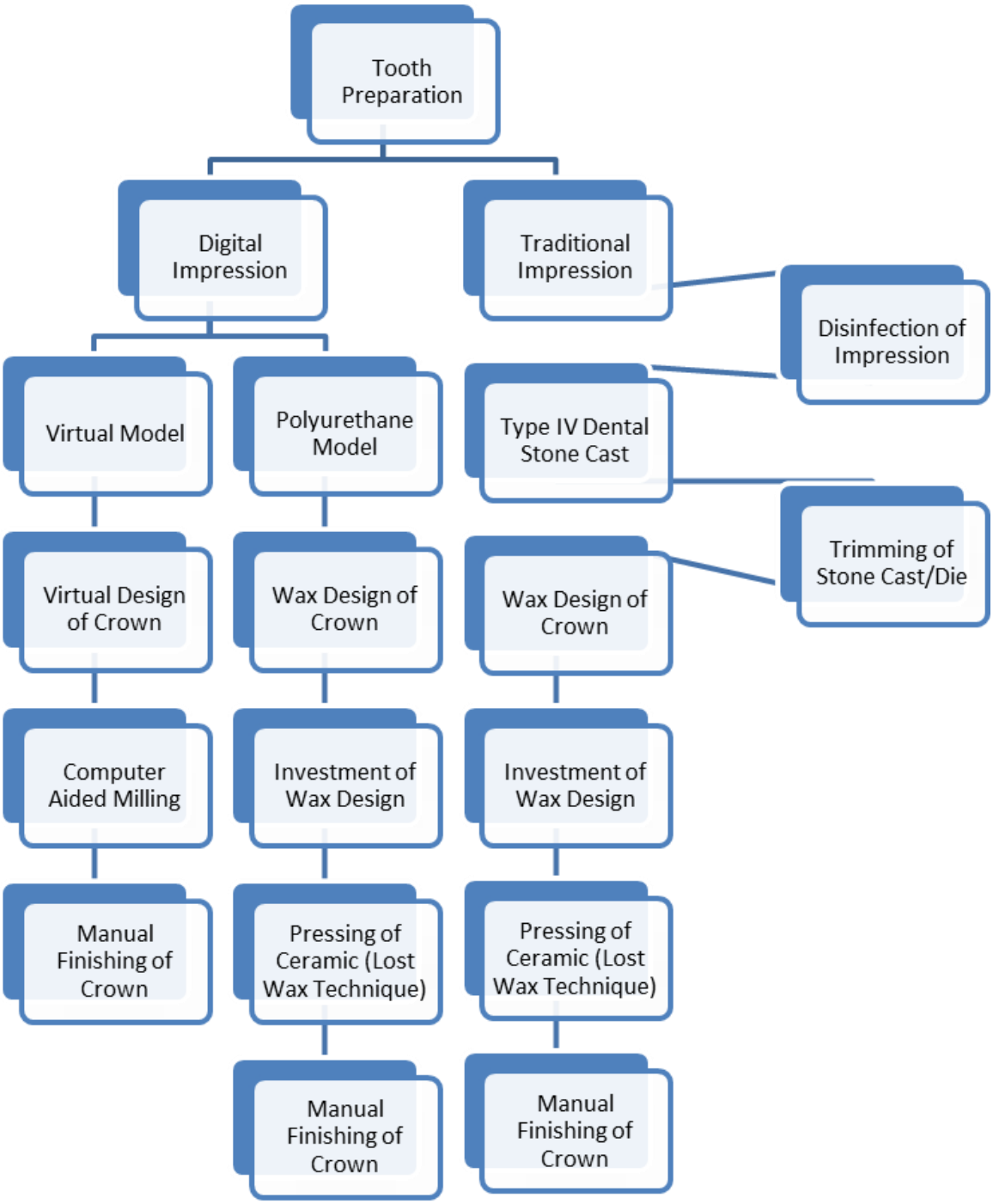
Dedication

I would like to dedicate this project to my dog Chanchita, the best pug in the world, and to my family, who have supported me through all of these years of education.

Chapter 1: Introduction

The use of dental laboratory fabricated crowns to restore structurally weak or fractured teeth has been standard of care for decades. Traditionally, in order to fabricate an indirect restoration, after the dentist has prepared the tooth, an elastomeric impression is made, a master cast is created for die preparation, the crown is waxed-up and invested in dental stone, and then is cast in a metal alloy or a ceramic. Each of these steps is subject to error, with the potential end result being an unacceptable fit of the crown to the tooth. The introduction of digital technology has revolutionized dentistry. Digital impression of the tooth preparation, along with computer assisted design (CAD) and manufacturing (CAM) by the dental laboratory and supporting companies, have eliminated the need for physical impression, therefore allowing crowns to be made without waxing and casting. The aim of this study was to assess the internal fit of crowns fabricated via a completely digital process, a partially digital process and a traditional process and to compare the fit of the 3 techniques. An example of the steps required of both the digital (complete and partial) and traditional "workflows" are illustrated in Figure 1.

Figure 1: Digital and Traditional Workflow for the Fabrication of Ceramic Crowns



1.1 Lithium Disilicate for Dental Restorations

Glass ceramics have been found to be clinically successful as bonded veneers, but have not demonstrated satisfactory performance as full coverage restorations, especially in the posterior region (Bona & Kelly, 2008). A strategy to improve the mechanical properties of all ceramic restorations is to introduce crystalline phases that augment the fracture toughness and flexural strength of the materials. Leucite, in concentrations of 35-45%, has been used as a reinforcing phase (Kelly, 2004) and these restorations have been found to be clinically acceptable in the anterior region and have also been successfully utilized in the posterior region (Bona & Kelly, 2008).

Lithium disilicate, first introduced to the market in 1998 (Guess et al., 2011), is another alternative to further improve the physical properties of all ceramic restorations. (Kelly, 2004). The concentration of lithium disilicate has been reported to be up to 70%, yielding a material that is no longer primarily glassy. This increase in crystalline component improves the physical properties substantially in comparison to unfilled or leucite reinforced ceramics (Kelly, 2004). Lithium disilicate reinforced materials for the manufacturing of all ceramic restorations are available from one manufacturer (Ivoclar Vivadent) in two varieties: IPS e.max Press and IPS e.max CAD. The former is intended to be used with the traditional lost wax technique while the latter is designed for the use with CAD/CAM technology. Pressable lithium disilicate can be used for inlays, onlays, crowns, or anterior 3 unit bridges and can be used either monolithic and full contour, or as a core. Lithium disilicate CAD is milled in a partially sintered phase (decreased flexural strength and fracture toughness),

which allows for easier milling and adjustment. It is then fully sintered after milling and adjustment, obtaining its final optical and physical properties. Lithium disilicate CAD can be utilized as monolithic prosthesis that is stained, or as a core material veneered with feldspathic porcelain. It can be prescribed for crowns, onlays, inlays, and veneers (Guess, et al., 2011).

1.2 Impression Materials

In order to fabricate a fixed prosthesis indirectly, the laboratory must be provided with a replica of the prepared tooth. The role of an impression is to accurately reproduce the anatomy of the prepared tooth and adjacent oral structures. Therefore, the accuracy of the impression plays a very important role in the fit of the final prosthesis: the more accurate an impression can reproduce fine detail, the better the marginal fit of the restoration (Hamalian, Nasr, & Chidiac, 2011). Most modern impression materials are available in varying viscosities, with lighter viscosity materials having a superior ability to capture fine detail (less than 50 µm). However, they are less dimensionally stable than heavier body materials and are therefore recommended as a wash to capture areas of fine detail and not as the bulk of the impression (Donovan & Chee, 2004).

An ideal impression material must possess various critical features. It must be biocompatible, dimensionally stable, accurately reproduce oral structures, have good tear resistance, pour accurate casts, set quickly and must be cost effective (Rubel, 2007). The inappropriate selection or manipulation of impression materials (mixing, moisture control,

etc.) can lead to errors further down the workflow of the fabrication of restorations (Donovan & Chee, 2004). Furthermore, it is imperative for these materials to be dimensionally stable after disinfection in the dental office and laboratory (Kotsiomiti, Tzialla, & Hatjivasiliou, 2008).

Many different impression materials have been utilized in the field of dentistry over the past century. Hydrocolloid impression materials were introduced in the 1930's, condensation silicone and rubber base impression materials were introduced in the 1950's, polyethers in the 1960's and hydrophobic addition silicone impression materials in the 1970's (Hamalian, et al., 2011). Addition reaction polyvinyl siloxanes (PVS) are currently the most common impression materials utilized for fixed prosthodontics (Donovan & Chee, 2004; Rubel, 2007).

PVS impressions have been found to be the most dimensionally stable impressions over a one-week period when compared to polysulfide, condensation silicones or polyether impressions. When PVS was used in combination with a custom tray and adhesive, a minimal 0.16 % volumetric reduction in size has been recorded (Ciesco, Malone, Sandrik, & Mazur, 1981). This long term dimensional stability is favourable if there are to be any delays in transportation of the impression to the laboratory for pouring (Donovan & Chee, 2004). The accuracy of the resultant dies has also been shown to be affected by the bulk of material in the impression tray, where an increase in the thickness of impression material from 1 mm to 4 mm caused an increase in diameter of 6 µm and a decrease of almost 40 µm in the length of the resultant stone dies. The most accurate dies were found to be fabricated in impressions

made with 2-3 mm of PVS impression material. In order to ensure an even amount of impression material around the oral structures, the use of a custom tray has been advocated (Rueda, Sy-Munoz, Naylor, Goodacre, & Swartz, 1996). The use of a custom tray with 2.5 mm of spacer has been shown to decrease dimensional discrepancies of dies for fixed dental prostheses in comparison to stock trays. Inter-preparation discrepancies as low as 0.1 % have been found with custom trays, while this value increased to 0.33 % (100 µm linearly) when a stock tray was utilized. These discrepancies can create misfit in the prostheses, especially if a multiple unit fixed dental prosthesis is to be fabricated (Gordon, Johnson, & Drennon, 1990).

In addition to the role of impression material bulk, it has been demonstrated that as the amount of undercut in a preparation increases, the resultant die becomes more dimensionally inaccurate (de Araujo & Jorgensen, 1985); therefore, the utilization of a material with good elastic rebound will result in improved accuracy of the dies in this situation. PVS impression materials have been shown to have a great capacity for elastic recovery, with virtually no permanent deformation (0.07 %) being found in strain tests (Klooster, Logan, & Tjan, 1991). This property of PVS materials becomes critical when removing an impression from an undercut area because the strain induced in the material upon removal causes deformation of the material. Adequate elastic recovery is therefore required in order for the impression to return to its original dimensions upon removal from these undercut areas (de Araujo & Jorgensen, 1985). In addition to excellent elastic recovery, the lower stiffness of PVS impression material allows it to be removed from the mouth easier than stiffer impression materials such as polyether, thus reducing the probability of damaging fragile tooth preparations or the resultant casts and dies (Donovan & Chee, 2004).

The hydrophobicity or hydrophilicity of an impression material can play a large role in how the material adapts to a preparation, especially in the presence of moisture in the form of saliva, blood and other contaminants. When PVS materials were introduced in the 1970's, they were hydrophobic, but manufacturers have since added surfactants to improve wettability (Cullen, Mikesell, & Sandrik, 1991). This improved wettability, however, is more beneficial in the pouring of the casts in comparison to during the impression procedure, therefore, proper moisture control is imperative when using these materials (Donovan & Chee, 2004). The wettability of an impression material is traditionally measured by the contact angle a drop of water makes on a film of the material, with the lower the angle, the more wettable the material (Cullen, et al., 1991). The presence of salivary films on hydrophobic impressions has been found to increase the number of voids in the resultant stone casts (Vassilakos & Fernandes, 1993) , exemplifying the importance of adequate moisture control during the impression making and cast fabrication procedures.

After the making of an acceptable impression, it must be disinfected prior to transportation to the laboratory for pouring. All impressions that have not been disinfected have been found to be contaminated with oral microflora, such as *streptococcus mutans;* methicillin resistant *staphylococcus aureus* was also present in 25 % of the cases. The use of disinfection agents, such as 0.25 % benzalkonium chloride or 1 % sodium hypochlorite, has been shown to reduce, but not completely eliminate, the presence of these oral microflora on impressions (Egusa et al., 2008). Of the available methods of disinfection, immersion appears to be the simplest and most favourable, with minimal detrimental effects on impression dimensional stability or on the quality and accuracy of the resultant casts (Kotsiomiti, et al.,

2008). Dimensional changes due to disinfection are more notable on water based impression materials such as alginate, but are virtually non-existent for PVS impression materials, regardless of the mode of disinfection (al-Omari, Jones, & Wood, 1998). The disinfection of silicone impression materials has been found to have dimensional changes of less than 0.5 %, a clinically insignificant change. PVS materials, showed less dimensional change after immersion disinfection in comparison to polyether, which demonstrated a slight expansion, likely due to its more hydrophobic nature (Melilli, Rallo, Cassaro, & Pizzo, 2008). The surface quality of PVS impressions is also not affected by disinfection, regardless of technique, with the material retaining a smooth glossy finish after the treatment. Polyether materials, however, are adversely affected by immersion in sodium hypochlorite, with 100 % of impressions disinfected in this manner showing pitting and mottling of the surface (Walker, Rondeau, Petrie, Tasca, & Williams, 2007).

The favourable physical and handling properties of PVS, in addition to its accuracy and dimensionally stability, made it the impression material of choice for this study.

1.2.1 Digital Impression Technology

While not a recent introduction to the dental field, the use of digital technologies for the direct impression of oral structures is still quite a novel technique. There are various purported advantages to the utilization of digital impressions in dentistry, including a reduction in the cost, procedural complexity, and waste compared with the use of impression materials, improved patient acceptance, no need for disinfection of the impression, no need

for the manual pouring and trimming of the cast, and the potential for digital articulation (Christensen, 2009). Furthermore, in addition to allowing for the milling or printing of models for use for the traditional manual fabrication of indirect restorations, digital impressions also allow for the digitally directed fabrication of crowns (van der Meer, Andriessen, Wismeijer, & Ren, 2012). Previously, to digitize full arch impressions, either a traditional impression or cast could be scanned in the laboratory to obtain a digital model for the digital design of crowns; digital impressions now allow for the omission of this step.

The first commercially available system for direct digital impressions, CEREC ® 1 (Sirona Dental Systems, Charlotte, NC), was introduced over 25 years ago and is now in its fourth generation (Seelbach, Brueckel, & Wöstmann, 2012). It is, however, still primarily utilized for the fabrication of individual restorations and not for the general impression for the creation of full arch models. The CEREC ® system requires the application of a thin, evenly distributed, reflective layer of titanium dioxide, which requires adequate moisture control and retraction of soft tissues. The abutments and neighbouring teeth are digitally impressed with an LED blue light camera and the images are reconstructed into three dimensions (Galhano, Pellizzer, & Mazaro, 2012). The fourth generation scanner, the CEREC ® Blue Cam, has reported accuracies within 17 µm for the single tooth and within 35 µm for the full quadrant (Mehl, Ender, Mormann, & Attin, 2009). Powder-less digital impression systems, such as the iTero System (Cadent, Calstadt, NJ), have been available since 2007 and utilize parallel confocal imaging technology that has a resolution under 50 µm (Galhano, et al., 2012).

Newer digital impression systems, such as the LAVA Chairside Oral Scanner (LAVA COS, 3M, Lexington, KY), have been recently introduced (2008) in to the market and can be utilized for both the impression of abutments for specific restorations and for the impression for diagnostic models (Seelbach, et al., 2012). This system utilizes active wavefront sampling to capture information in video format, versus the still images of other systems, and is the fastest system on the market, capturing 20 three-dimensional images per second (Galhano, et al., 2012). The accuracy of the LAVA COS system for full arch scans has been found to be within 40 µm and it was found to not vary significantly from traditional impressions (60 µm for medium body polyether) when the scans were virtually superimposed over a digitized in-vitro model (Ender & Mehl, 2011). As previously mentioned, the indirect digitization of casts via the utilization of optical or physical scanners has been previously utilized to allow for a digital model for digital crown design. The use of the LAVA COS for the direct digital impression of oral structures have been shown to be more accurate (15 µm) than the indirect technique (36 µm) of scanning of gypsum casts (Güth, Keul, Stimmelmayr, Beuer, & Edelhoff, 2012).

1.3 Dies

The impression is poured in dental gypsum and the cast portion that replicates the prepared tooth is sectioned and trimmed to create a die. Dental stone is classified in five types, based upon its hardness: Type I stone (impression plaster), Type II stone (modeling/mounting plaster), Type III stone (dental stone), Type IV stone (high strength/low expansion) and Type V stone (high strength/high expansion). The American Dental

Association (ADA) limits for the setting expansion of these stones is: 0.15 % for Type I, 0.30 % for Type II, 0.20 % for Type III, 0.15 % for Type IV and 0.30 % for Type V (Craig & Powers, 2002).

Just as the handling of impression material affects the accuracy of impressions, dental stone must be accurately manipulated in order to obtain accurate casts of the oral structures (Donovan & Chee, 2004). The mixing of the stone has specific requirements for water to powder ratio, spatulation rate and duration, and the setting of the stone be affected by both temperature and the presence of moisture (Craig & Powers, 2002). For example, when evaluating the effect of the type of water utilized for pouring dental stone, expansion ranges from 0.121 % for distilled water to 0.139 % for hard water were found (Brukl, McConnell, Norling, & Collard, 1984). These expansion differences, while significantly different, were however within the ADA specification of 0.20 % for type III stone. In addition to the quality of the water, strict attention to the water to powder ratio must be adhered to in order to obtain accurate dies. The water to powder ratio has been shown to be inversely proportional to setting expansion of type IV stone. A significant difference was found in the expansion of stone for a water/powder ratio of 0.276 (0.102 % expansion) versus a ratio of 0.204 (0.131 %), but again, both fall within the ADA specification of 0.15 % for Type IV stone (Alberto et al., 2011).

As previously mentioned, the wettability of impression materials is highly variable, with polyethers and hydrophilic polyvinyl siloxanes being very wettable and therefore easier to pour than polyvinyl siloxanes without hydrophobic additives (Reddy, Reddy, Itttigi, &

Jagadeesh, 2012). The contact angle of type IV stone on polyether impression material has been found to be 40º, with hydrophilic PVS ranging from 64-74º, depending on manufacturer, and hydrophobic PVS at 90º. This difference in wettability resulted in less voids in the casts of polyether versus the other materials, with hydrophobic PVS performing worse than hydrophilic PVS (Chong, Soh, Setchell, & Wickens, 1990).

Upon separation of impressions from their die stone, cross contamination of oral pathogens may still result in a contaminated cast surface, even if proper disinfection protocol for the impression material had been followed (Leung & Schonfeld, 1983). In light of this knowledge, the stone casts may be further disinfected by different methods. The incorporation of disinfectants, such as glutaraldehyde, into the dental stone before pouring has been shown to kill 100 % of the pathogens within one hour without affecting setting time or the hardness of the stone. Other agents, such as chlorhexidine or iodine, were found to either be ineffective at reducing pathogens or cause changes in the physical properties of the stone (Ivanovski, Savage, Brockhurst, & Bird, 1995). The use of steam to disinfect dental cast can cause over 50% loss in compressive strength of the set plaster and is therefore an unacceptable means of disinfection, even in the presence of surface treatments (Whyte & Brockhurst, 1996).

Dental stones, however, are not the only materials that are available for the pouring of dental casts. Epoxy resin and polyurethane resins have been utilized for the fabrication of dies and have shown an excellent capacity to replicate fine detail (1 to 2 µm) at a level more accurate than die stone (20 µm) (Derrien, Menn, Jendresen, Malone, & Taylor, 1995). The

resins, however, are subject to shrinkage during polymerization. The addition of silica fillers has been shown to reduce these dimensional changes but it also reduced the transverse strength of the dies in comparison to the dies of unfilled resins (48.68 MPa vs. 94.82 MPa, still being stronger than dental stone at 18.76 MPa) (Derrien & Sturtz, 1995). In a study comparing seven different die materials, resin reinforced Type IV stone (0.0219 % vertical distortion) and copper plated dies (-0.074 % vertical distortion) were found to be the most accurate at replicating a master die, in comparison to Type IV stone (0.3024 % vertical distortion), Type V stone (0.3038 % vertical distortion), polyurethane resin (0.4282 % vertical distortion), epoxy resin (-0.3018 % vertical distortion), or bis-acryl composite (-0.4875 % vertical distortion) (Kenyon, Hagge, Leknius, Daniels, & Weed, 2005)

In addition to these various dies, introduction of digital impressions has allowed for the fabrication of digitally manufactured dies. Accurate and durable polyurethane dies can be fabricated either by milling of polyurethane blocks or via sterolithography (SLA), where the resin is polymerized in layers via a laser (Kachalia & Geissberger, 2010). The accuracy of stereolithographic dies (23.9 µm) has been found to be clinically acceptable and comparable to the accuracy of resin reinforced type IV dental stone (17.6 µm) (Kim et al., 2013). Virtual casts for the digital design of indirect restorations have also been evaluated, with no statistical difference being found between the virtual cast and the original scanned model (Hwang et al., 2013).

1.3.1 Die Spacer

Before a wax up for an indirect restoration is fabricated, it has become customary to utilize die spacer in order to provide space for cement, in an attempt to improve the retention and fit of the indirect restoration. The most common methods in use are a paint on die spacer, or the use of foil (Carter & Wilson, 1997). The use of die spacer has been found to improve seating of cemented castings by almost 100 µm (from 143 µm to 45 µm) and to improve the post cementation retention of these crowns by 25 % (Eames et al., 1978).

The improvement in the seating of castings is greatest when the die spacer is applied over the entire die to within 0.5 mm of the margin, in comparison to techniques that paint the die spacer only in the occlusal 1/3-2/3 (Olivera & Saito, 2006). It has been recommended that the die spacer be a thickness in the range of 25-40 µm, but various variables affect the consistency of the spacing liquid: evaporation of the liquid causes increases in the film thickness (Psillakis, McAlarney, Wright, & Urquiola, 2001) and the spacer thickness varies depending on the manufacturer (Campbell, 1990). The use of die spacer less than 30 µm thick may result in the incomplete seating of the prosthesis during cementation (Fusayama, Ide, Kurosu, & Hosoda, 1963). Digital systems allow for the incorporation of a digital die spacer into the milling process, which should be consistent and accurate.

1.4 Manufacturing of Pressed and Milled Lithium Disilicate Crowns

All ceramic restorations are commonly fabricated by three methods: hand layering, pressing, or milling (Craig & Powers, 2002). Lithium disilicate crowns are commonly manufactured via the pressing and milling methods.

1.4.1 Pressed Lithium Disilicate

In the mid-1990's, pressed ceramic technology was introduced to the market place. Ingots of feldspathic (e.g. Vita PM9) or leucite reinforced ceramic (e.g. IPS Empress Esthetic) were made available for pressing into investments (Craig & Powers, 2002), similar to the lost wax technique that has been utilized for centuries in the casting of alloys. In this method, the restoration is waxed to full contour, sprued, invested and burnt out. The ceramic ingot is then melted and pressed into the investment (Craig & Powers, 2002). The resultant restoration is monolithic and therefore may require cutback and veneering with a traditional feldspathic porcelain if staining and glazing do not offer the characterization required for ideal aesthetics (Kelly, 2004). The marginal fit of pressable ceramics (55.8 µm) has been found to be not clinically different from the marginal fit of metal ceramic crowns (72.2 µm) (Holden, Goldstein, Hittelman, & Clark, 2009).

In the late 1990's, a pressable lithium disilicate reinforced ceramic were introduced, originally as IPS Empress 2, then as IPS e.max Press (Ivoclar Vivadent, Lichtenstein). Unlike the feldspathic glass ceramic and leucite-reinforced glass ceramic, this new ceramic contains

more crystalline substance than glass, which reduces its translucency (Kelly, 2004). Due to its increased strength, of approximately 400 MPa (Drummond, King, Bapna, & Koperski, 2000), it can be utilized at thicknesses as thin as 0.8 mm, as stated by the manufacturer. Pressed lithium disilicate can be used in full contour with customized staining and glazing, or as a coping for the layering of feldspathic porcelain (Guess, et al., 2011). Clinically acceptable margins have been found with both chamfer (27.2 µm) or shoulder preparations (35.1 µm) for pressed lithium disilicate crowns and minimal distortions (0.33 µm) have been found after subsequent firing cycles (Cho, Nagy, Goodman, Solomon, & Koike, 2012).

1.4.2 Milled Lithium Disilicate

All ceramic restorations can also be fabricated via milling technology. Currently, millable blocks of feldspathic, leucite reinforced and lithium disilicate reinforced ceramic are available for both in-office and in-laboratory fabrication of porcelain restorations (Guess, et al., 2011). Like the pressable ingots, the millable blocks are monolithic and may require post-milling layering or staining to achieve acceptable aesthetic results (Kelly, 2004). The lithium disilicate blocks that are available for milling via CAD/CAM are in a partially sintered state (metasilicate), because the milling of fully sintered lithium disilicate would be too demanding to the milling units. The milled partially sintered prosthesis can then be fully crystallized in a conventional ceramic oven (Kurbad & Reichel, 2005). Again, like pressed lithium disilicate, the CAD version can be milled full contour or as a coping (Guess, et al., 2011).

Milling technology comes in a range of options, from compact in-office machines like CEREC (Sirona Dental Technologies, Charlotte, NC) or E4D (D4D technologies, Richardson, TX) (Kachalia & Geissberger, 2010), to larger in-laboratory machines such as Lava (3M, Lexington, KY) or Procera (NobelBiocare, Kloten, Switzerland) (Miyazaki & Hotta, 2011). In office milling machines have been shown to have marginal accuracies within 46-66 μm (Akbar, Petrie, Walker, Williams, & Eick, 2006) and laboratory based systems 56-63 μm (May, Russell, Razzoog, & Lang, 1998).

1.5 Internal Fit

The internal gap has been defined as the perpendicular distance from the surface of the axial wall of a preparation to the internal surface of the casting (Conrad, Seong, & Pesun, 2007), and is the volume of space that will be filled with cement upon the luting of the indirect restoration to the tooth. In addition to affecting the fit of the crown, this internal gap, and the resulting cement thickness and morphology, may affect the performance of the restoration, or the cement itself. For example, porcelain veneers bonded with resin cement were found to have maximal bond strengths with a die spacer thickness of 2 layers (12.8 μm), and decreased bonds if the space was thinner or thicker (Cho, Chang, Lim, & Lee, 2006). Furthermore, fractures of cement and porcelain have been found to increase with cement thicknesses over 100 μm, with optimal cement properties found to occur between 50 and 100 μm for resin cement (Molin, Karlsson, & Kristiansen, 1996). There is currently no

consensus, however, on clinically proven guidelines based on success rates, for the appropriate volume of cement required for a given restoration type or material.

Various techniques have been utilized to determine the cement space in all-ceramic restorations, but unfortunately, the measurement has primarily been limited to analysis in a single dimension (Schaefer et al., 2013). One method that has been used involves impressing the cement space with a light body silicone impression material (PVS replica technique). The internal surface of the prosthesis is thus coated with the impression material and it is then seated on the abutment. After the complete setting of the PVS, the crown is removed from the die, leaving the impression material inside against the intaglio surface of the restoration. The crown is then filled with a heavy body material of a different colour to reinforce the light body material that is already inside. This impression can then be sectioned and the thickness of the light body impression material can be measured either from digital photographs or directly with an optical microscope. Utilizing this technique, internal spaces of 148um (61 SD), 227 µm (83 SD) and 284 µm (95 SD) were found in milled lithium disilicate crowns at mid-axial, axio-occlusal line angle, and mid occlusal measurement points, respectively (Reich, Uhlen, Gozdowski, & Lohbauer, 2011). It has been found that the thickness determined with the replica PVS technique correlates significantly with the cement thickness in crowns luted with resin modified glass ionomer cement (Rahme, Tehini, Adib, Ardo, & Rifai, 2008).

The PVS replicas can be analyzed with different methods. The optical translucency of the replica has been utilized to calculate the thickness of the internal space and has been

shown to correlate to the luted thickness of zinc phosphate cement (Kelly, Davis, & Campbell, 1989). Researchers have also attempted to determine the volume of the internal space from the weight of the PVS replica, but found no correlation to the thickness measurements of the replica (Colpani, Borba, & Della Bona, 2013). Digital evaluations of the PVS replica have also been attempted. Optical scanning of the replica shows high accuracy below thicknesses of 15 μm, but lower accuracy at thicknesses above 100 μm, while micro CT analysis of the replica has a the benefit of a large amount of volumetric data, but the accuracy is limited when the thickness of the replica is below 10 μm (Rungruanganunt, Kelly, & Adams, 2010).

Another method of determining the internal cement space is to section crowns that are luted to natural teeth or dies and to make measurements of the internal space with microscopes or on photographs; internal gaps of 75 μm and 105 μm have been found in mid-orobuccal and mid-mesiodistal measurements, respectively, via this method (Bindl & Mormann, 2005).

To date, there are no reports of the direct measurement of the internal gap on single crowns. Most studies have some sort of intervening medium such as impression material, or cement, therefore not truly representing the internal space that is available upon fabrication of the prosthesis. The internal space, however, has been directly investigated in vitro for 3 unit all ceramic fixed dental prostheses (Borba, Cesar, Griggs, & Della Bona, 2011) and for ceramic onlays of various designs (Seo, Yi, & Roh, 2009). Borba et al (2011) utilized Micro CT at 17 μm resolution to evaluate the fit of ceramic fixed dental prostheses on metal dies. In

their image analysis they took axial slices and made vertical measurements at 10 points around the internal space, every 800 µm. Although the CT data allows for volume calculations, this was not performed because of artifacts in the images; two dimensional analysis was performed instead, yielding internal fit measurements ranging from (68 to 300) µm (Borba, et al., 2011). Seo et al (2009) utilized micro CT at 15.7 µm resolution to evaluate the internal fit of onlays of various designs. In order to isolate the internal space, they selected the area of the crown and die surrounding the internal gap and determined the negative space via subtraction of the radiopaque die and porcelain. They reconstructed all axial slices into a 3 dimensional volume measurement. The average internal gap was found to range from 152.7 µm to 197.3 µm (Seo, et al., 2009). As of May 2013, there are no published reports of the analysis of the internal fit of all ceramic crowns utilizing Micro CT analysis.

Chapter 2: Research Protocol

2.1 Purpose

The aim of this study was to assess the internal fit of all ceramic crowns fabricated using computer aided design and computer aided manufacturing techniques (CAD/CAM) and to compare it with that of all ceramic crowns impressed and fabricated using traditional techniques.

2.2 Hypothesis

The hypothesis of the study is that there is no difference between the internal fit of ceramic crowns fabricated by digital impression and CAD/CAM fabrication (digital method – DM) and those fabricated with either digital impression and traditional press manufacturing (digital impression, press manufacturing – DP) or traditional impression and manufacturing techniques (traditional process – TP).

Ho = There is no difference between the internal fit of DM, DP, TP

Ha = There is a difference between the internal fit of DM, DP, TP

2.3 Expectations

While it is not expected to find a statistical difference between the three groups of indirect restorations, it may be possible that the entirely digital process allows for the creation of crowns with a smaller volume of internal space, and therefore a more intimate fit, due to the reduced amount of physical materials in the manufacturing process, which and potentially decrease the incidence of errors.

2.4 Materials and Methods

2.4.1 Master Zirconia Model

Tooth #15 was prepared for a ceramic crown restoration on an ivorine dentoform (Frasaco USA; Greenville, NC). The occlusal reduction was 2 mm on the functional cusp and 1.5 mm on the non-functional cusp, with a 1 mm circumferential reduction with a chamfer margin with rounded internal line angles, prepared with medium grit diamond burs (Brasseler, Savannah, GA), as recommended by the manufacturer (Ivoclar Vivadent; Lichtenstein) for full contour lithium disilicate IPS e.max crowns.

The maxillary and mandibular arches of the typodont were then digitized using a 3Shape D700 lab scanner (3Shape Inc., New Jersey, NY) and a duplicate of each were milled from a monolithic block of 25 mm thickness Wieland translucent yttria-stabilized zirconia (Wieland Dental, Schwenninger, Germany) in a DMG-20 5-axis milling machine (DMG /

Mori Seiki, Cypress, CA). The resultant zirconia dies were to-scale replicas of the original ivorine typodonts and included a removable zirconia die of the prepared #15. The master zirconia models were then impressed utilizing either a traditional (PVS) or digital technique (LAVA COS).

2.4.2 Traditional Polyvinyl Siloxane Impressions

The traditional impression technique utilized a single-step dual viscosity PVS impression in a custom made acrylic tray with the manufacturer's recommended adhesive, as this combination has been shown to be dimensionally stable at 1 week (Ciesco, et al., 1981) The primary reason to utilize a custom tray was to ensure an even thickness of impression material (Bomberg, Hatch, & Hoffman Jr, 1985). In order to fabricate a master custom tray, an alginate (Jeltrate® Alginate; DENTSPLY Caulk, Milford, DE) impression of the master zirconia cast was made using a perforated plastic stock tray and a cast poured in type III stone (Microstone; Whip Mix Corporation, Louisville, KY).

A single master custom tray was fabricated with a visible light cure urethane dimethacrylate resin (Triad® Custom Tray Material; DENTSPLY Caulk, Milford, DE) at a thickness of 3 mm with 2 mm of wax spacer (Gordon, et al., 1990). A 2 mm thickness of spacer was used since it has been found to result in a low variation in the dimensional accuracy of casts made from custom tray impressions (Rueda, et al., 1996). A single layer of tin foil was used over the wax spacer, because this has been shown to improve the adhesion of the impression material to the tray by preventing wax from contaminating the tray surface

(Abdullah & Talic, 2003). This master tray was then duplicated, utilizing a denture duplication flask and cold cure acrylic resin (Ivolen; Ivoclar Vivadent, Lichtenstein). In total, 15 custom trays were fabricated.

The trays were coated with the manufacturer's recommended adhesive (Caulk® Tray Adhesive; DENTSPLY Caulk, Milford, DE) and left drying for five minutes. A single-step dual viscosity technique was utilized to make the PVS impressions, which has been shown to produce accurate impressions of single teeth (Schaefer, Schmidt, Goebel, & Kuepper, 2012) and has been demonstrated to result in better fitting crowns in comparison to monophase or two-step putty wash impression (Luthardt, Walter, Weber, Koch, & Rudolph, 2008). All set impressions were removed from the zirconia casts with an anterior dislodging force (Gordon, et al., 1990) after being allowed to set for 5 minutes, as per manufacturer's instructions. The opposing master zirconia model was impressed with a dimensionally stable irreversible hydrocolloid impression material (Kromopan 100; LASCOD, Firenze, Italy). In total, 15 sets of impressions were made, with the zirconia models being washed and dried in between impressions to ensure thorough removal of any debris. The impressions were not disinfected, as they did not come into contact with a patient's mouth, and were transferred to the laboratory for pouring. Upon arrival at the laboratory, the impressions were poured with Type IV stone (Silky Rock; Whip Mix Corporation, Louisville, KY) for the fabrication of pressed lithium disilicate crowns.

2.4.3 Digital Lava COS Impression

LAVA COS impressions of the zirconia models were taken as per manufacturer's instructions, utilizing LAVA COS powder (titanium dioxide). This system utilizes active wavefront sampling to capture the oral structures in real time three dimension (Andreas Syrek et al., 2010), with data acquisition as fast as twenty three-dimensional data sets per second (Kachalia & Geissberger, 2010). The system uses a hand held optical camera, which is attached to a portable computer and monitor. The images appear in real time on the monitor, and the areas that have been properly impressed are highlighted on the screen. Upon completion of a maxillary scan, mandibular scan and bite registration scan of the master zircona models, the files were exported in .STL (Standard Tessellation Language) format, then input into digital design workflow (Core3dcentres®; Las Vegas, Nevada). A total of 15 scans were taken, with each scan being utilized in two methods: once into the fully digital work flow with digital articulation, digital wax-up and 5-axis milling of IPS e.max CAD crowns, and then also into a partially digital workflow, where SLA polyurethane models were printed for the fabrication of IPS e.max Press crowns.

2.4.4 Fabrication of Pressed Lithium Disilicate Crowns (DP and TP)

Thirty pressed lithium disilicate crowns were fabricated using the traditional lost wax technique. Half of the crowns were waxed up by a dental technician on the type IV dies (TP) and the other half were waxed up by the same technician on the polyurethane dies (DP); it was requested to the laboratory, Aurum Ceramics Calgary, that the same technician fabricate

all 30 of the pressed restorations. The crowns were waxed up to full contour, removed from the dies, invested and cast with monolithic lithium disilicate (IPS e.max Press; Ivoclar Vivadent, Lichtenstein). After removal of the sprues, the crowns were put through staining and glazing procedures and were then etched for one minute with 4.5 % hydrofluoric acid. The crowns were measured after glazing, staining and etching in order to measure the crown as it would be delivered to the dentist for insertion.

2.4.5 Fabrication of CAD All-Ceramic Crowns (DM)

For the fabrication of the milled lithium disilicate (IPS e.max CAD; Ivoclar Vivadent, Lichtenstein) crowns, the LAVA COS .STL files were input into digital design software (Core3dcentres®; Las Vagas, NV) for wax up of the full contour crown, by one technician. The IPS e.max CAD blocks were milled in a DMG-20 5-axis milling machine (DMG, Bielefeld, Germany), at Aurum Ceramics Calgary, in their presintered state, with a shrinkage of 0.02 % at milling. The DMG-20 utilizes Ivoclar Vivadent diamond grit burs (0.5-1.2mm diameters), with a mill time of 12 minutes per crown. The prescribed die space was 20 μm. After milling, the crowns were fully sintered (Programat 500; Ivoclar Vivadent) with a 0.05 % shrinkage during sintering. Crowns were stained, glazed and etched and returned for evaluation. In total, 15 IPS e.max CAD crowns were fabricated.

2.4.6 Fabrication of Replica Dies of the Original Zirconia Die

In order to avoid damage to the master zirconia die during the multiple measurements that were to be made and to allow for the scanning of multiple crowns at one time in the micro CT machine, it was decided to replicate the master die. A single master LAVA COS scan was made of the master zirconia die and the .STL file virtually transferred to Aurum Ceramics Calgary for milling at the DMG 20 milling centre. Forty-five duplicate dies were milled out of polyurethane, from the same digital scan of the master die. The dies were returned with bases that needed hand trimming with a lab hand piece in order to allow them to fit in the specimen tube of the micro CT scanner.

2.4.7 Micro CT Scanning

In total, 45 crowns were fabricated (15 DM, 15 DP, 15 TP) and each had their own polyurethane die fabricated as previously described (2.3.6). All 45 samples were seated on their respective dies with finger pressure (Kokubo, Tsumita, Kano, Sakurai, & Fukushima, 2011; A. Syrek et al., 2010), as it has been found that increases in pressure do not improve the seating of castings (Weaver, Johnson, & Bales, 1991). A pilot scan was taken at 10 µm, 17 µm and 30 µm resolution to determine a cost and time effective protocol without compromising image quality and also in order to determine the method of securing the crown to the dies. Previous authors have sealed the margins with cyanoacrylate (Kokubo, et al., 2011), but in evaluating the pilot scan, it was found that the cyanoacrylate would enter the internal space, thus creating noise in the CT Scan image and potentially interfering with

seating. Utility wax has also been utilized (Seo, et al., 2009), and when placed on the buccal and lingual margins of the crowns for the pilot study, was found to satisfactorily prevent movement of the prosthesis while not entering the internal space or appearing on the image, due to its radiolucency. The results of the pilot scan yielded the following optimal scanner settings:

- Scanner: Scanco Medical µCT100
- Energy = 90 kVp
- Intensity = 200 µA
- Power = 18 W
- Resolution = 20 µm
- Samples per scan: 12
- Duration: Approximately 30 minutes per sample

For the 20 µm resolution, the specimen holder was a cylindrical tube that allow for the placement of 3 samples. The samples were inserted vertically in the specimen tube and were stabilized and separated by packaging foam to ensure the samples did not move during scanning. Four tubes with 3 samples each were placed in the micro CT per session. In order to calibrate the scan field, a pilot scan of each specimen tube was made (scout view) and the region of each specimen to be scanned was selected individually for each sample. In total, 49 scans were made: all 45 samples were scanned once, with 2 re-scans required due to the loss of data, and 2 additional scans of one randomly selected sample performed, to allow for an analysis of the reproducibility of the technique.

2.4.8 Image Analysis

The resultant CT Scan images were analyzed with the proprietary software that is available with the scanner. In order to analyze the samples in the coronal axis, all 45 scans had to first be processed to allow for axial analysis within the software. After conversion, it was possible to select for the internal space in the axial slices. Two methods have been previously been utilized to evaluate the internal space in CT images. In one method, a large segment which includes the crown, the die and the internal space is selected and the threshold settings are reduced to remove any radiopaque structures, in theory leaving only the internal space (Seo, et al., 2009). The other method involves the outlining of the internal space by hand and excluding the radiopaque materials surrounding it (Borba, et al., 2011). In both methods, the internal space has to be selected slice by slice in one axis until the entire space is selected. A trial analysis via both methods was completed and it was found that the subtractive method yielded a volume that was 25 % larger than the outlining method. It was speculated that this increased volume was due to the inclusion of artifacts and porosities in the radiopaque materials that would show up as negative space (radiolucency), therefore overestimating the actual volume of the space. It was therefore decided to utilize the hand selection option to isolate the internal space from the images. Upon the hand selection of the internal fit on each slice of each crown in one axis, the images were reconstructed on the proprietary software to create a three dimensional rendered image of the internal space, complete with colour graded thickness maps.

The analysis software allows for the evaluation of various characteristics of the internal space that was rendered, including minimum, maximum and mean thicknesses values for the space and total volume of internal space. Furthermore, a numerical table indicating what volume and what percentage of the internal space is found at a specific thickness, in 20 μm increments (the scanning resolution), is created by the software, allowing for the evaluation of the distribution of the internal space. For example, from this data it was possible to calculate the percentage of the internal space that was at or below 120 μm thickness, for each crown individually. This value was selected as a maximum optimal thickness of internal space, and was set at 120 μm for various reasons. First of all, it has been demonstrated in laboratory studies that cement thicknesses in excess of 100μm result in poor performance of the cement and restoration (Molin, et al., 1996). This 120 μm value also correlates with historical means reported for the internal space for lithium disilicate crowns (Al-Rabab'ah, Macfarlane, & McCord, 2008), fits within the range of reported clinically acceptable ranges for internal fit (50 to 150μm) (Schaefer, et al., 2013), and matches the recommended value for maximum marginal discrepancy (McLean & von Fraunhofer, 1971).

While the exact location of the distribution of the fit was not available from the numerical data, this information was visible graphically in images of the 3 dimensional renderings of the internal space. It was possible to rotate these images 360 degrees to evaluate the whole volume of internal space, and the scale of the images were adjustable to allow for different comparisons. To visually compare the fit of all of crowns, it was possible to set the same maximum thickness (460 μm; the maximum thickness across all groups) on the scale for the images for the 3 dimensional renderings. Then, the images could be

compared to evaluate areas of intimate of poor fit. It was also possible to change the scale of the images so that any volume of space that was beyond the optimal thickness of 120 μm was highlighted in red. It was therefore possible to easily visualize the parts of the crowns, and the amount of volume of the crowns, that was beyond this optimal range.

In order to evaluate the precision of the imaging and measurement technique, two duplicate scans were made of a randomly selected sample, and the resultant images were analyzed. A statistical comparison of the values for these repeated scans and analyses did not real a significant variation for the measurement of the volume of the internal space. The standard deviation (0.022 mm^3) of the repeated measures was only 1.5% of the average value of the 3 readings (15.12 mm^3).

2.4.9 Statistics

One-way ANOVA was utilized to evaluate for differences between the three groups in various categories, including maximum thickness, mean thickness, and total volume. In order to determine the distribution of the internal fit, the percentage of the volume of the internal space that was at or below 120 μm was also calculated and compared between the three groups.

After ANOVA, if warranted, multiple means comparison modified t-tests (Scheffé) were performed. All analyses were performed at $\alpha = 0.05$ using SPSS (SPSS for Windows, version 12.0; Chicago, IL).

2.5 Results

2.5.1 Total Volume

The mean of the total volume of the internal space was calculated as 12.49 mm^3 (SD 1.50) for DM, 15.40 mm^3 (SD 2.59) for DP, and 18.01 mm^3 (SD 2.44) for TP (Table 1; Figure 2). One- way ANOVA indicated significant differences between the groups, and post hoc Scheffé analysis (Table 2) demonstrated that there was a significant difference between the volume of the internal space for all three prosthesis groups, with DM having a smaller volume than DP and TP, and DP having a smaller volume than TP (DM<DP<TP).

Table 1: Average Total Volume of the Internal Space for DM, DP, TP

Procedure	Mean (mm^3)	Standard Deviation (mm^3)	Number
Digital/Milled (DM)	12.49	1.50	15
Digital/Pressed (DP)	15.40	2.59	15
Traditional/Pressed(TP)	18.01	2.44	15

Figure 2: Mean Total Volume of the Internal Space for DM, DP, TP

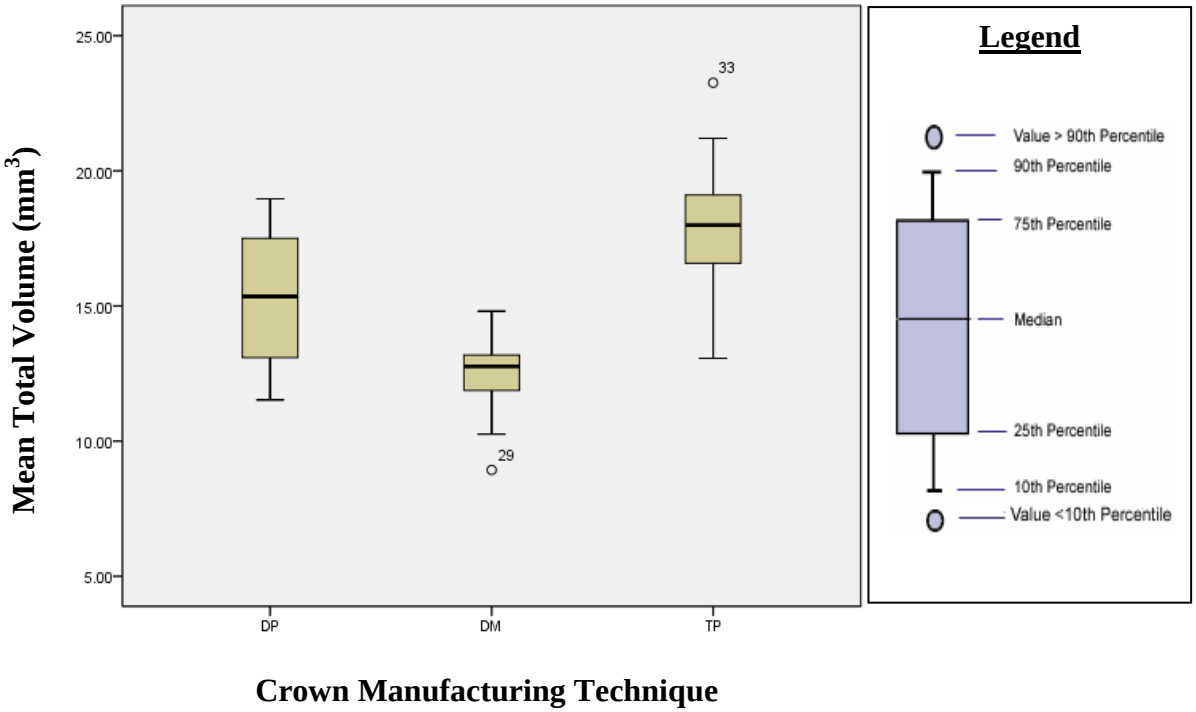


Table 2: Scheffé Test Results for the Comparison of the Internal Fit of DM, DP, TP

procedure	N	Subset		
		1	2	3
DM	15	12.4858		
DP	15		15.4036	
TP	15			18.0123
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 4.987.
a. Uses Harmonic Mean Sample Size = 15.000.
b. Alpha = .05.

2.5.2 Percentage of the Internal Volume at or Less Than 120 μm Thickness

The average percentage of the internal space at a thickness of 120 μm and below was calculated as 46.73 % (SD 5.66) for DM, 37.08 % (SD 17.69) for DP, and 22.87 % (SD 9.72) for TP (Table 3; Figure 3). One-way ANOVA indicated significant differences between the groups, and post hoc Scheffé analysis (Table 4) demonstrated that there was a significant difference between the averages of the percent of internal space at or below 120 μm for both of the digital crown groups in comparison to the "traditional" crowns. The two groups of digital crowns, DM and DP, were not found to be significantly different from each other, but both groups (DM, DP) had a significantly larger percentage of their internal space at or below 120 μm in comparison to TP (TP<DM=DP).

Table 3: Average Percentage of the Internal Space That is 120 μm or Smaller for DM, DP and TP

Procedure	Average (%)	Standard Deviation (%)	Number
Digital/Milled (DM)	46.7267	5.6550	15
Digital/Pressed (DP)	37.0847	17.6930	15
Traditional/Pressed(TP)	22.8651	9.7178	15

Figure 3: Average Percentage of the Internal Space That is 120 µm Thickness or Smaller for DM, DP and TP

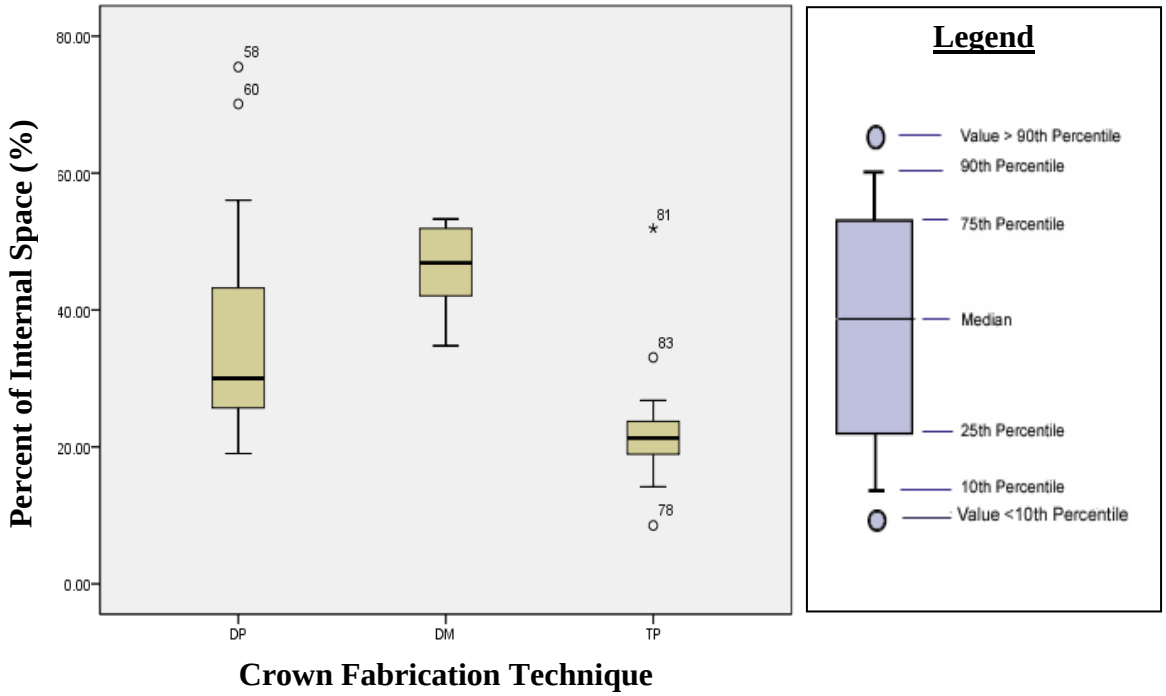


Table 4: Scheffé Test Results for the Comparison of the Percent of the Internal Fit of DM, DP, TP that Lies Between 20 µm and 120 µm

procedure	N	Subset	
		1	2
TP	15	22.8651	
DP	15		37.0847
DM	15		46.7267
Sig.		1.000	.105

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = 146.496.

a. Uses Harmonic Mean Sample Size = 15.000.
b. Alpha = .05.

2.5.3 Mean Thickness

The mean thickness of the internal space was calculated as 0.161 mm (SD 0.007) for DM, 0.171 mm (SD 0.033) for DP, and 0.206 mm (SD 0.035) for TP (Table 5; Figure 4). One-way ANOVA indicated significant differences between the groups, and post hoc Scheffé analysis (Table 6) demonstrated that there was a significant difference between the averages thickness of the internal space for both groups of the digital crowns in comparison to the "traditional" crowns. The two groups of digital crowns, DM and DP, were not found to be significantly different from each other, but both groups (DM, DP) had a significantly smaller average thickness of the internal space in comparison to TP (TP>DM=DP).

Table 5: Mean Thickness of the Internal Space of DM, DP and TP

Procedure	Average (mm)	Standard Deviation (mm)	Number
Digital/Milled (DM)	0.161	0.007	15
Digital/Pressed (DP)	0.171	0.033	15
Traditional/Pressed(TP)	0.206	0.035	15

Figure 4: Mean Thickness of the Internal Space of DM, DP and TP

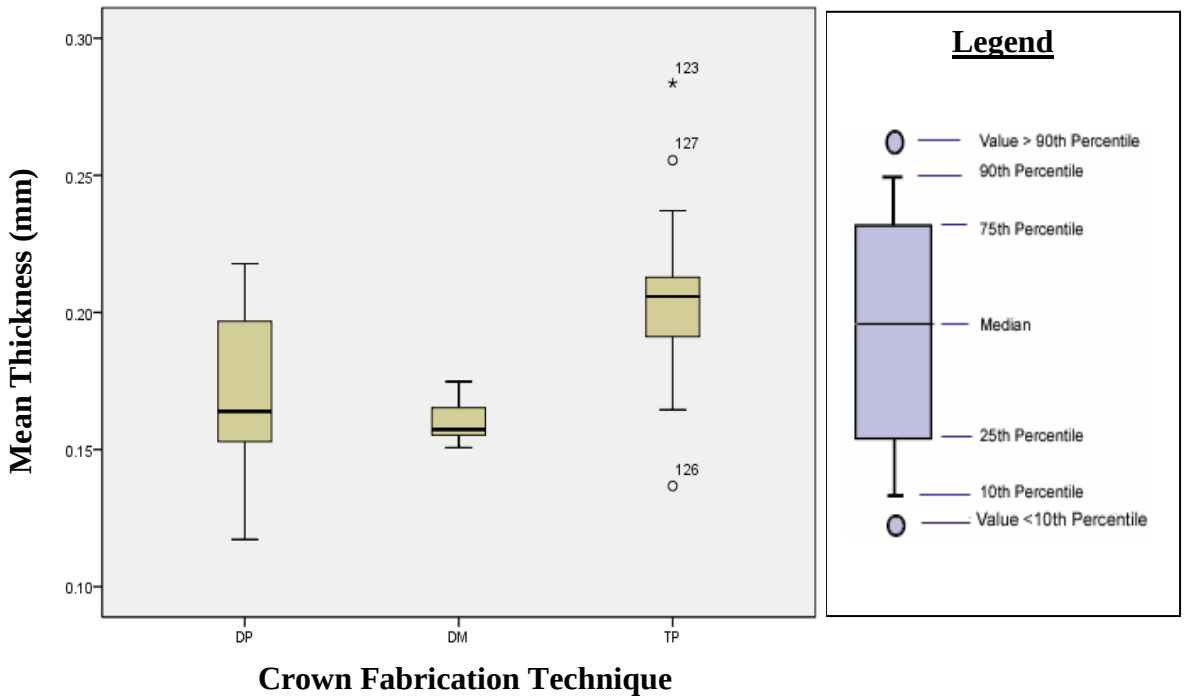


Table 6: Scheffé Test Results for the Comparison of the Average Thickness of the Internal Fit of DM, DP, TP

procedure	N	Subset	
		1	2
DM	15	.1605	
DP	15	.1708	
TP	15		.2062
Sig.		.609	1.000

Means for groups in homogeneous subsets are displayed.
Based on observed means.
The error term is Mean Square (Error) = .001.

a. Uses Harmonic Mean Sample Size = 15.000.
b. Alpha = .05.

2.5.4 Maximum Thickness

The mean maximum thickness of the internal space was calculated as 0.365 mm (SD 0.026) for DM, 0.361 mm (SD 0.081) for DP, and 0.407 mm (SD 0.062) for TP (Table 7; Figure 6). Neither One-way ANOVA nor post hoc Scheffé analysis (Table 8) could demonstrate any significant difference between the groups (DM=DP=TP).

Table 7: Maximum Thickness of the Internal Space of DM, DP and TP

Procedure	Average (mm)	Standard Deviation (mm)	Number
Digital/Milled (DM)	0.3653	0.0256	15
Digital/Pressed (DP)	0.3613	0.0812	15
Traditional/Pressed(TP)	0.4067	0.0617	15

Figure 5: Maximum Thickness of the Internal Space of DM, DP and TP

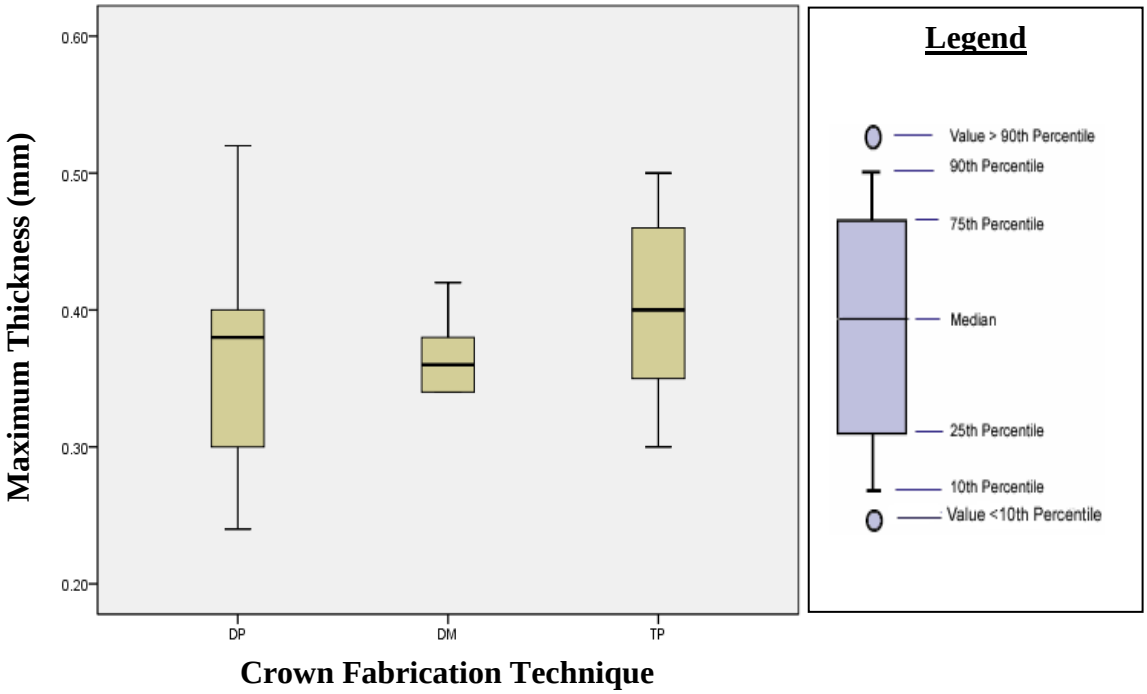


Table 8: Scheffé Test Results for the Comparison of the Maximum Thickness of the Internal Fit of DM, DP, TP

Procedure	N	Subset
		1
DP	15	.3613
DM	15	.3653
TP	15	.4067
Sig.		.136

Means for groups in homogeneous subsets are displayed.

Based on observed means.

The error term is Mean Square (Error) = .004.

a. Uses Harmonic Mean Sample Size = 15.000. b. Alpha = .05.

2.5.5 Qualitative Analysis

The three-dimensional images rendered by the micro CT image analysis allowed for a qualitative analysis of the internal space of all 45 crowns that were fabricated, but was not utilized for a statistical analysis. The internal fit images were set to the same scale in order to compare the distribution of the space for the three different prosthesis types. Sample images of the standardized scale images are presented in Figures 5, 6 and 7.

Figure 6: Sample Standardized Scale (460 µm Maximum) Three-Dimensional Reconstruction of the Internal Space of DM

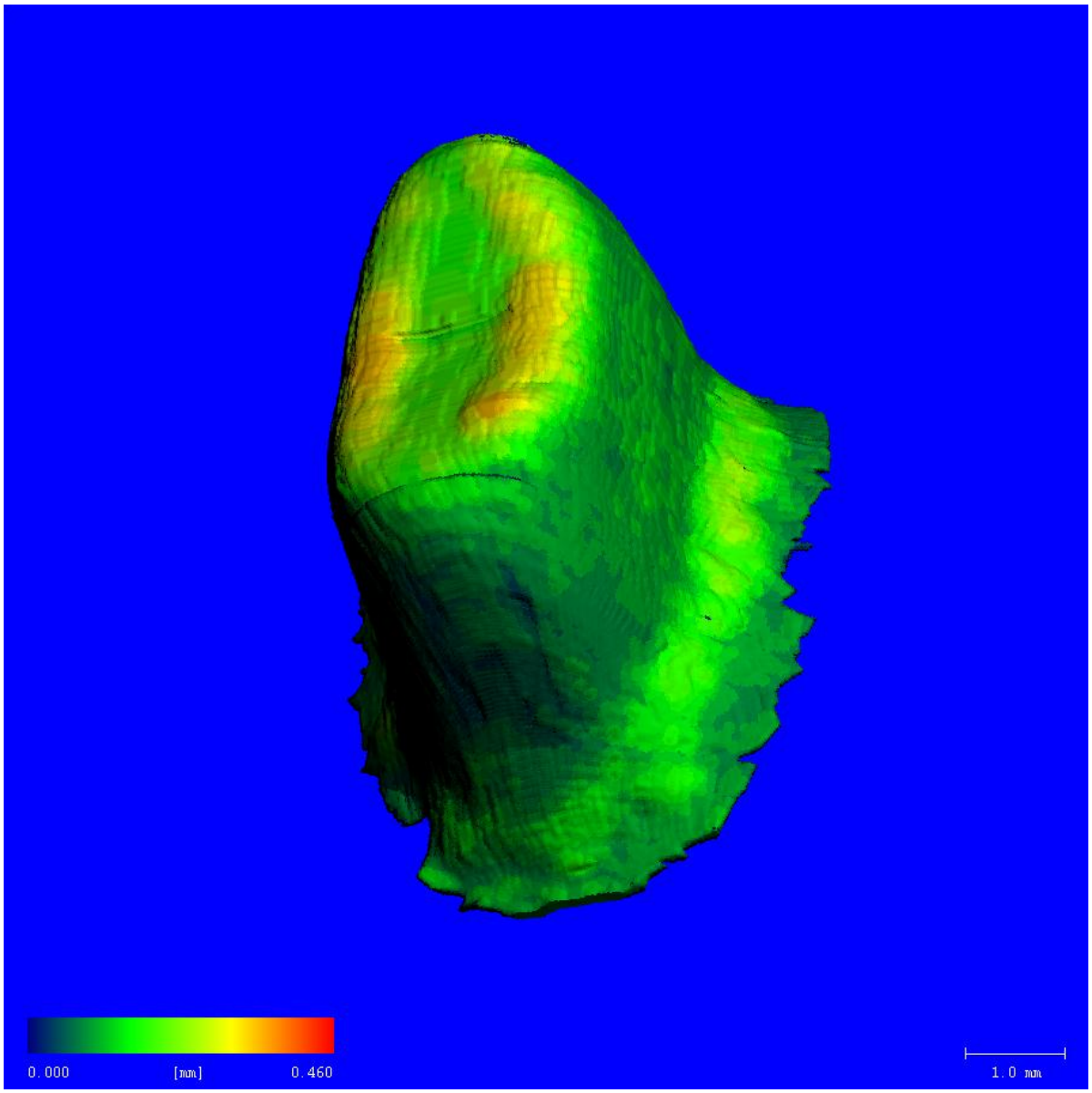


Figure 7: Sample Standardized Scale (460 µm Maximum) Three-Dimensional Reconstruction of the Internal Space of DP

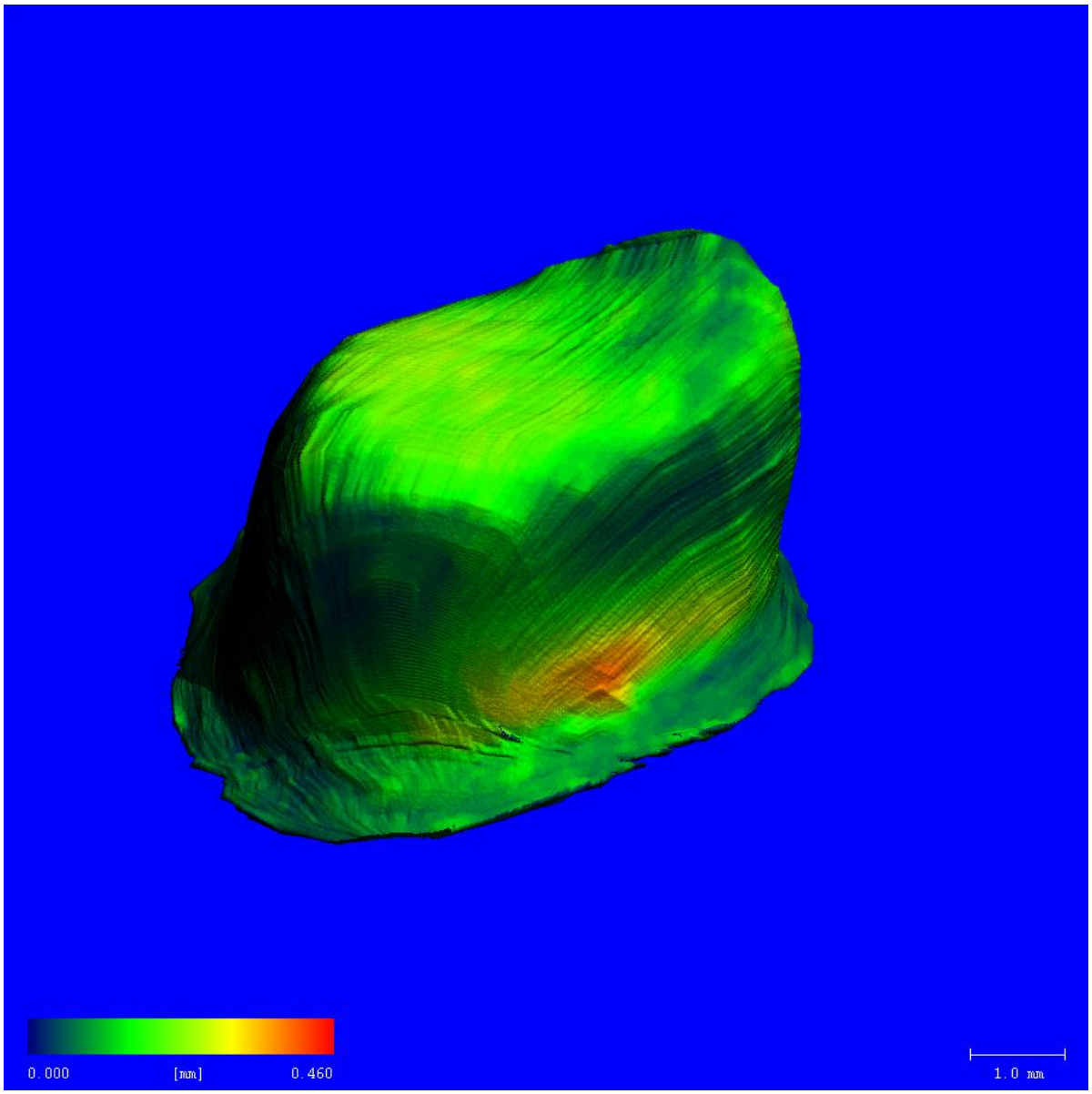
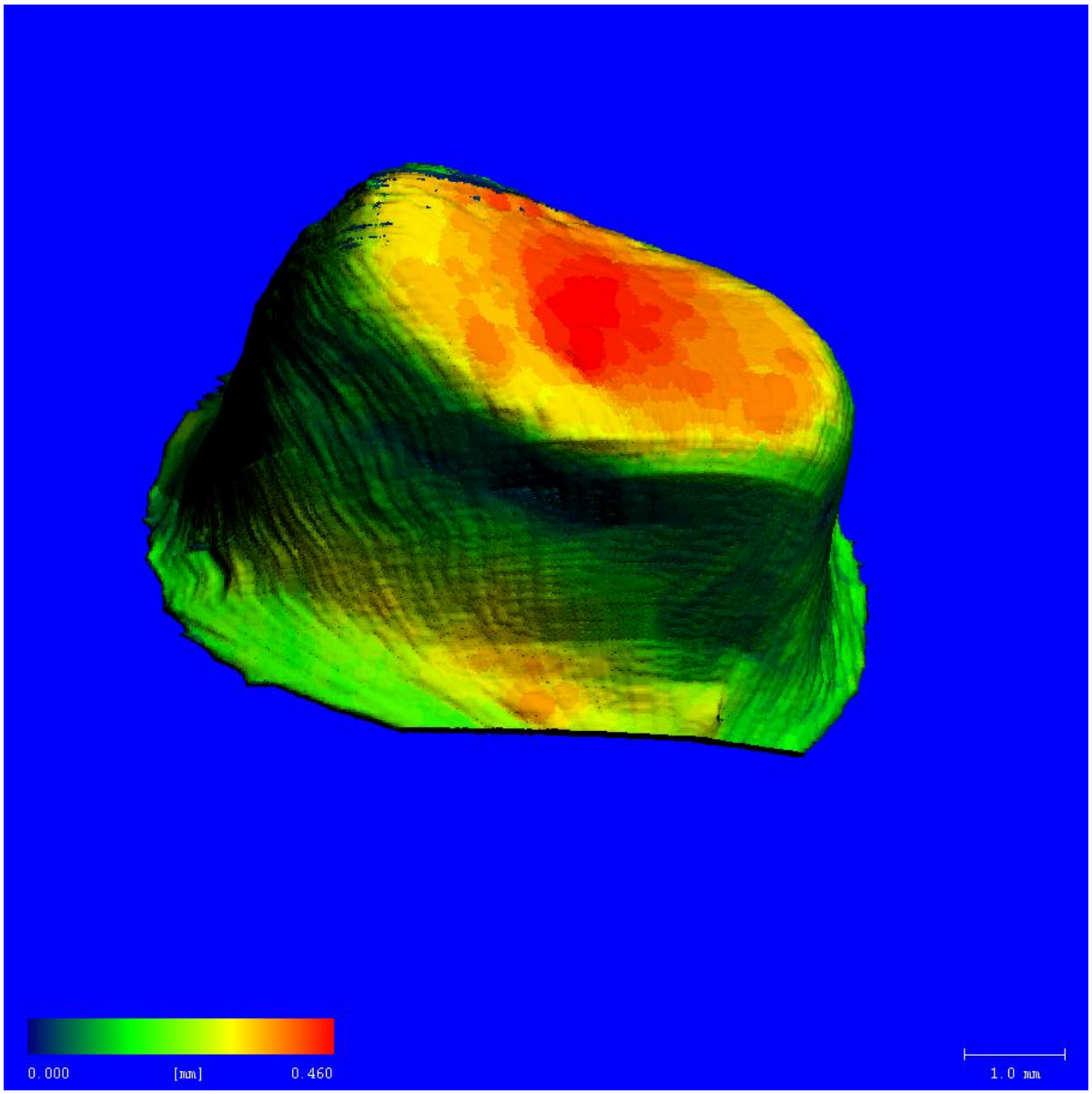


Figure 8: Sample Standardized Scale (460 µm Maximum) Three-Dimensional Reconstruction of the Internal Space of TP



As can be seen in Figure 7, TP visually has a larger portion of the internal space close to the maximum of the scale (460 µm), while the digital crowns (Figures 5 and 6) have less of the space approaching the maximum. As can be expected with a milled crown, larger

spaces tended to be found in the line angles of the preparation (Figure 5). This is likely attributed due to limitations in the accuracy of milling due to the dimensions of the burs (Kurbad & Reichel, 2005; Reich, et al., 2011). This discrepancy, however, was also found for the pressed crowns (Figure 7 and Figure 8), regardless of impression technique, which was not expected, due to the theoretical ability to cast the ceramic into these rounded areas.

The three-dimensional reconstructions could also be scaled to demonstrate where the internal space was beyond the range of 120 µm, in order to visualize where the crown could be considered poorly fitting. Sample images of these reconstructions can be found in Figures 9, 10 and 11.

Figure 9: Sample Three-Dimensional Reconstruction Highlighting Areas Above 120 µm of Internal Gap Thickness for DM

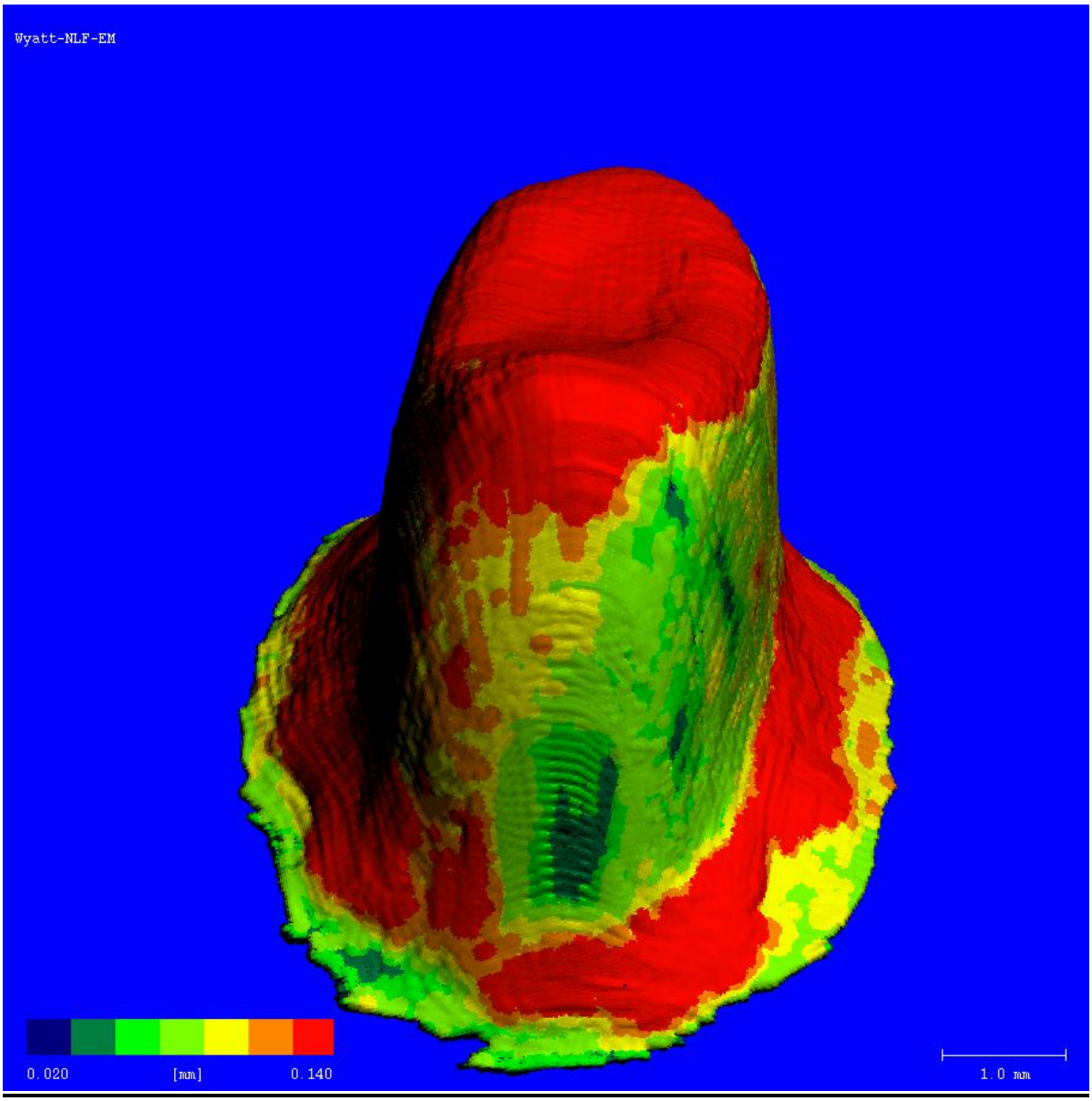


Figure 10: Sample Three-Dimensional Reconstruction Highlighting Areas Above 120 µm of Internal Gap Thickness for DP

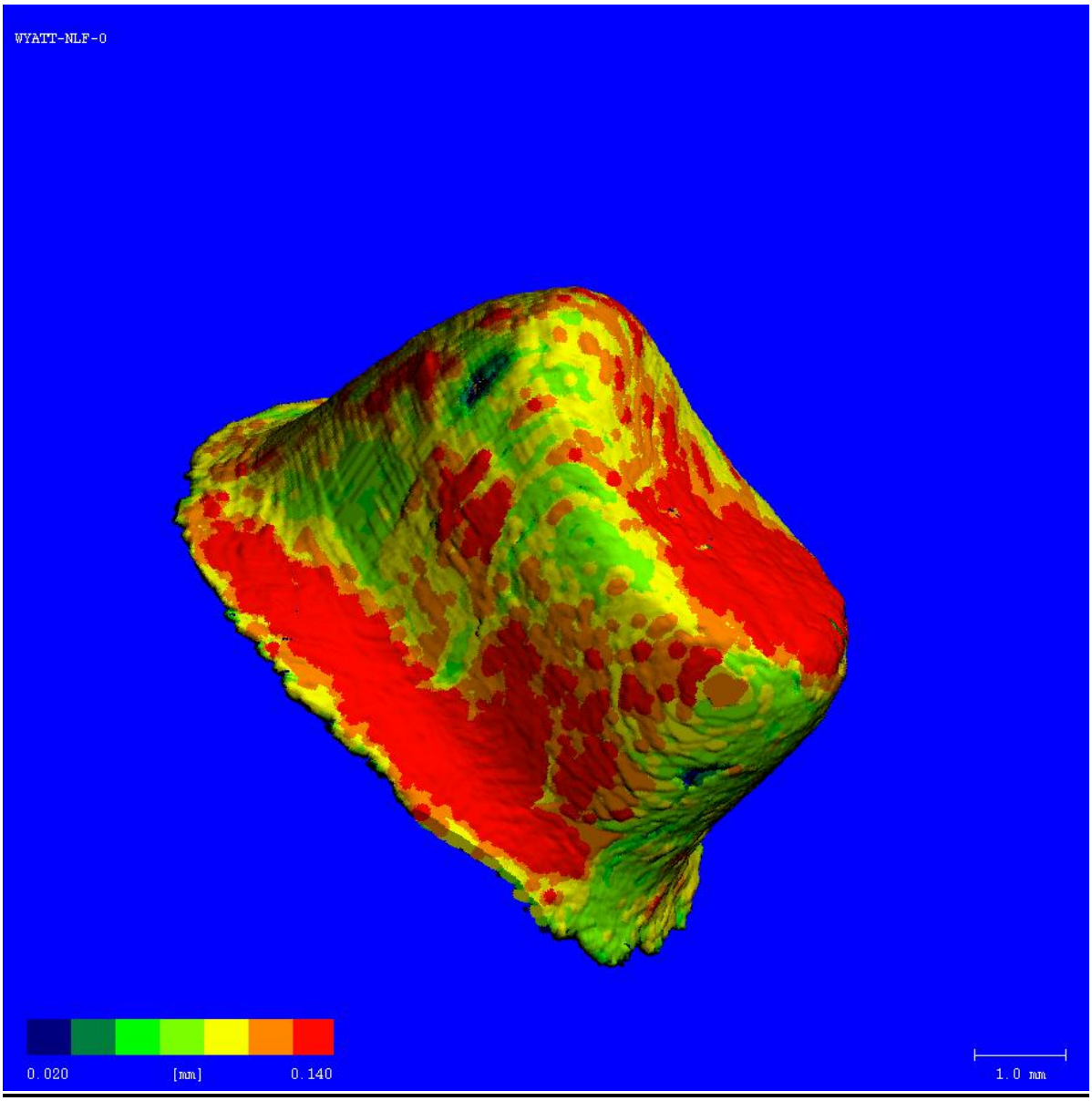
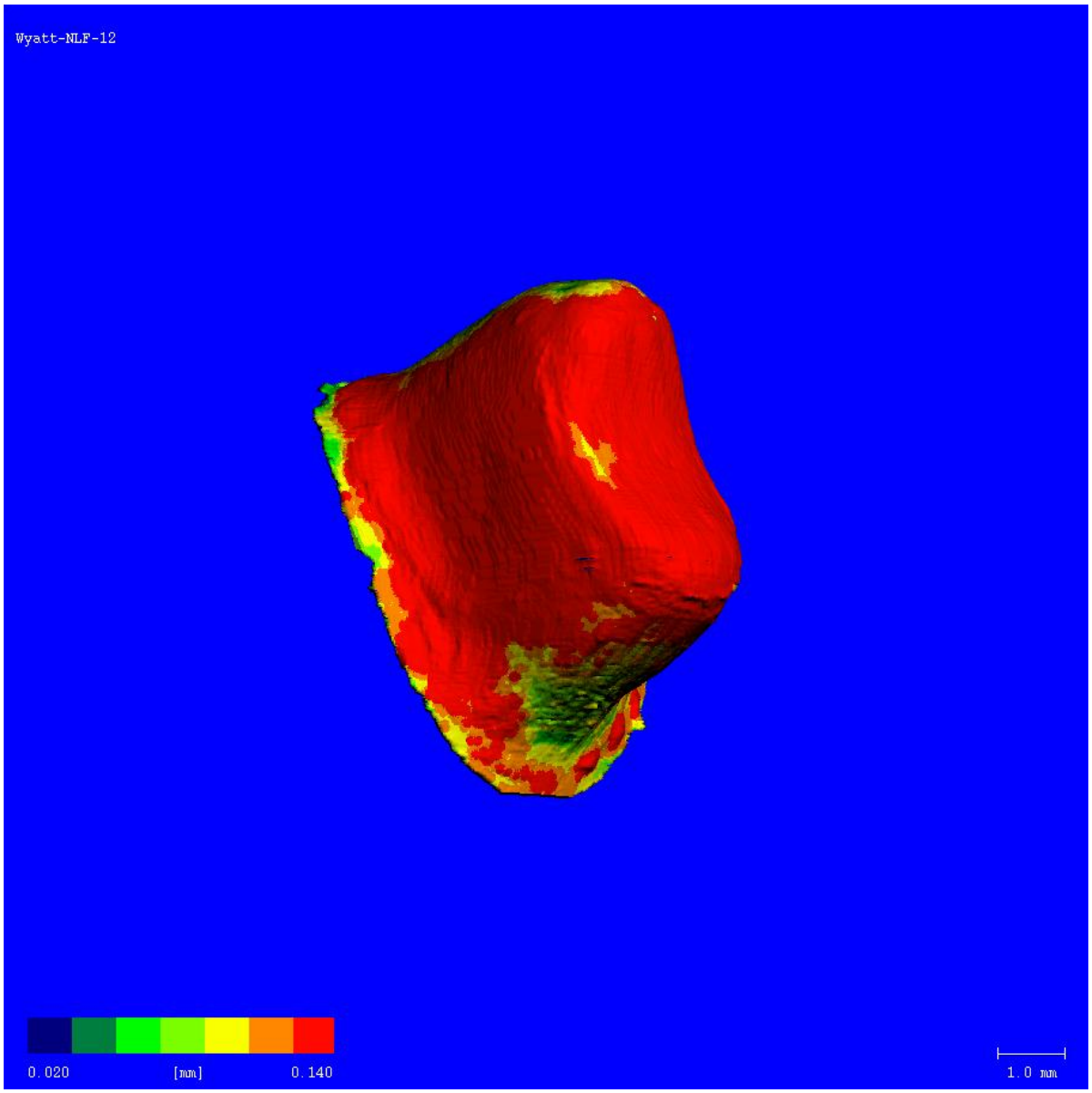


Figure 11: Sample Three-Dimensional Reconstruction Highlighting Areas Above 120 µm of Internal Gap Thickness for TP



The three-dimensional images correlate with the statistical data which indicated that TP had large areas of poor fit (Figure 11) in comparison to either of the digital crown groups (Figures 9 and 10).

Chapter 3: Discussion

The results indicate that digital impression technology offers dentists and technicians a viable option that is superior to the traditional impression techniques for the fabrication of lithium disilicate crowns. Crowns fabricated based on digital impressions (DP and DM groups) demonstrated lower and more consistent values for internal fit in volume, mean thickness and percent clinically acceptable, in comparison to the traditional pressed crowns (TP group). These results support the findings of other authors who have compared digital and traditional workflows and have found the digital workflow to allow for the fabrication of restorations of equal to or superior fit to those fabricated by traditional technologies (Brawek, Wolfart, Endres, Kirsten, & Reich, 2013; Seelbach, et al., 2012). Moreover, the results obtained are in agreement with those of a concurrent study to this project, which has also demonstrated that the completely digital process had a more accurate marginal fit in comparison to traditional techniques (Ng, Wyatt, & Ruse, Submitted for publication, 2013).

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The fabrication of a traditional prosthesis is a complex process with various sources of error. As has been previously described, dimensional inaccuracies can occur in various stages of the fabrication process. The impression material must be properly manipulated in order to obtain an accurate impression. For example, moisture can adversely affect the surface detail of an impression, resulting in voids or improperly set materials. Furthermore, the proper mixing of the material and manipulation of the impression is imperative to ensure that all of the impression sets completely and without drags or distortion (Donovan & Chee, 2004). Digital impressions, while still facing the challenges of moisture control, allow the

operator the opportunity to evaluate the impression in real time, therefore providing immediate feedback as to which part of the impression requires additional scanning if it was not captured properly the first time. In addition, there are no concerns of the dimensional changes that occur in traditional impressions during setting or upon the removal of the impression from undercut areas, when digital impressions are utilized.

The type of die utilized for the wax-up can also be a source of error in the fabrication of traditional prostheses. The strength and accuracy of a die can be greatly affected by the type of material that is being utilized (Derrien & Sturtz, 1995), and these materials must be manipulated properly in terms of water/powder ratio, spatulation rate and duration in order to obtain a minimal amount of expansion (Craig & Powers, 2002). Digital impressions, however, can allow for the technician to completely bypass the need for a physical die, by allowing for digital design and milling. Our study demonstrates that this virtual process created crowns with better internal fit than the traditional technique. The marginal fit was also better for the digitally created crowns than the conventional technique created crowns in the concurrent study by Ng et al. (2013). Digital impressions can also enter the traditional workflow by the fabrication of dies, which are either milled or SLA printed from a polyurethane resin. These dies have been shown to be as clinically acceptable alternatives to traditional stone dies (Kim, et al., 2013), and offer the benefit of milling a fully polymerized product which theoretically will be subject to less distortion and dimensional change in comparison to dental stone.

The traditional design of an indirect restoration is still primarily based on the lost wax technique, which was introduced to dentistry in the 1800's and formally introduced by Taggart in 1907 (Morey, 1991). While technicians have in essence mastered the art of the lost wax technique, with indirect gold restorations having high success rates, even beyond 25 years (T. Donovan, Simonsen, Guertin, & Tucker, 2004), the process is not without error. Casting waxes suffer from a variable amount of distortion (0.2-0.6 % linear expansion), depending on their composition and consistency and how the investment is treated (hygroscopic expansion, use of a liner) (Morey, 1991). Again, this is an area where digital technology can reduce the error in the workflow. The digital design of indirect prosthesis is without distortion and has the added benefit of allowing for the specific prescription of a virtual die spacer. This is a critical advantage, because although specific brands may indicate that one coat of spacer is of a specific thickness, it is not always consistent and can vary as the bottle is utilized (Psillakis, et al., 2001). The methodology in this study may help evaluate where the digital virtual space is necessary and what effects it has on the overlying prosthesis. Many studies have looked at the effect of die spacer on the retention and physical properties of crowns (Campbell, 1990; Carter & Wilson, 1997; Cho, et al., 2006; Fusayama, et al., 1963; Molin, et al., 1996; Olivera & Saito, 2006), and the use of micro CT now offers us the ability to directly visualize the intimacy of the fit of the prosthesis and to plan further clinical studies to evaluate the performance of the prostheses based on the amount of internal space. Furthermore, the quantification of this volume of space may also have benefits in terms of determining the amount of cement that is required per crown, which can have benefits in the standardization of packaging and dispensing of materials.

While the accuracy and precision of the dies utilized in this study was not directly evaluated and statistically analyzed, it can be inferred that the process was acceptable due to the low standard deviations in the measurements within each group; if there was a high variance in each group, one of the contributing factors could have been inaccuracies in the dies, but this was not the case.

One of the intriguing findings of the study was that the cast restorations did not seem to fit better at the line angles in comparison to the milled prosthesis. While chair-side milling has demonstrated the ability to produce marginal adaptations within (50 to 100) µm (Mörmann, 2006), a common belief is that this technology has limitations in its ability to mill highly contoured areas such as line angles. For example, a large chamfer was found to have better internal adaptation at the gingivo-axial line angle (191µm) and at the occlusal pit (244 µm) in comparison to rounded shoulders (248 µm, 399 µm), while not varying at the axial walls (Souza et al., 2012). Therefore, many manufacturers recommend the utilization of rounded line angles in the preparation form for chair-side milled prostheses. The 5-axis milling machine utilized in this study, however, demonstrated a statistically significant better performance in overall fit in comparison to the traditional technique. While it was not amenable to statistical analysis, the qualitative analysis of the three-dimensional reconstructions of the internal space suggest that, while within each milled prosthesis the line angles fit poorer than the axial portions, overall they performed better than the traditional prostheses; the traditional prostheses demonstrated poor fit throughout the whole internal space. Again, this goes against the concept that a pressed prosthesis would be better adapted to the line angles than a milled prosthesis.

In fact, the results of our study suggest that, while the milled crowns tended to fit better than the cast crowns, this difference was only statistically significant for the digital versus traditional techniques. When the two restorations (milled and pressed) were compared from the same digital impression, the milled crowns from the digital impression were no better than the pressed crowns from the same digital impression. This indicates that the difference arises not from the pressing technology, but is due to other sources of error.

Various studies have compared the accuracy of milled polyurethane dies and type IV stone dies and have indicated that they are clinically acceptable and comparable (Hwang, et al., 2013; Kim, et al., 2013). Therefore, it is unlikely that is the type of die utilized for the wax-up that is creating the inaccuracy in the traditional prostheses for this research project. The findings of our study support that it is more likely that inaccuracies in the elastomeric impression in comparison to the digital impression were responsible for the poorer fit of the traditional prostheses.

The ability to select an entirely digital process offers many advantages over the traditional techniques. The digital workflow allows for an increased role of the dental assistant in the office. The dentist is only required to scan the prepared tooth, which takes less than a minute on most systems. Once the preparation is scanned, the assistant can complete the rest of the scan, allowing the dentist to attend to other patients during this time. The total scan time varies between machines and operators, but the LAVA COS has a

maximum total scan time of 7 minutes per arch and the scans can usually be completed in 2 to 3 minutes (Fasbinder, 2012).

When comparing the efficacy of traditional impressions to digital impressions, the modern option reduces total treatment time in half, even in the hands of inexperienced users. In an educational setting clinical trial, the total treatment time of digital impressions has been found to be 12 minutes, including re-scans, in comparison to over 24 minutes for conventional techniques. Interestingly, more digital rescans were required in comparison to remake traditional impressions, but, the rescan time only added 1 or 2 minutes in comparison to almost 7 minutes to remake a traditional impression (Lee & Gallucci, 2013). This reduction in treatment time is not only beneficial to the patient, but can allow for improved productivity in a busy dental practice.

This faster treatment time is only one of the ways that digital impressions can improve patient comfort. In addition to this benefit, patients do not have to sit through the entire setting time of the impression material as they would for traditional impressions. The setting time can be as long as ten minutes for impression materials such as polysulfide, which is still often used in educational settings (Craig & Powers, 2002). Digital impressions can be started and stopped multiple times, and if retakes are necessary, only the areas that were missed require further impression. This is especially beneficial when taking impressions of patients with strong gag reflexes (Christensen, 2009), with anxious patients, or for patients with temporomandibular disorders. Powder-less digital impression systems are advantageous

in this situation because there is no risk of having the powder brushed off the surface of the teeth by the tongue, buccal mucosa or saliva, which may alter the scan (Fasbinder, 2012).

Furthermore, digital impressions allow for the immediate direct visualization of the prepared and unprepared teeth. This can be beneficial to the patient in terms of oral health education, and to the dentist in terms of being able to see if the preparation is adequate, especially considering that in the traditional technique, sometimes errors are not seen until the impression is poured (Wassell, Barker, & Walls, 2002). These errors can be quite catastrophic and may result in the need for a retake of the impression. It is not uncommon to find drags, voids, tears or un-polymerized impression materials in impressions (Wassell, et al., 2002). A recent study found that almost 5% of hydrophilic polyvinyl siloxane impressions for fixed restorations had clinically unacceptable errors, with over 7% of the acceptable impressions still having some sort of void or error (Beier, Grunert, Kulmer, & Dumfahrt, 2007). Retakes of traditional impressions can be costly for a practice both in time and materials. As a strategy to reduce this cost of impression making, some authors advocate the use of dual arch trays and have found clinically acceptable results (Lane, Randall, Lane, & Wilson, 2003). These impressions, however, do not provide the laboratory technician with valuable information about the occlusal scheme or of the morphology of the opposite arch and may be best reserved for simpler indirect restorations.

Digital impressions can also reduce the waste and complexity of traditional impression materials (Christensen, 2009), do not require extra material if a remake is needed (Lee & Gallucci, 2013) and can be transported to the laboratory digitally, without need for

disinfection (Brawek, et al., 2013), which has the potential to reduce the ecological impact of the dental practice. The digital transportation and storage of the digital scan has some distinct advantages on its own. There are no concerns with distortion, damage, or loss of the master impression during transportation, which can occur during the transport of traditional impressions (Sadan, 1999). The data file is also available almost instantaneously for the lab technician to evaluate, and feedback can be given to the dentist without the delays of pouring a cast (Craddock, 2011).

As previously mentioned, the virtual casts are extremely accurate (Hwang, et al., 2013), and the digital design process on the casts can be pretty straight forward. Even though it would appear that the learning curve for digital design would be steep, most digital design programs can be learned in a couple of days (Fasbinder, 2012), and most of the design software have a variety of tools that facilitate the design of the prostheses, including anatomic libraries, the ability to superimpose contralateral teeth, and virtual wax-up instruments similar to those used for traditional methods (Kachalia & Geissberger, 2010). In addition to the ease of the virtual design, the digital technology has the advantage of not suffering from the dimensional changes and that traditional waxes are subject to during the wax-up for prostheses fabricated via the lost wax technique. Casting waxes can experience up to 1% expansion depending on the temperature, and can distort if the wax is not heated above 50C or if warmed instruments are not used (Craig & Powers, 2002). One further advantage is that the file can be stored indefinitely and takes up no physical space, unlike traditional impressions.

A computerized production process also has its advantages. First of all, the materials available for milling have consistent properties and the dimensional changes due to milling and sintering can be accounted for by the milling programs (Miyazaki & Hotta, 2011). The automation of the milling process has many advantages as well. One advantage is that the impressions and casts do not have to be transported to the milling centre, but are transferred digitally, saving time and shipping costs (Craddock, 2011). This also allows for the milling centre to be located remotely. For example, for our study, the digital files were sent from the Nobel Biocare Oral Health Centre in Vancouver, British Columbia, to Aurum Ceramics in Calgary Alberta, where the files were digitally received, the crowns digitally designed and milled via computer assistance. It would be impractical and financially ineffective to send elastomeric impressions that far, when local laboratories are available for traditional techniques.

In terms of laboratory procedures, CAD/CAM technology also allows for a more efficient production workflow. For a traditional cast restoration, every step has to be performed by a technician, which can be labour and material intensive. Milled crowns on the other hand can be set-up to be fabricated at any time of the day, even outside of business hours. Some larger laboratory milling machines even have the ability to mill multiple crowns in one session. The DMG 5-axis milling machine utilized to fabricate the prostheses for this study, for example, can be programmed to run multiple cases overnight and has the capacity to produce almost 100 single-unit indirect restorations in that time span.

For this study, the image analysis proved to be a time consuming process that was not easily automated. One of the challenges that previous authors found was the presence of artifacts in the scans, which did not allow for an automated selection of the internal space (Rungruanganunt, et al., 2010; Seo, et al., 2009). While our samples did not have very many artifacts or scatter, the software was challenged in automatically selecting contours based on contrast when the internal space became very small. This may have been a limitation of the scanning resolution. Also, the crowns were delivered after being etched with hydrofluoric acid in the laboratory, which creates micromechanical voids in the internal surface in the range of a few microns (Zogheib, Bona, Kimpara, & McCabe, 2011); it is possible that this inherent surface roughness decreased the sharpness of the image at the internal surface of the prosthesis, therefore adding to the difficulty of automating the selection of the outline of the internal space. Furthermore, as per the manufacturer's instruction, IPS e.max Press is etched for a full 60 seconds, and IPS e.max CAD is etched for only 20 seconds, it is therefore a potential source of discrepancy in the internal fit between these types of restorations, but did not seem to affect the results of this project, as these two restorations only differed on one statistical category, total volume of internal space; pressed and milled restorations from the same impression were not different from each other in maximum or mean thickness or in percent of volume at or below 120 µm, therefore, it is unlikely that the etchant played a major role in the internal fit.

Another limitation of the scanning resolution is that it is impossible to determine if areas recording less than 20 µm of thickness were closed contacts between the crown and the die, or if they are areas of were a gap below 20 µm exists. Clinically, either situation is un-

favourable because a premature contact could prevent the full seating of the crown, and an internal space below 20 µm could affect the performance of the cement. The crowns in this study, however, were not assessed for fit with fit-checker and adjusted because it would have been difficult to control for that variable. The methodology introduced in this project, however, may be useful in future studies that evaluate changes in the fit of restorations, pre and post adjustment.

An increased resolution, however, would have greatly increased the scan time and costs. It would have also increased the amount of time required to analyze the images. At the current resolution, 400-500 slices had to be analyzed per crown, on average taking between 45 and 90 minutes to complete. Doubling the resolution would double the amount of slices, and would therefore theoretically double the analysis time. The broad range in analysis time was due to various factors, with the major one being the positioning of the sample in the micro CT scanner. When the sample was positioned so the slices were perpendicular to the internal space, the outline was well defined and the space was continuous, allowing for the borders to be better recognized by software. The analysis software has two features that automate the selection of contours based on contrast. Both options required that a slice be manually selected, with one option then predicting the contours of future slides. This option was found to lose its accuracy within 2 to 3 slides and required manual adjustment from then on. The second option required the manual outline of two slices at a distance from each other and then the software predicted the outline of the slices within the range, based on the first and last slice. This method was found to be the most efficient method of outlining multiple slides, allowing for 10 slices to be analyzed at a time, if the contours had relatively small

changes. If the contours had large transitions from slice to slice, or if the internal space was not continuous and had multiple areas, the automatic selection tools were not efficient. Regardless of the method, however, every slice had to be verified manually to confirm the proper contours.

The accuracy of the measurement methodology was evaluated by performing three separate scans and three separate measurements on one sample. While the amount of repeat measurements was not high enough to obtain results with a high power statistically, there was no gross difference in the three measurements obtained. This finding, in combination with the low variance of all the measurements, supports the validity of the measurement technique.

The three dimensional representations of the internal space are images that are novel data that currently do not exist in the dental literature for the direct visualization of the cement space for full contour ceramic prostheses. The results of this study are therefore unique and unfortunately cannot be directly compared to the results of other studies because many look at the internal space in one dimension (Schaefer, et al., 2013) or evaluate the three dimensional fit of restorations other than single unit full coverage crowns. While being a novel approach to the measurement of the internal fit of a prosthesis, the methodology is adapted from existing publications (Borba, et al., 2011; Rungruanganunt, et al., 2010; Seo, et al., 2009; Swain & Xue, 2009), and was supported by the low variance in the data.

Chapter 4: Conclusions

The digitally impressed crowns had significantly better internal fit than the traditionally impressed crowns, as measured by volume of internal space, mean and maximum thickness of the internal space. The digitally impressed crowns likely have a decrease in manufacturing errors, and therefore an improved fit as measured by a smaller internal gap. While the traditionally fabricated lithium disilicate crowns have demonstrated poorer internal fit, the results do not necessarily indicate that these numerical differences will correlate in a significant clinical difference.

It would be prudent to attempt to validate the micro-CT 3-dimensional imaging methodology. While the technique allows for reliable measurement of the internal fit of ceramic crowns, a "gold standard" value or measurement does not currently exist. Statements, therefore, on the accuracy of the results obtained for internal volume would be premature.

The novel methodology of using micro-CT 3-dimensional imaging for the measurement of the internal gap of all-ceramic crowns can potentially be utilized in future bench-top and clinical studies. For example, a split-mouth clinical trial could be performed on patients requiring the extraction of teeth for orthodontic purposes. Two teeth could be prepared for indirect restorations and crowns could then be fabricated via digital impressions and CAD/CAM milling. One of these crowns could then be cemented prior to the extraction of the tooth, with the second tooth being extracted without cementation of its crown. Micro

CT comparison of the fit of the crowns on both of the extracted teeth and the replica dies could then be performed, therefore allowing for a determination of the accuracy of the methodology introduced in this project. The validation could be taken further by luting the crowns to the dies or teeth and comparing pre and post cementation values.

The data collected for this study has the potential for further quantitative and qualitative analysis. The 3-dimensional renderings could be analyzed to quantify the actual value of spaces at the specific areas of the crown. The 3-dimensional evaluation of the internal space underneath crowns, and the potential to measure cement volumes and morphologies, will both be major advancements in the ability to evaluate the performance of cements and restorative materials. The methodology introduced could be utilized in-vitro, or in combination with clinical trials, to obtain a 3-dimensional record of the abutment/cement/restoration complex, allowing for the evaluation of the performance of restorations in full contour.

The measurement technique utilized in this study has introduced micro CT as a valuable instrument in the evaluation of indirect restorations. As well, the improved internal fit of ceramic crowns created using digital technology provides valuable information for dentists and dental technicians in deciding on the selection of this technology for their patients.

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