Fracture Resistance of Various Thickness e.max CAD Crowns

Cemented on Different Supporting Substrates

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THESIS

Submitted as partial fulfillment of the requirements
for the degree of Master of Science in Oral Sciences
in the Graduate College of the
University of Illinois at Chicago, 2021

Chicago, Illinois

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ACKNOWLEDGMENTS

I would like to thank my thesis committee – Bin Yang, Stephen Campbell, Spiro Megremis, Judy Yuan – for their support and guidance. I would also like to thank Ivoclar Vivadent, Inc. for supplying the dental materials used in this study and the American Dental Association for providing their Universal Testing machine.

CONTRIBUTION OF AUTHORS

All chapters in this thesis details the work from a previously published manuscript (Chen SE, Park AC, Wang J, Knoernschild KL, Campbell S, Yang B. Fracture Resistance of Various Thickness e.max CAD Lithium Disilicate Crowns Cemented on Different Supporting Substrates: An In Vitro Study. *Journal of Prosthodontics*. 2019 Dec;28(9):997-1004) for which I was the primary author and major contributor to the research project. Dr. Albert Park assisted me in the experiments shown in Figure 1 and Figure 2. Dr. Jingxu Wang assisted in fabricating a portion of the specimens (CADCAM lithium disilicate crowns) for the project. Dr. Albert Park assisted me in creating the SEM images in Figure 6 and Figure 7. My research mentors – Dr. Bin Yang, Dr. Kent Knoernschild, and Dr. Stephen Campbell – contributed to the editing of the manuscript.

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LIST OF ABREVIATIONS

ADA	American Dental Association
CAD/CAM	Computer-Aided Design / Computer-Aided Manufacturing
CV	Coefficient of Variation
MD	Minimal thickness crowns cemented on dentin analog (MZ100 composite) abutments
ME	Minimal thickness crowns cemented on enamel analog (lithium disilicate) abutments
SEM	Scanning Electron Microscope
STL	Standard Tesselation Language
TC	Thermocycles
TD	Traditional thickness crowns cemented on dentin analog (MZ100 composite) abutments

SUMMARY

An in vitro study to investigate the influence of abutment material properties on the fracture resistance and failure mode of aged and non-aged monolithic lithium disilicate (IPS e.max) CAD/CAM (computer-aided design/manufacturing) crowns on traditionally and minimally prepared simulated tooth substrates was completed by comparing three digitally controlled groups: MD (minimal thickness crown supported by a dentin analog - MZ100 composite), ME (minimal thickness crown supported by an enamel analog – e.max), and TD (traditional thickness crown supported by a dentin analog – MZ100 composite). Fracture loads were determined for each group (n=20) using a universal testing machine. Fracture modes were visualized using SEM (Scanning electron microscopy) analysis. Fracture patterns were observed with and without trans-illumination.

No statistically significant difference between the mean fracture loads of all three groups was observed when all data (non-aged and aged) was analyzed. However, some aged groups had statistically significantly higher mean fracture loads when compared to the non-aged group. All groups demonstrated similar fracture mechanisms from SEM observation. All restorations regardless of the magnitude of the fracture defects exhibited fracture origins at the crown/cement interface. SEM analysis revealed fracture defects in Group MD were larger in magnitude than in Group ME. All specimens were visually inspected after fracture and were categorized. Group TD had the greatest number of catastrophic fracture lines. Group MD had the greatest number of total visible fracture lines at the surface of the restorations. The smallest magnitude of fracture lines and the least number of visible fractures was observed in Group ME. Group ME had the lowest coefficient of variation suggesting that minimal thickness lithium disilicate restorations may have

more predicable mechanical behavior and fewer catastrophic failures when supported by a substrate with a higher elastic modulus (i.e. enamel).

I. INTRODUCTION

This chapter details the work originally published in the *Journal of Prosthodontics* and has been authorized to be used for the purposes of this thesis and oral defense.

Chen SE, Park AC, Wang J, Knoernschild KL, Campbell S, Yang B. Fracture Resistance of Various Thickness e.max CAD Lithium Disilicate Crowns Cemented on Different Supporting Substrates: An In Vitro Study. *Journal of Prosthodontics*. 2019 Dec;28(9):997-1004.

A. Background

Minimal thickness restorations offer a treatment modality for patients with limited restorative space, advanced wear, and esthetic rehabilitation for young patients that do not warrant excessive removal of sound tooth structure. Additional tooth reduction to create restorative space may not be appropriate following a substantial amount of pathological tooth loss if progressive tooth eruption has compensated for wear/erosion.[1] Preservation of remaining sound tooth structure and tooth vitality is imperative to long term survival.[2] Up to 40% of prepared tooth structure in the posterior area can be preserved with minimally invasive preparations compared to conventional full coverage crown preparations.[3] Minimal reduction to avoid pulp exposures and the use of ultra-thin restorations may be the best treatment alternative.[3-5] The fracture strength and longevity of ultra-thin all-ceramic restorations need to be considered before incorporating these restorations in everyday practice.

Ceramic fracture patterns have been studied extensively. Ceramic cracks generally develop either as cone cracks or radial cracks. Cone cracks initiate at the restoration surface

from contact damage beneath the point of load. The contact damage generally presents first as a surface ring and then spreads into the bulk of the ceramic. The radius of the indenter is a large factor in determining the critical load for cone cracks. The contact radius on a natural tooth varies between 2 to 10 mm depending on the anatomy of the opposing tooth.[6,7] Clinically, wear facets are usually 0.5 - 3 mm in diameter. Contact typically occurs simultaneously at 4 circular wear facets and generate a load range between 100-700N. While in function, chewing consists of low cyclic loads in high frequencies. In vitro experiments studying ceramic fracture strength should try to mimic the method of loading as seen in vivo.[6]

Ceramic fractures can also initiate at the cement restoration interface in the form of radial cracks. Radial cracks are the result of tensile stresses at the ceramic surface directly above the underlying compliant substrate. Radial cracks are common when the thickness of ceramic is less than 1mm and when a difference in elastic modulus is present between the ceramic and substrate.[8] Radial cracks originate at the cement crown interface and extend towards the occlusal surface and outwards towards the margins.[9] This is the typical bulk fracture pattern seen clinically in dentistry[10] based on fractographic analysis of clinically failed all ceramic restorations.[8] Clinical failures in crowns are not reported to originate from surface damage at the occlusal surface. [6]

The initial and long-term clinical success of all ceramic prostheses are influenced by many different factors.[11] Fabrication and post fabrication processes can influence the ceramic strength and longevity. Adjustments made to a ceramic crown by a dental bur to improve the fit of a prosthesis can introduce a variable amount of damage and flaws depending on the bur and types of coolants used during the process. Shaping, milling,

grinding, post shaping adjustments, sandblasting, and additional post processing modifications can introduce damage and flaws in the ceramic prosthesis. Due to the introduction of flaws and damage to the material, fracture strength has been shown to be reduced by as much as 50% post machining.[12] Damage caused by CAD/CAM milling machines have been shown to induce surface flaws and microcracks as large as 0.1mm in depth.[13] Hydrofluoric acid etching of the intaglio surface of all ceramic crowns can remove some internal surface damage.[14] However, surface flaws especially on the intaglio surface of crowns are problematic as they can become a point of fracture initiation.

The environment surrounding the ceramic prosthesis plays a large factor in the longevity of the restoration. The all-ceramic dental crown is typically supported by a cement – substrate system in a wet environment. A dental crown can be supported by a variety of materials dependent on the clinical situation. The substrate may be a titanium or ceramic implant abutment, metal post and core on a root canal treated tooth, a core build-up material with either composite or amalgam, or a natural vital tooth with varying thicknesses of dentin or enamel. Malament et al reported that 35% of glass infiltrated alumina posterior crowns supported by dentin had failed at 10 years while no crowns supported by gold cores had failed during that same time period. The material properties and elastic modulus of different substrate materials affect the clinical outcome and longevity of all ceramic restoration.[15]

The adhesive system used to attach the restoration to the underlying substrate can also vary in thickness and in elastic modulus. The cement material properties are extremely critical since it is directly contacting the ceramic intaglio surface. The elastic modulus of cements is generally quite low, ranging from 3-10 GPa.[11] Anytime a brittle material is

supported by a substrate with such a low elastic modulus, higher risks of radial fractures can result from surface loads. Theoretical analysis with flat glass-cement-silicone fracture testing has shown that radial fractures occur less when increasing the elastic modulus of the resin cement. Beier et al evaluated the failure characteristics of all-ceramic restorations in a 20 - year clinical study. They found that all ceramic crowns cemented with Ivoclar Variolink Cement had significantly fewer failures than all ceramic crowns cemented with Pentron Optec Cement and Ivoclar Dual Cement. The author noted that Variolink had the highest viscosity when compared to the other resin cements used in their study.[2] Variolink II has been identified as having a higher elastic modulus, 11±0.5, when compared to Rely X Veneer cement and Variolink Veneer cement.[16] Currently Variolink Esthetic DC has replaced Variolink II. In this study, Variolink esthetic DC was used based on previous literature stating that it has a very high elastic modulus and favorable mechanical and esthetic properties. Based on the Ivoclar Variolink Esthetic Report, the flexural strength of Variolink Esthetic DC is 124±14 MPa.[17]

Theoretical analysis also indicates that radial fractures increase with thicker cement layers.[18] Cement thickness can vary clinically from 20 to 120 microns. Thicker cement layers have more complexities and potential complications which decrease the bond strength to the substrate. Thick resin cement layers have a higher potential for defects and voids. There is an increased level of water sorption, greater swelling[19], increased solubility, greater dimensional change and decrease in elastic modulus when a thicker layer of resin cement is present.

Previous studies have shown that the elastic modulus of resin cement is increased when the cement layer is thinner. [11,18,20,21] Silva et al looked at the reliability of a glass

ceramic - resin cement - composite system stored in water with varying cement layer thicknesses. And they found that after 60 days of water storage, thick (>100 micron) resin cement layers had significantly lower reliability under fatigue testing compared to the specimens with thin (<100 micron) layers of cement. In addition, for the thin cement layer (<100 micron) group, the reliability under fatigue testing did not decrease with water aging. Stress in the ceramic restoration during function can be affected by the variations in the resin cement layer.[18]

All dental restorations are exposed to a wet environment. The wet environment plays a role in the durability of the ceramic-adhesive-tooth system. Composite resin has been shown to expand in a wet environment.[19] Composite resins are used in adhesive cement systems, core build up material, and post and core materials. Composite resins are an integral part of the abutment-cement-crown complex. Expansion of composite resins play a critical role in the longevity and clinical outcome of ceramic crowns. Water can cause a composite core to expand non-uniformly creating stress points on the ceramic crown leading to fracture lines. In a study by Huang et al, ceramic cemented to an air stored composite base was submerged in water. The ceramic spontaneously fractured when the composite base became hydrated and composite swelling occured.[22] All ceramic crowns are often bonded to dentin in a clinical setting. Dentin contains a varying degree of water content which will affect the resin properties and dimensions, and potentially degrade the resin cement mechanical properties.[23]

In vitro studies investigating ceramic fracture strength should occur in a hydrated environment in order to simulate a clinically relevant environment. An aqueous environment has been shown to enhance crack propagation in ceramics. Water can

decrease the strength of ceramic by chemically condensing into a crack tip which can open the flaw. Moisture can also lower the activation energy associated with slow crack growth.[24] Kelly et al found that when using a dry, load-to-failure experimental set up, the fracture loads needed to induce cementation surface cracking were too high to be clinically relevant. However, when the same specimens were aged in water for 2 months before cyclically loaded under water, the mean failure load dropped significantly. The failure loads when tested cyclically in an aqueous environment were within the range reported clinically in function. The specimens cyclically loaded under water after being aged in an aqueous environment also showed no instances of cone cracking or surface damage. This is similar to all ceramic crown failures seen clinically.[25]

Restorations are clinically exposed to fluctuations in temperature as patients breathe, drink, and eat.[26] Studies have looked at the upper range of temperatures tolerated comfortably in the mouth. Subjects were able to comfortably drink liquids that were 55ºC to 60ºC. Anything above 68 ºC was typically too hot to tolerate in the mouth without physically causing pain.[26] When a patient eats something frozen, the lowest possible temperature to enter the mouth would be 0ºC.[27] The lowest comfortable temperature typically tolerated is higher than 0ºC. In a study, Peterson et al determined the lowest comfortable temperature tolerated is around 10ºC [28] Cycles between temperature extremes are estimated to occur 20 to 50 times a day. When performing in vitro experiments, cooling and heating the specimens to extreme temperatures in an aqueous environment for 10,000 cycles could represent around a year of temperature exposures in the mouth. Dwell times are necessary between temperatures so that the specimens can return to a resting temperature. Gale et al reviewed 130 thermocycling experimental reports and found the

average temperature ranges were 5 ºC to 55.5 ºC and the mean dwell time used was 53s. The aim was to standardize thermocycling conditions to allow comparisons between reports while creating a meaningful simulation of what temperatures typically occur clinically in vivo. Thermocycling has been a common method of artificial aging specimens for shear bond strength and tensile bond strength tests of dental materials[26,29]

Material selection plays a large role for the long-term clinical outcomes of monolithic ceramic crowns. Anterior or posterior restorations require different material selection based on the magnitude of forces the restoration will have to endure. Lithium disilicate was first used in dentistry in the early 2000's. Over the past two decades, lithium disilicate has become a popular restorative material specifically in anterior restorations since it is highly esthetic but also has higher fracture strengths than some previous all ceramic materials. However, lithium disilicate with a fracture toughness of 2.54MPa and flexural strength of 470 MPa has been a debatable material for use as a posterior restorative material.[30] A 10-year clinical study reported the survival rate for conventionally prepared full coverage posterior monolithic lithium disilicate crowns was 96.5%.[14] Malament et al in 2020 reviewed the survival rate of complete and partial coverage e.max press lithium disilicate posterior restorations. The overall survival rate was 96.5% over 16.9 years and there was no difference in the performance of complete or partial coverage restorations. This in vivo study also documented the thickness of the restorations and was able to analyze the survival rate of posterior e.max press restorations when thicknesses were <1mm and >1mm. They found that the thickness of the restorations had no statistical significance on the survival rate of posterior e.max press complete or partial restorations. The survival of e.max press posterior restorations with at least 1 surface being less than 1mm in thickness

was 93.9% after 10.9 years. [31] Long term clinical studies have shown that monolithic e.max press lithium disilicate when acid-etched and adhesively bonded demonstrate excellent survival rates when used as a material for posterior teeth restorations.

Apart from material selection alone, prosthesis and preparation design also influence clinical success. The amount of reduction of a tooth will vary depending on the clinical situation and this dictates the ceramic thickness of the restoration. Conventional all ceramic posterior crowns are recommended to have thicknesses of at least 1.5mm. However certain areas of all ceramic posterior crowns particularly the central groove area may be less than the recommended thicknesses due to the complex geometries of posterior teeth. In other clinical scenarios, additional reduction may be limited in order to avoid pulp exposures. The most conservative approach would be the use of ultra-thin restorations.

Previous studies have shown minimum thickness all ceramic crowns may have fracture strengths suitable for use as a single posterior restoration.[1,5,32-34] Guess et al studied the fracture strength of e.max press onlays ranging from 0.5mm to 1mm to 2mm thick. Extracted premolars were hand prepped to include a palatal onlay group, complete occlusal onlay group and a three-quarter crown group. They found significantly higher fracture loads in the 0.5mm ultra-thin palatal onlay group only when supported by enamel. The crack initiation was influenced by the elastic modulus mismatch between the restoration and substrate. A limitation of this study is the variability in geometry and thickness since every sample was hand prepared and each individual restoration was hand pressed.[35]

Therapy that includes minimally invasive crown preparations and lithium disilicate crowns could lead to predictable care and improved survival. Traditional crown preparation requires removal of 1.5 to 2mm of tooth structure, where all enamel is typically removed

leaving the restoration to be supported by dentin. Minimally invasive crown preparations require much less tooth reduction and provide the potential for the restorations to be supported by enamel. Theoretical analysis[36] suggested that smaller mismatch in elastic modulus between the abutment and the restoration, can significantly increase the load-bearing capacity of monolithic lithium disilicate crowns. Studies have investigated the impact of adhesive substrates on the fracture resistance of all ceramic restorations. Ceramic restorations bonded to dentin with resin cement may show a lower bond strength and lower fracture resistance than those bonded to enamel.[37,38] Conservative preparation not only could preserve tooth structure but also provide a desirable enamel surface for bonding and lithium disilicate crown support.

Clinically relevant, controlled *in vitro* or *in vivo* studies that assess the influence of preparation design and supporting tooth structure on fracture strength of minimal thickness lithium disilicate crowns are limited. Previous *in vitro* studies have utilized extracted teeth as substrates where each specimen is individually hand prepared to create abutments within dentin or enamel. Although this study design allows fracture strengths to be measured on anatomical teeth, it also introduces different morphologies of substrates and restorations which can affect the fracture strength results of all ceramic restorations. Standardizing geometry, dimensions, internal fit, and die space on extracted natural teeth can be challenging. Complex geometries with varying internal edges can present predetermined breaking points and cause a variation in fracture strength [37-40]

Use of digital technology may be a way to design and fabricate meaningful standardized abutments. The ability to carefully create standardized dimensions and geometries for a variety of substrate materials provides reproducibility in studying the

fracture resistance for complex geometries. Laboratory studies indicate the elastic modulus of Paradigm MZ100 [41,42] composite (3M, St. Paul, MN, USA) is similar to dentin,[43] whereas, the elastic modulus of e.max[44] (Ivoclar Vivadent Inc., Amherst, NY, USA) is similar to enamel.[45,46] Simulation of support from dentin or enamel respectively, could be accomplished with such materials in a controlled digitally designed study to determine the influence of preparation design and underlying support on fracture resistance.

B. Objective and Hypotheses of the Study

The objective of this *in vitro* study is to investigate the influence of abutment material properties on the fracture resistance and failure mode of e.max CAD/CAM crowns on traditionally and minimally prepared simulated tooth substrates. The null hypotheses were: (1) Restoration thickness has no influence on the fracture strength of CAD lithium disilicate crowns. (2) The elastic modulus of the substrate has no influence on the fracture strength of CAD lithium disilicate crowns. (3) Fracture mechanisms of CAD lithium disilicate crowns are not affected by the crown thickness or the elastic modulus of the substrate. (4) Aging has no effect on the fracture strength of lithium disilicate CAD crowns.

II. MATERIALS AND METHODS

This chapter details the work originally published in the *Journal of Prosthodontics* and has been authorized to be used for the purposes of this thesis and oral defense.

Chen SE, Park AC, Wang J, Knoernschild KL, Campbell S, Yang B. Fracture Resistance of Various Thickness e.max CAD Lithium Disilicate Crowns Cemented on Different Supporting Substrates: An In Vitro Study. *Journal of Prosthodontics*. 2019 Dec;28(9):997-1004.

A. Design

Sixty lithium disilicate (IPS e.max CAD MT, Ivoclar Vivadent Inc.) CAD/CAM (computer-aided design/ computer-aided manufacturing) crowns were divided into three groups (n=20). Group TD: traditional thickness crowns cemented on Paradigm MZ100 (3M, St. Paul, MN, USA) abutments. Group MD: minimal thickness crowns cemented on MZ100 abutments. Group ME: minimal thickness crowns cemented on e.max CAD abutments (Figure 1a).

The 3Shape CAD system (3Shape, Copenhagen, Denmark) was used to scan, design and mill all abutments and crowns with the die space set to 40 micrometers and 30 micrometers extra occlusal die space. This allowed all abutments and restorations to have standardized dimensions and geometries. Traditional thickness crowns were designed based on manufacturer guidelines with a 1.5mm uniform occlusal thickness, and 1.0mm rounded shoulder margins. Minimal thickness crowns were designed with a 0.7mm uniform occlusal thickness and 0.5mm rounded shoulder margins (Figure 1b).

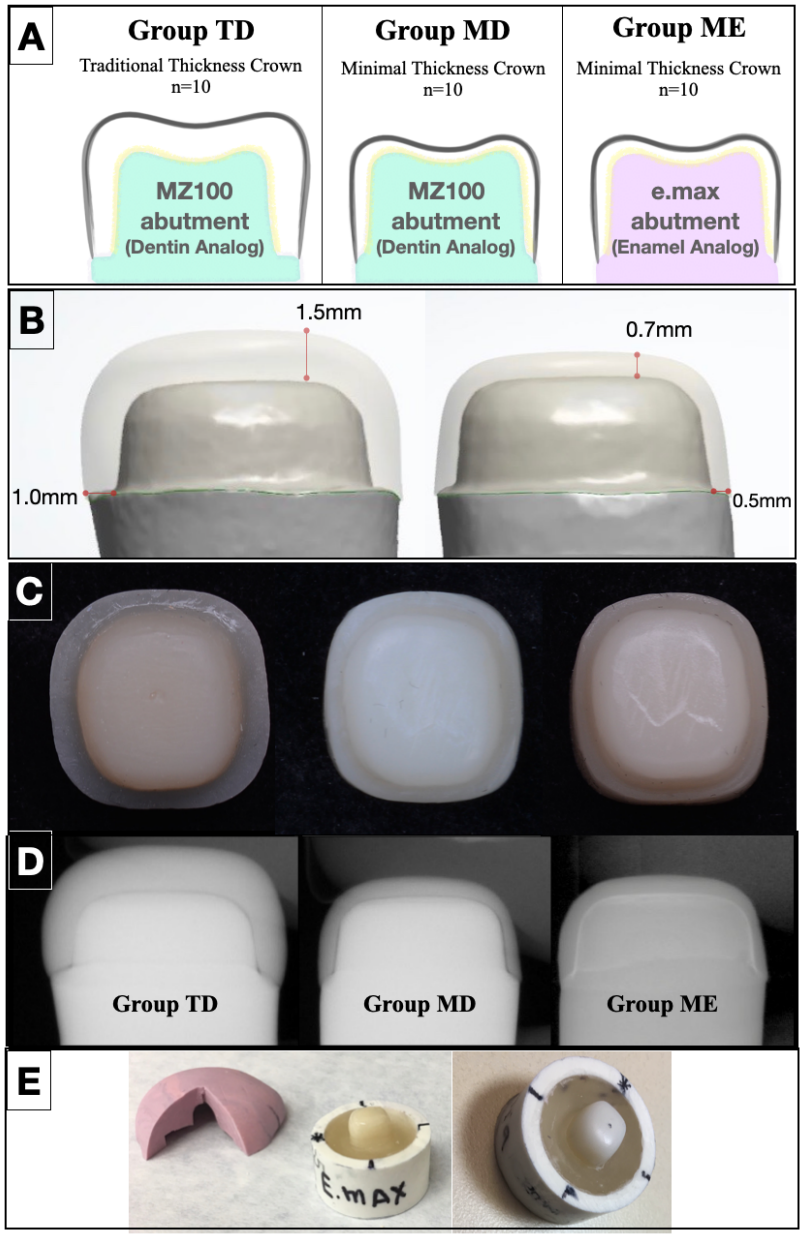

Figure 1. Design
A, Study design. TC = thermocycles from 5°C and 55°C
B, 3 Shape design of traditional thickness crown (left) and minimal thickness crown (right).
C, Milled traditional thickness MZ100 abutment (left), minimal thickness MZ100 abutment (middle), minimal thickness e.max abutment (right).
D, Cross section of Group TD before cementation (left), Group MD before cementation (middle), Group ME after cementation (right). Bite-wing radiographs of specimens were taken before and after cementation
E, Specimen mounted in PVC pipe and orthodontic resin.

B. Abutment Fabrication

A mandibular first molar typodont tooth was prepared with a traditional thickness design using a diamond bur to include rounded, smooth and flat occlusal anatomy with 1mm wide rounded shoulder margins. The traditionally prepared typodont tooth was used to create the minimal thickness abutment, to maintain the same rounded internal line angles, taper, and occlusal geometry; while only changing the width of the finish line. The original typodont was modified by circumferentially trimming 0.5mm from the external edge of the finish line to reduce the finish line width from 1mm to 0.5mm. The axial walls, axial-cervical line angle and coronal preparation design were unaltered.

The pre-modified traditionally prepared typodont tooth and the minimal thickness preparation were scanned with a laboratory scanner (3 Shape D700, Copenhagen, Denmark) and STL (Standard Tessellation Language) files of the abutments were created. Twenty traditional thickness abutments were milled in detail mode with a PlanMill40 milling unit (Planmeca, Helsinki, Finland) using MZ100 blocks for E4D. Forty minimal thickness abutments were milled: 20 with MZ100 blocks and 20 with IPS e.max CAD blocks (Figure 1c). All milled lithium disilicate abutments were sintered in an oven (Programat CS2; Ivoclar Vivadent, Inc.) following the manufacturer's sintering guidelines.

C. Crown Fabrication

3Shape software was used to scan a milled MZ100 traditional thickness abutment and a traditional thickness crown was designed on the abutment. The resulting traditional thickness crown STL file was used to mill 20 traditional thickness crowns with IPS e.max CAD MT blocks. A minimal thickness MZ100 abutment was scanned and a minimal

thickness crown was designed. The resulting STL file was used to mill 40 minimal thickness crowns with IPS e.max CAD MT blocks. All crowns were milled in detail mode with the sprue located on the axial surface 2mm away from the margins. Restoration thicknesses were designed and milled as specified, 0.7mm for minimal thickness restorations and 1.5mm for traditional crowns. The occlusal surfaces were polished with a porcelain polishing kit (Dialite Extra-Oral Porcelain Polishing, Brasseler, Savannah, GA, USA). All milled blue stage lithium disilicate crowns were sintered following the manufacturer's sintering guidelines. Thicknesses were verified post milling using an Iwanson spring caliper.

D. <u>Cementation</u>

All MZ100 composite abutments were submerged in water for 7 days to allow abutments to fully hydrate prior to cementation to avoid stress on the ceramic restorations from expansion of the composite abutment from water absorption. [47] A Variolink Esthetic DC System Kit (Ivoclar Vivadent, Inc, Albany, NY, USA) was used to cement all specimens following manufacturer's instructions. All e.max surfaces (crowns and e.max minimal abutments) were steam cleaned and dried. All e.max surfaces were then etched with 5% hydrofluoric acid (IPS Ceramic etching gel) for 20s. The 5% hydrofluoric acid was rinsed with water for 15s and dried with oil-free air. Ceramic primer (Monobond Plus) was applied for 60s. Once the pre-treatment for all e.max abutments and crowns was finished, the MZ100 abutments were prepared for cementation. The MZ100 abutments were steam cleaned, air dried, and then etched with 35% phosphoric acid for 30s. The 35% phosphoric acid etch was rinsed with water for 15s and dried with oil free air. The MZ100

abutments were scrubbed with a bonding agent (Adhese Universal Vivapen) for 20s and oil/moisture free compressed air was used to disperse the bond evenly on the MZ100 abutment.

A thin layer of resin luting cement (Variolink Esthetic) was applied simultaneously to the occlusal surface of the abutment with a microbrush and the intaglio surface of the crown. The crown was firmly seated onto the abutment and held with finger pressure for 1 min to allow chemical cure. Excess cement was removed with a microbrush and the margins were covered with an air-blocking barrier (Ivoclar Liquid Strip). A curing light with 500-1000 mW/cm^2 was applied to crown for 30s on each surface. The air-blocking barrier was rinsed with water and the cemented specimens were left at room temperature for 30 minutes.

Specimen holders were created by cross sectioning a 1-inch diameter PVC pipe to 10mm tall pieces. The specimens were mounted in the center of the PVC pipe with self-curing orthodontic resin. A putty matrix was used to secure all specimens in a reproducible position and to ensure the top of the crowns were leveled. The abutments were embedded in orthodontic resin 1mm below the margin of the crown.

Half of the specimens (n=10) in each group were stored in distilled water for 7 days at ambient temperature and the other half were stored for 120 days with 37,500 thermocycles from 5°C and 55°C with a 1-minute dwell time.[26,27,29] The specimens stored for 7 days were labeled ME_o, MD_o, and TD_o. The specimens aged for 120 days with thermocycling were labeled ME', MD' and TD'. After the different storage conditions were completed, load-to-fracture was tested.[48]

E. Measurement of Fracture Load

The fracture load of the specimens was measured using a universal testing machine (Instron 5582; Instron, Co, Norwood, MA, USA). A 3mm radius stainless steel hemispherical tip was applied to the center of each crown. This radius for the indenter was selected because the contact radius on a natural tooth varies between 2 to 10mm depending on the anatomy of the opposing tooth. [6,7] A 1mm thermoplastic film was placed between the loading tip and crown surface to distribute forces and ensure a broad even contact (Figure 2).[6] The force was loaded along the longitudinal axis at a crosshead speed of 0.5mm/min until audible fracture. The loading values vs. crosshead position were plotted continuously during loading and a slight drop in load on the graph in conjunction with the audible fracture noise defined the fracture. Acoustic monitoring for crack detection has been shown to be reliable.[49]

All crowns were then inspected for visible fracture lines on the restoration surface with and without the use of trans-illumination. Fractures were categorized as catastrophic failure, fracture lines visible only with transillumination, and no fracture lines visible.

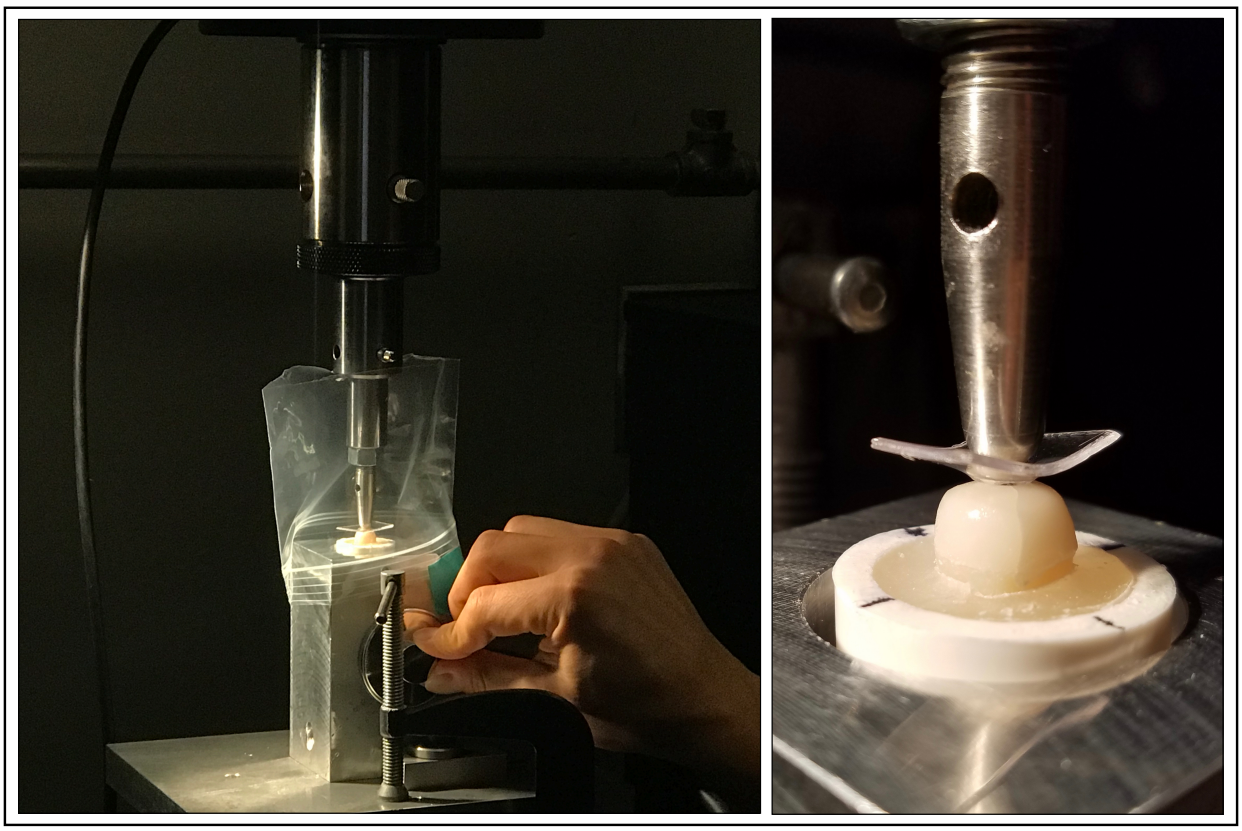

Figure 2. Fracture testing under compressive forces using a universal testing machine. A 1mm thermoplastic film was placed between the loading tip and crown surface. The loading force was positioned at the center of the occlusal surface and loaded along the longitudinal axis of the crown.

F. Data Analysis

Data was analyzed with statistical software (IBM SPSS version 22, Armonk, New York, USA) using a two-way analysis of variance and post hoc Bonferroni correction. The coefficient of variation (CV) for each group was calculated. A CV of 15% or greater was defined as a critical measure of dispersion of a probability distribution.

G. Fractographic Analysis

In order to prepare specimens for fractographic analysis, one specimen from group ME and group MD were cross-sectioned to a 1mm thin slice along the long axis of the crown with an IsoMet 1000 precision wafering diamond saw (Buehler, Lake Bluff, USA) at 250 RPM. The cross section was taken from the center of the specimen where the load was applied. The specimens were mounted on aluminum stubs with carbon adhesive tabs and sputter coated with 5.0nm of gold/palladium at a low-pressure argon atmosphere. Morphology, origin and magnitude of fractures were analyzed using a variable pressure scanning electron microscope (Hitachi S-3000N, Krefeld, Germany).

III. RESULTS

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A. Fracture Load

The mean fracture load, standard deviations and coefficient of variation are shown in Table I. When comparing the means of all data for each group (non-aged and aged), no statistically significant difference between groups was observed (p=0.970, F=0.030) (Figure 3). However, when comparing the fracture load values between the 7-day and 120-day storage groups, statistically significant differences were observed (p= <0.001, F= 7.561). Some of the 120-day storage groups were significantly higher in value than the 7-day storage groups indicated in Table I and labeled by the red brackets in Figure 4. MD_o (7-day storage minimal crown on MZ100 abutment) had significantly lower fracture loads than MD' (120-day storage minimal crown on MZ100 abutment), ME' (120-day storage minimal crown on e.max abutment), and TD' (120-day storage traditional crown on MZ100 abutment).

When comparing within the 120-day storage groups, no statistically significant difference between the groups ME', MD', and TD' was observed (P=0.285, F=1.328). When comparing within the 7-day storage groups, no statistically significant difference

between the groups ME_o, MD_o, and TD_o was observed (P=0.053, F=3.331), although the p value was very close to 0.05. Within the 7-day aged groups the abutments with high elastic modulus (Group ME_o) showed slightly higher fracture resistance with a narrower standard deviation compared to abutments with low elastic modulus (Group TD_o and MD_o).

The coefficient of variation (CV) was calculated for all groups. The CV's for all groups except for group ME_o were greater than 15% (critical measure of dispersion of a probability distribution). The CV of group ME_o was 7.0%. The dispersion of a probability distribution in all groups were statistically higher than that of group ME_o (Table I).

TABLE I
FRACTURE LOAD MEAN, STANDARD DEVIATION, AND COEFFICIENT OF VARIATION OF EXPERIMENTAL GROUPS

	Fracture Load Mean (STD)			Coefficient of Variation		
Groups	**7 days**	**120 days/TC**	**Total**	**7 days**	**120 days/TC**	**Total**
ME	1376.6 (96.2) [a]	1765.4 (301.4) [b]	1571.0 (295.2)	7.0%	17.1%	18.8%
MD	1228.0 (287.1) [b]	1961.8 (319.9) [abc]	1594.9 (479.0)	23.4%	16.3%	30.0%
TD	1499.2 (240.5) [c]	1701.7 (424.8) [b]	1600.4 (350.7)	16.0%	25.0%	21.9%

[abc] The superscript letters indicate which groups have statistical significant difference in values ($p<0.05$).

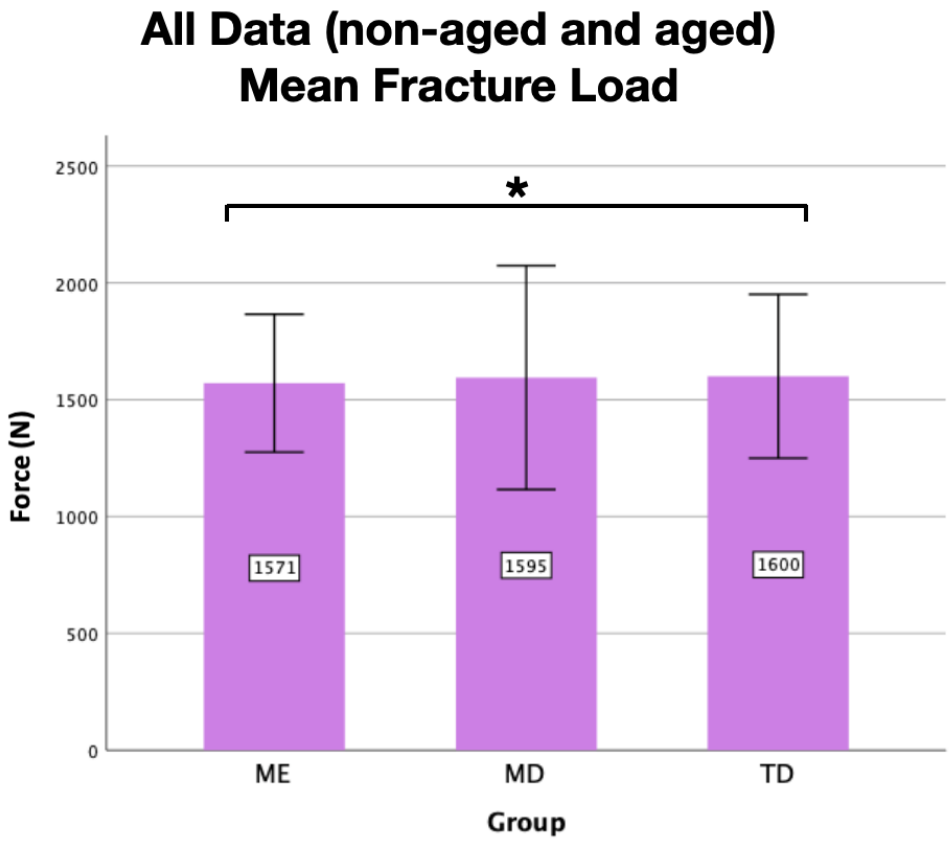

Figure 3. Mean fracture load with all data (7-day and 120-day groups) combined.

* indicates no statistical difference among the three groups (P>0.05).

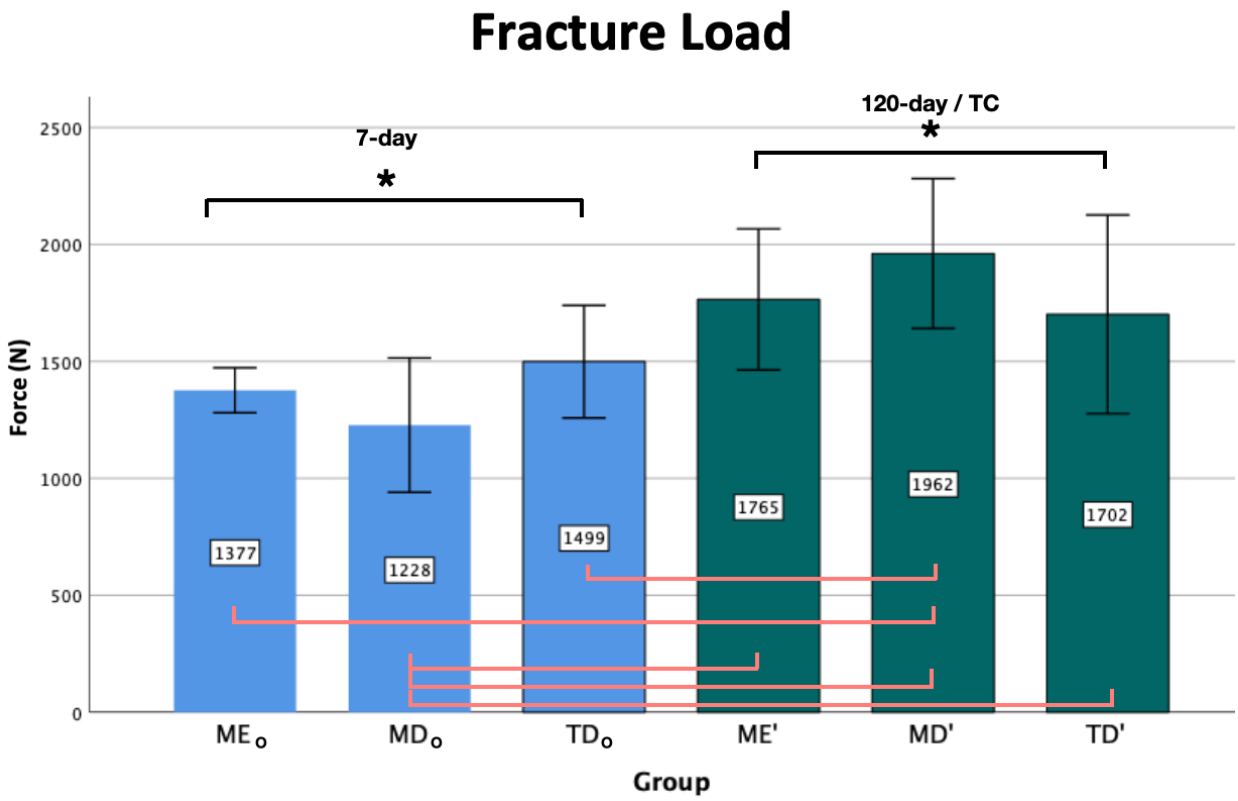

Figure 4. Mean fracture load and statistical significance presented for each subgroup.
The blue bars indicate the 7-day storage subgroups:

ME_o (minimal crown on e.max abutment),
MD_o (minimal crown on MZ100 abutment),
TD_o (traditional crown on MZ100 abutment).

The green bars indicate the 120-day storage subgroup with 37,500 thermocycles from 5°C and 55°C:

ME' (minimal crown on e.max abutment),
MD' (minimal crown on MZ100 abutment),
TD' (traditional crown on MZ100 abutment).

The black * indicates no statistically significant difference (P>0.05) among the three groups within their respective storage categories.
The red brackets indicate statistically significant difference (P<0.05) between the designated groups.

B. Fracture Categories

Catastrophic failures were defined in this study as specimens with clearly visible fracture lines at the surface of the restoration. Only eight specimens were defined as catastrophic failures after loading the specimens to audible fracture sounds with a deviated loading graph. All catastrophic failures still remained intact even when visible surface fracture lines were observed (Figure 5). Catastrophic failures were mainly from Group TD (5 specimens). Two catastrophic failures were observed in Group MD and only was observed in Group ME.

Further trans-illumination inspection was conducted for the remaining specimens without clearly visible catastrophic fracture lines. Additional fractures were identified upon trans-illumination inspection and recorded. In group MD, trans-illumination inspection revealed 12 specimens with small fractures (1-2mm in length) within the occlusal portion of the restorations. In group ME, trans-illumination inspection revealed 3 specimens with smaller fracture lines (≤ 1mm in length) within the axial walls of the restorations. Overall group MD had the most specimens with visible fractures (catastrophic and trans-illuminated crack lines) but group TD had the greatest number of catastrophic failures. Group ME had the least number of catastrophic fractures. The trans-illuminated fracture lines for group ME were also located on the axial walls unlike the other fracture lines visible on the occlusal surface in groups TD and MD (Table II)

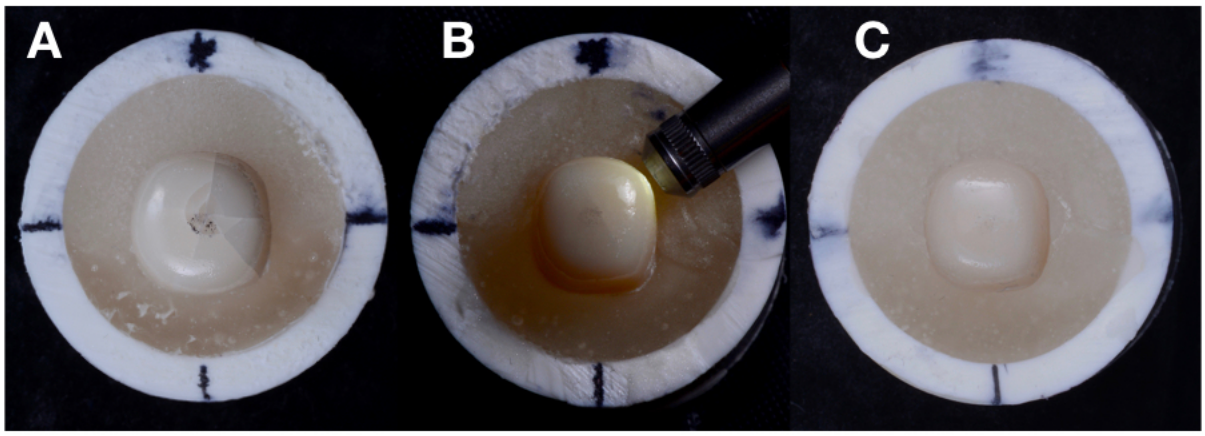

Figure 5. Fracture Categories
A, Catastrophic fracture from Group TD
B, Fracture lines visible only using transillumination from Group MD
C, Sample from Group ME that displayed no visible fracture lines with and without transillumination. These fractures were identified by initial audible fracture sound upon loading and verified by dip in force vs. crosshead plotting graphs.

TABLE II
FRACTURE CATEGORIES

Fracture Category:	**Group TD (n=20)**	**Group MD (n=20)**	**Group ME (n=20)**
Catastrophic failures	5	2	1
Fracture lines visible only with transillumination	0	12	3
No visible fracture lines with audible fracture sound	15	6	16

C. Fracture Modes

Different fracture modes were demonstrated through SEM observation. Figure 6 illustrates the fracture mode from Group MD and ME. Fracture origin was visualized at the interface between the crown and luting resin cement in both groups. The fracture defects in group ME were smaller in dimensions than in group MD. One specimen in group TD was loaded beyond initial audible crack to complete catastrophic failure in order to examine with SEM analysis. Figure 7 illustrates the remaining piece of traditional thickness crown bonded to the abutment surface. The fracture lines (arrows labeled a, b, c, d) were wider when close to the cementation interface than the fractures lines close to the restoration surface, indicating fracture origin at or near the interface between the crown and luting resin cement with propagation towards the restoration occlusal surface. All groups showed similar fracture trends; originating at the internal interface between the crown and luting resin cement, and propagating towards the restoration occlusal surface.

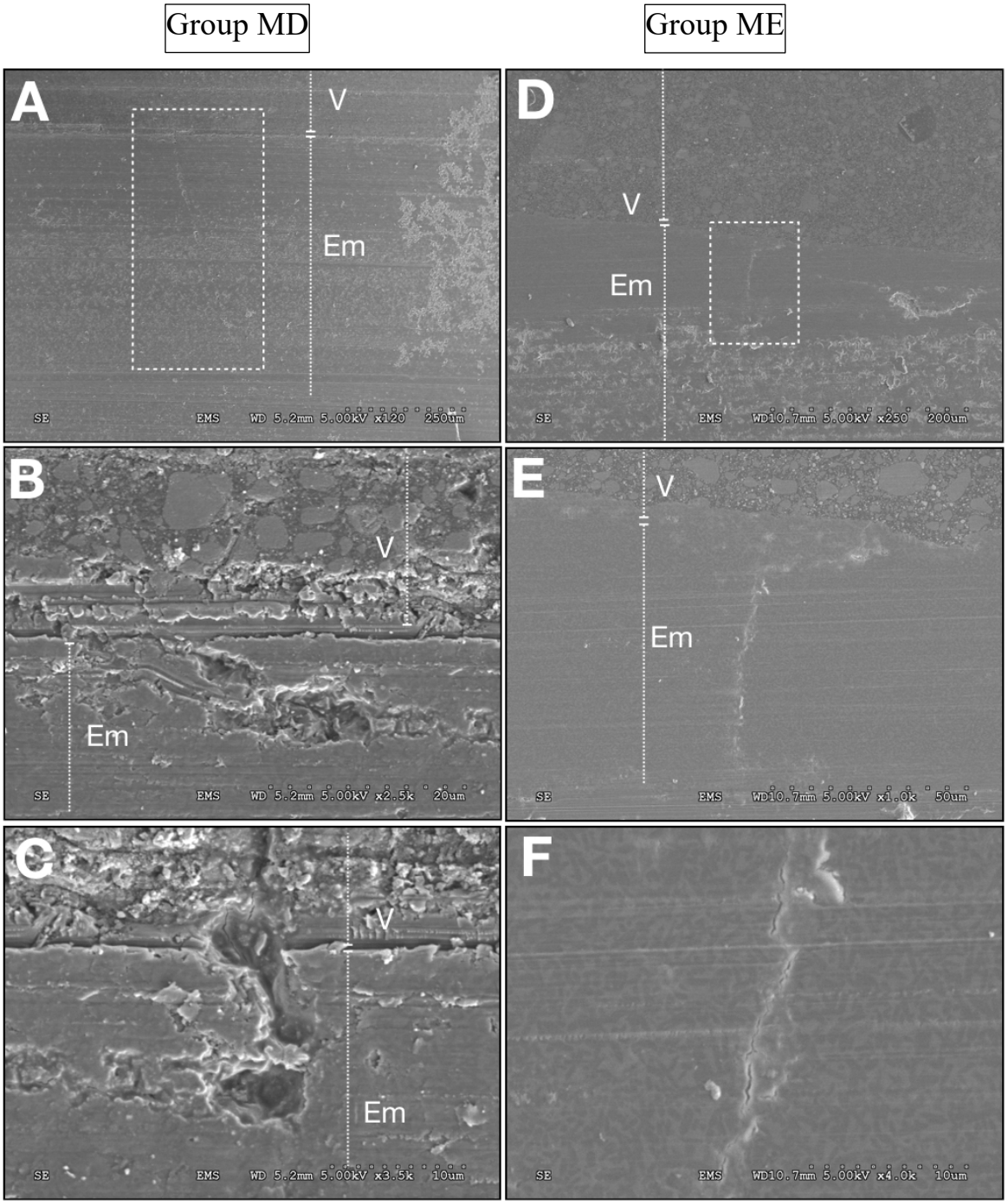

Figure 6. SEM Group MD and ME

Randomly selected specimens from Group MD (minimal thickness crown on MZ100 abutment) and ME (minimal thickness crown on e.max abutment) are illustrated. Cross sections from group MD (left column) and group ME (right column) were examined with SEM under low and high magnifications. The layer of Variolink Esthetic cement is labeled with "V" and the e.max crown is labeled with "Em." No fracture lines were detected in the cement or abutment layers, but micro-fracture lines were found in e.max ceramic (labeled in dotted boxes in 6A,6D). Fracture origin was visualized at the interface between the crown and luting resin cement in both groups. Fracture defects in Group MD (6B,6C) were larger in dimension than defects in group ME (6E, 6F).

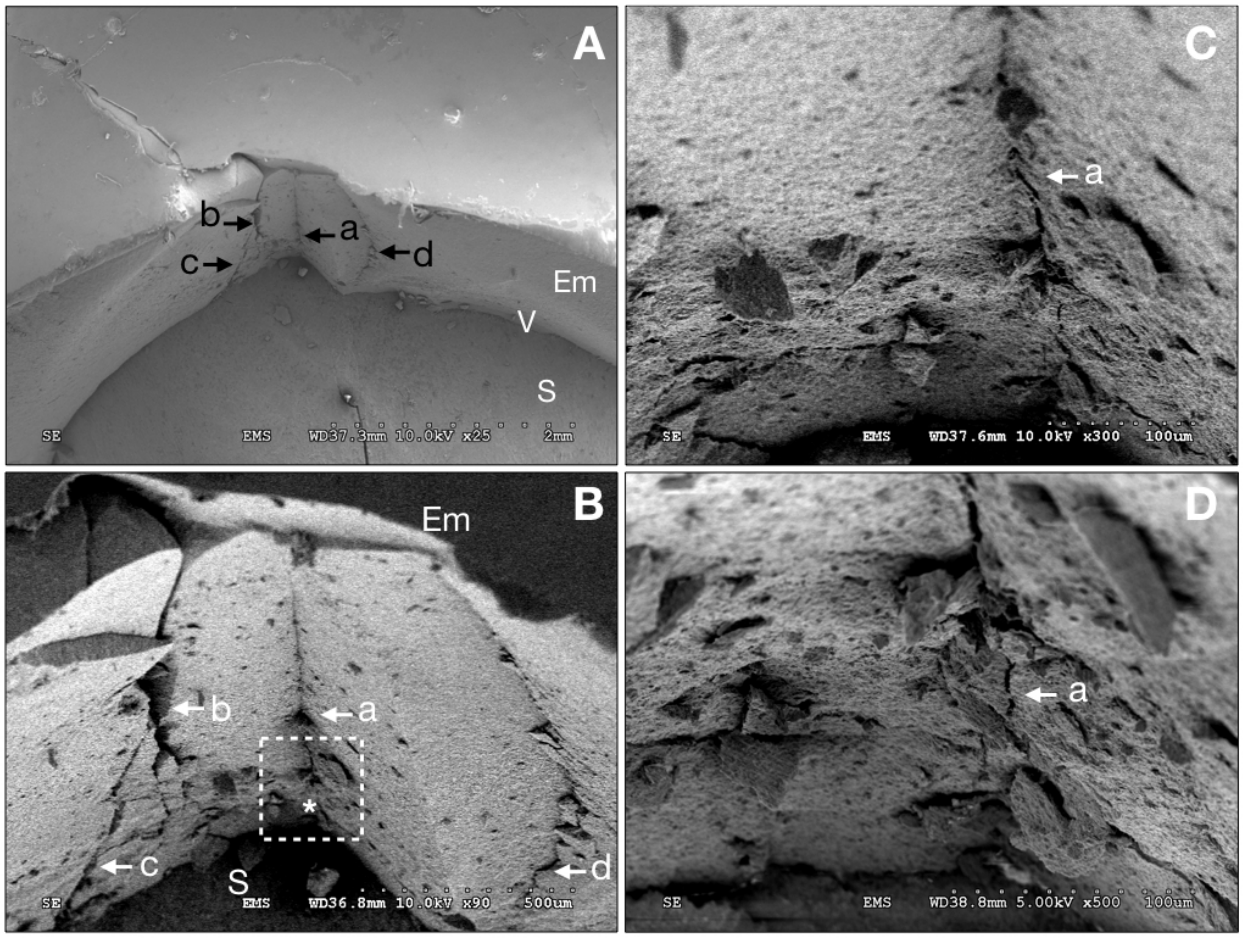

Figure 7. SEM Group TD
A randomly selected traditional thickness crown was purposely fractured beyond initial audible crack sound in order to create a catastrophic failure to analyze under SEM at x25, x90, x300, x500 magnifications. Images illustrate the remaining piece of crown bonded to the abutment surface. The substrate is labeled with "S," the layer of Variolink Esthetic resin cement is labeled with "V," and the e.max crown is labeled with "Em". The fracture lines (arrows labeled a,b,c,d) are wider when close to the cementation interface than the fracture lines close to the surface, indicating fracture origin (labeled with *) at or close to the interface between the crown and cement with propagation towards the restoration occlusal surface. Dotted box in 7B indicates area that is magnified in figure 7C and 7D.

IV. DISCUSSION

This chapter details the work originally published in the *Journal of Prosthodontics* and has been authorized to be used for the purposes of this thesis and oral defense.

Chen SE, Park AC, Wang J, Knoernschild KL, Campbell S, Yang B. Fracture Resistance of Various Thickness e.max CAD Lithium Disilicate Crowns Cemented on Different Supporting Substrates: An In Vitro Study. *Journal of Prosthodontics*. 2019 Dec;28(9):997-1004.

This study demonstrated lithium disilicate crowns fabricated for minimally reduced preparations had fracture resistance similar to traditionally prepared lithium disilicate crowns when a single load-to-failure is used. The difference in fracture load were compared between groups within the study. The mean fracture load (standard deviation) was 1600 (351) N for Group TD; 1595 (479) N for Group MD (Figure 3). Group TD and MD used the same substrate material; therefore, we were able to look at the e.max thickness alone to determine the outcome of the 1st null hypothesis. There was no statistically significant difference between these two groups. The mean fracture load for group TD was only slightly higher by 5N which would be expected intuitively since group TD had thicker all ceramic crowns. The 1st null hypothesis, that restoration thickness had no statistically significant difference on the fracture strength of CAD e.max crowns, is accepted.

This study also looked to see if the elastic modulus of the substrate had an influence on the fracture strength of CAD lithium disilicate crowns. In order to determine whether the 2nd null hypothesis could be accepted or rejected, we looked at the results of group MD

and ME. These two groups had the identical crown thicknesses (minimal design of 0.7mm occlusal thickness and 0.5mm margins). The only design variation between these two groups was the substrate material. Group ME had e.max abutments and Group MD had MZ100 composite abutments. Ivoclar e.max CAD lithium disilicate blocks were selected as the abutment material for Group ME because it has an elastic modulus of ~95 Gpa[44] which is similar to human enamel with an elastic modulus of ~91 GPa.[45,46] 3M Paradigm MZ100 composite blocks were selected as the abutment material for Group MD because it has an elastic modulus of 18GPa[41,42], which is comparable to human dentin with an elastic modulus of 16-18 GPa.[43] The substrate materials selected were able to be digitally designed and milled with CAD/CAM technology. This allowed for composite abutments with minimal defects and voids compared to using traditional methods of packable composites. CAD/CAM technology was used to control the material properties; the geometry, dimensions, and internal fit of all abutments and crowns in group MD and ME.

The mean fracture load (standard deviation) was 1595 (479) N for Group MD and 1571 (295) N for group ME (Figure 3). However, there was no statistically significant difference in the mean fracture loads. The mean fracture load for group MD was higher than group ME which was unexpected. The 2nd null hypothesis, that the elastic modulus of the substrate has no influence on the fracture strength of CAD lithium disilicate crowns, can only be partially rejected. Since group ME had substrate materials with much higher elastic moduli, we expected to see group ME with a higher mean fracture load than group MD. [15,48] Variation in cement thickness between group MD and ME could be one reason why the results were opposite from what was expected.

During the cementation process, the fit of the crowns in group ME felt looser when compared to the fit of the crowns in group MD. A larger cement die space seemed to exist in group ME even though all crowns in group MD and ME were designed with the same die space settings. In fact, identical STL files were used to mill all abutments and crowns in group ME and MD. The variation in cement thickness could have resulted because the crowns were digitally designed on a scan of a dehydrated MZ100 abutment. However, the crowns in group MD were cemented onto hydrated MZ100 abutments. The MZ100 abutments were stored in water for 7 days immediately prior to the cementation process to allow complete water absorption and swelling. The MZ100 composite abutments are likely to expand when stored in water, creating a change in the MZ100 abutment dimensions.[22] This change in MZ100 abutment dimensions may have altered the fit of the crowns in group MD and ultimately could have decreased the cement layer thickness in these specimens. Ideally, the crowns in group MD should have been digitally designed on a STL file of a fully hydrated MZ100 abutment in order to best control the cement thickness and fit of the crowns.

Unfortunately, every single specimen was not sectioned and analyzed under SEM in this study. Only one specimen from each group was analyzed with SEM. If every specimen was analyzed, the cement thickness for each specimen could have been measured and observed. Definitive statements on the cement thickness of each group could have been made with that data. However, based on the one specimen in group ME that was sectioned and analyzed with SEM, the cement thickness was 178 microns and voids were visualized in the cement layer. The observed 178-micron cement layer is actually large. Ideally the cement layer would be 20-50 microns thick[11,71] All ceramic crowns with >100-

micron resin cement layers have been shown to have lower fracture strengths compared to the all ceramic crowns with thin (<100-micron) layers of cement.[18] Existing literature indicates that the radial fractures increase with thicker cement layers.[18,71] Thick resin cement layers have a higher potential for defects and voids. There is an increased level of water sorption, greater swelling, increased solubility, greater dimensional change and decrease in elastic modulus when a thicker layer of resin cement is present. [19] If group ME had a thicker cement space, this could explain why there was no difference in the fracture strength of the ME and MD groups.

Fracture mode and mechanism was observed in the three groups of this study. The group with the least number of catastrophic fractures and least number of visible crack lines at the restoration surface was group ME - minimal thickness e.max crowns on e.max abutments (enamel analog). The smaller mismatch in elastic modulus between the abutment and the restoration may result in a more predictable load-bearing capacity of monolithic lithium disilicate crowns. Group ME also demonstrated the smallest magnitude of fracture lines. Group MD, minimal thickness e.max crowns on MZ100 abutments (dentin analog), demonstrated the most visible crack lines at the restoration surface. Group TD, traditional thickness e.max crowns on MZ100 abutments, demonstrated the most catastrophic failures. The smaller mismatch in elastic modulus between the abutment and the restoration for the ME group may result in less catastrophic and smaller fracture line magnitude.

Under SEM observation, some similarities were noted between the three groups. Although definitive conclusions are very difficult to make due to the small sample size of specimens (one from each group) which were analyzed with SEM. In Figure 6, no fracture

lines were detected in the abutment materials, but micro-fracture lines were found in the lithium disilicate ceramic, with origins at the cementation interface. The fracture lines in Figure 7 (labeled with arrows a, b, c, and d) are wider when close to the cementation interface than the fracture lines close to the surface, indicating fracture origin at or near the interface between the crown and luting resin cement with propagation towards the restoration occlusal surface.[50,70] All restorations regardless of the magnitude of the fracture defects seem to have exhibited fracture origins at the crown/cement interface based on the limited amount of slides reviewed with SEM. Interestingly, fracture defects seen in Group MD were larger in magnitude than in Group ME (Figure 6).

Visible fracture location seemed to be affected by the elastic modulus of the substrate. Group ME had only one catastrophic fracture and it was a crack line on the axial wall at the margin of the crown. All the other catastrophic fracture lines in group MD and TD were at the occlusal surface. In addition, all the visible trans-illuminated fracture lines in group ME were along the axial walls. The visible trans-illuminated fracture lines in group MD and TD were located at the occlusal surface, indicating local contact damage and fracture origin. Monolithic lithium disilicate crowns supported by a substrate with a higher elastic modulus (enamel analog) tend to have smaller visible fracture lines located on the axial walls of the crown, away from the area of loading forces. Whereas monolithic lithium disilicate crowns supported by substrates with a lower elastic modulus (dentin analog) tend to have visible fracture lines directly under the area of loading forces. The third null hypothesis, fracture mode and mechanisms of CAD lithium disilicate crowns are not affected by the crown thickness or the elastic modulus of the substrate is rejected.

There are many techniques to simulate the aging process for dental ceramics.[51] An aqueous environment has been shown to enhance crack propagation in ceramics. Water can decrease the strength of ceramic by chemically condensing into a crack tip which can lengthen and sharpen the crack tip of the flaw. Moisture can also lower the activation energy associated with slow crack growth.[24] Kelly et al found that when ceramic crowns were aged in water for 2 months before cyclically loaded under water, the mean failure load dropped significantly. [25] Yazigi et al artificially aged half of their specimens with thermo-mechanical fatigue in a dual-axis masticatory simulator. Slightly higher fracture loads were seen in the aged groups when compared to the non-aged groups though not enough to be statistically significant.[39] Most other studies have shown decreased fracture strengths in monolithic all-ceramic crowns after artificial aging.[52-54] The diversity in results could be due to different artificially aging techniques: varying time, temperatures, and cyclic loading protocols.

In this study, half the specimens were aged for 120 days with 37,500 thermocycles from 5°C and 55°C with a dwell time of 1min. Thermocycling has been a common method of artificial aging specimens for shear bond strength and tensile bond strength tests of dental materials. Restorations are clinically exposed to fluctuations in temperature as patients eat, drink and breathe.[26,69] Typically temperatures of food or liquids that would be introduced to a patient's mouth will range from 0ºC to 60 ºC. Anything above or below this range would result in physical pain.[26-28] Cycles between temperature extremes are estimated to occur 20 to 50 times a day. Cooling and heating specimens to extreme temperatures in an aqueous environment for 10,000 cycles could represent around a year of temperature exposure in the mouth clinically. Dwell times are necessary between

temperatures so that the specimens can return to a resting temperature. Standardized thermocycling conditions of temperatures ranging from 5 ºC to 55.5 ºC and a dwell time of 1 minute have been used in previous literature.[26]

In this study, the fracture load of all aged groups (ME', MD', TD') were higher than the fracture load of the groups aged for 7 days without thermocycling (ME_0, MD_0, TD_0). Many aged groups had statistically significantly higher fracture means than the non-aged groups. The fourth null hypothesis: aging has no effect on the fracture strength of lithium disilicate CAD crowns, is rejected. These results were not expected. Aged specimens were expected to have lower fracture means than the non-aged groups since storing ceramics in an aqueous environment over time has been shown to enhance crack propagation. Water is expected to decrease the strength of ceramic by chemically condensing into a crack tip which can open the flaw.[24]

All specimens were mounted in a PVC pipe ring and orthodontic resin (Figure 1E) for preparation of the universal testing machine mount. The specimens were aged in the PVC pipe mounting surrounded by a large mass of orthodontic resin. Resin has been shown to expand in a wet environment.[19] Perhaps the complex system of water absorption and dimensional changes in the 3 separate areas containing resin within each mounted specimen (the PVS-orthodontic resin mounting system, MZ100 abutments and Variolink Esthetic DC resin cement) led to the interesting change in fracture results in the aged groups.

The unexpected higher fracture load results of the aged groups in this study may be attributed to a change in the cement with time. Mendonça et al studied resin cement hardness after 7 days and 3 months of water storage. E.max press lithium disilicate crowns

were cemented to various substrates: dentin, metal core, and composite core. Variolink II Dual Cure resin cement was used to cement all crowns. The specimens were stored for 7 days or 3 months in water. They found that Variolink cement was significantly harder after 3 months of water storage for the composite core group. The authors speculated a delay in the complete cure of the cement and adhesive occurred due to interactions of free radicals of the composite core with the adhesive initiators resulting in lower cement hardness values at 7 days compared to 3 months of water storage.[72] Increased cement hardness in the aged specimens could help explain an unexpected higher fracture mean in this study.

A. Implications for Clinical Practice

Reduced thickness restorations with sufficient fracture strength may have a tremendous impact on clinical applications. Minimal thickness all ceramic restorations may be warranted in clinical situations of limited restorative space, excessive wear, or desire to avoid pulp exposure. Monolithic lithium disilicate restorations of various thicknesses can be bonded to dentin or enamel substrates depending on the amount of tooth reduction. Failure due to tensile stresses is more dependent on the similarities of elastic moduli between the restorative material and substrate, and less reliant on the inherent material strength and thickness of the restorative material.[48]

Minimal thickness crowns luted to enamel may be more predictable and consistent than traditional thickness restorations or minimal thickness restorations luted to dentin. This further suggests that minimal thickness restorations may have more predictable mechanical behavior and fewer catastrophic failures when supported by a substrate with a higher elastic modulus.

Minimal thickness crowns luted to enamel may be more predictable and consistent than traditional thickness restorations or minimal thickness restorations luted to dentin. The coefficient of variation (CV) is a measure of dispersion of a probability distribution, and a lower CV value may suggest greater predictability in results. Group ME had the lowest coefficient of variation.

The smallest magnitude of fracture lines was observed in Group ME. And the least number of catastrophic fractures was observed in Group ME. This further suggests that minimal thickness restorations may have more predictable mechanical behavior and fewer catastrophic failures when supported by a substrate with a higher elastic modulus. The observations from this study show a positive pattern suggesting an indication for lithium disilicate crowns to be supported by a material with high elastic modulus (e.g. enamel) to achieve the most predictable results.

B. Implications for Research

In this study, 3M Paradigm MZ100 composite blocks were selected as the first abutment material because it has an elastic modulus of 18GPa,[41,42] which is comparable to human dentin with an elastic modulus of 16-18 GPa.[43] Milling MZ100 composite abutments allowed for minimal defects and voids in the composite compared to traditional methods of packable composites. Lithium disilicate was selected as the second abutment material because it has an elastic modulus of ~95 Gpa[44] which is similar to human enamel with an elastic modulus of ~91 GPa.[45,46] In addition to using CAD/CAM technology to control the material properties; the geometry, dimensions, internal fit, and die space design of all abutments and crowns were standardized, making this study unique.

Previous studies[4,5,32,33,59-61] have investigated fracture loads of monolithic lithium disilicate CAD posterior restorations with various abutment materials, loading techniques, ceramic thicknesses, and cementation methods. Although it is difficult to compare previous studies to the current study due to varying methodologies, most have reported fracture load ranges higher than what was reported in the current study. This may be attributed to anatomical crown designs in some studies with occlusal thicknesses of >1.5mm in cusp areas. Also, some of these studies were investigating fracture strength on titanium abutments, which have an elastic modulus much higher than MZ100 composite.[35,62,63]

Our results justify further *in vitro* investigation with fatigue loading in a simulated oral environment and clinical investigation with well-designed trials. The mean fracture load values in this study ranged from 1228N to 1962N. These *in vitro* findings cannot be directly applied to clinical conditions since load-to-failure testing provides information only at extreme conditions.[6,33] However, all crowns even with minimal thickness of <1mm may have fracture loads high enough to withstand the average maximum posterior biting force of 600-900N in healthy young adults.[55-58] Further in-depth investigation is indicated.

More investigation is needed to determine the true reliability of ultra-thin e.max posterior restorations intra-orally. Although the present study was able to digitally standardize the dimensions and geometries for all crown and abutment materials, limited information for the long-term performance can be provided. The current results can provide information on the initial performance of ultra-thin restorations on differing substrate materials at extreme loading conditions. Additional clinical parameters such as masticatory patterns, occlusal anatomy and antagonist conditions should be considered.

Additional studies incorporating a larger sample size, longer aging periods, fatigue testing, cyclic loading and ultimately controlled clinical trials to evaluate intraoral survival are needed.

C. Limitations

Although previous studies have demonstrated that CAD systems are able to successfully mill ultra-thin restorations,[1,3] we encountered minor chipping of margins in the minimal thickness groups using a three-axis mill. This is consistent with Magne et al 2015, who also experienced minor chipping of ceramic margins when milling ultra-thin feather-edge margins. This may be a limitation of three-axis mills and current material properties. It is anticipated that improvements will be made as the technology advances. Some have increased the bulk in the marginal area as part of the design and milling, with subsequent hand finishing to thin these areas to avoid this chipping.[5]

An additional limitation in this study occurred due to the nature of cross-sectioning specimens. Unfortunately, physically sectioning specimens can introduce smear marks from the sectioning discs and artifacts. Only a snapshot of the fracture in one plane is viewed with each section. Ideally, we could follow the crack propagation in more than just one section at a time for each specimen. In addition, it would have been beneficial and meaningful if we had sectioned every single specimen in this study to truly understand every fracture origination and propagation. Additional data such as cement layer thickness for each specimen could have been gathered by more SEM analysis. Cement void size and distribution would have also been useful data to gather through SEM analysis. Unfortunately, only three specimens were sectioned and analyzed using SEM in this study

due to restrictions in time and resources. Microscopic analysis and documentation of the occlusal surface of every specimen would have also added additional insight to the fracture mechanism of all groups. Surface damage and cone cracks may have contributed to many of the fractures seen in some of the specimens but were not visualized in the limited SEM cross sections available in this study. More complex fracture mechanisms most likely existed in this study but were not recorded.

Even though we attempted to standardized all variables in this study digitally, finger pressure from a single operator was used to cement the crowns onto all the abutments. Variation in pressure of cementation can alter the thickness of cement.[64] Finger pressure even when applied by a single operator is variable.[65] The uniformity of cement film thickness is affected differently every time a variation in pressure is applied during cementation of crowns.[66] The die space was digitally set on 3Shape software on all crown designs for 40 microns with an addition 30-micron occlusal space. However, the actual cement thickness in this study was not completely standardized.[68]

In this study, 3M Paradigm MZ100 composite blocks were selected as the first abutment material because it has an elastic modulus of 18GPa,[41,42] which is comparable to human dentin with an elastic modulus of 16-18 GPa.[43] MZ100 behaves differently than dentin and MZ100 has different bond strengths and material properties. Lithium disilicate was selected as the second abutment material because it has an elastic modulus of ~95 Gpa[44] which is similar to human enamel with an elastic modulus of ~91 GPa.[45,46] Lithium disilicate behaves differently than enamel. Although lithium disilicate can be etched with HF acid, it still has different bond strengths and bond properties compared to real enamel. There are limitations when using simulated tooth substrates. The use of extracted natural

teeth as substrates may provide information more relevant to clinical settings, however it would be extremely difficult to standardize geometry, dimensions, internal fit of all specimens between groups when hand prepping natural teeth.

Another limitation of this study is the load-to-failure design. Load to failure tests do not reproduce what is seen clinically. Tooth to tooth contacts during function cannot be represented by a stainless-steel hemispherical indenter. The fracture to load study design provides information only at extreme loads. However, chewing consists of a high frequency of low cyclic loads. Restorations fail intraorally in a completely wet environment. Whereas in this study, the specimens were loaded to failure in a dry environment. Load to failure testing designs result in fracture loads that are extremely higher than any forces seen intraorally. Significant differences exist between the failure behavior of all ceramic crowns created during fail-to-load studies and what is observed during clinical failure. The *in vitro* load to failure findings in this study cannot be directly applied to clinical conditions.[6,33,67]

V. CONCLUSIONS

This chapter details the work originally published in the *Journal of Prosthodontics* and has been authorized to be used for the purposes of this thesis and oral defense.

Chen SE, Park AC, Wang J, Knoernschild KL, Campbell S, Yang B. Fracture Resistance of Various Thickness e.max CAD Lithium Disilicate Crowns Cemented on Different Supporting Substrates: An In Vitro Study. *Journal of Prosthodontics*. 2019 Dec;28(9):997-1004.

Minimal and traditional thickness e.max crowns demonstrated no significant difference in their fracture resistance. The group with the least catastrophic fractures was the minimal thickness e.max crowns on e.max abutments (enamel analog). Fracture mechanisms of minimal thickness e.max crowns appear to be affected by the elastic modulus of the substrate. Minimal thickness e.max crowns may behave more predictability when compared to traditional thickness restorations as noted by their smaller coefficient of variation. Aging had an effect on the fracture strength of lithium disilicate CAD crowns. Minimal thickness e.max crowns may be a viable restorative option when supported by high elastic modulus substrates such as enamel.

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APPENDIX

Portions of this thesis were previously published as:

Chen SE, Park AC, Wang J, Knoernschild KL, Campbell S, Yang B. Fracture Resistance of Various Thickness e.max CAD Lithium Disilicate Crowns Cemented on Different Supporting Substrates: An In Vitro Study. *Journal of Prosthodontics*. 2019;28(9):997-1004.

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PUBLICATIONS: Chen SE, Park AC, Wang J, Knoernschild KL, Campbell S, Yang B. Fracture Resistance of Various Thickness e.max CAD Lithium Disilicate Crowns Cemented on Different Supporting Substrates: An In Vitro Study. *Journal of Prosthodontics*. 2019;28(9):997-1004.

Chen S, Forman M, Sadow PM, August M. The Diagnostic Accuracy of Incisional Biopsy in the Oral Cavity. *Journal of Oral and Maxillofacial Surgery*. 2016;74(5):959-964.

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