Fracture Resistance of Non-Metallic Molar Crowns Manufactured with CEREC 3D

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A thesis submitted in conformity with the requirements for the degree of Master in Science
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Faculty of Dentistry
University of Toronto

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ABSTRACT

Objectives: To compare fracture strength and fatigue resistance of ceramic (ProCAD, Ivoclar-Vivadent)(C) and resin composite (Paradigm MZ100, 3M/ ESPE)(R) crowns made with CEREC-3D. Methods: A prepared ivorine molar tooth was duplicated to produce 40 identical prepared specimens made of epoxy resin (Viade). Twenty (C) crowns and 20 (R) were cemented to their dies using resin cement. Ten of each group were subjected to compressive loading to fracture. The remaining 10 of each group were subjected to mechanical cyclic loading for 500,000 cycles. The survivors were subjected to compressive loading to fracture. Results: No significant difference in mean fracture load was found between the two materials. However, only 30% of the (C) crowns vs. 100% of the (R) crowns survived the cyclic loading test. Conclusions: (R) crowns demonstrated higher fatigue Resistance than (C) crowns in-vitro and might better resist cracking in-vivo.
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Chapter 1

Introduction

1.1 Background

The need for esthetic restorations has increased tremendously over the past decade. Ceramics have gained large popularity as esthetic restorative materials due to their high esthetic quality [95, 103], wear resistance, durability, color stability [106], and biocompatibility [112, 4]. However, ceramics have several disadvantages including low fracture resistance [28], excessive wear of the opposing teeth [124], the need of more aggressive preparation design [95, 16], technique sensitivity [16], less than ideal marginal adaptation [9], repair difficulty [124], and high cost of fabrication. In ceramics, cracks initiate from defects in the fitted surface of the restoration. Sub-critical crack growth is facilitated in the aqueous environment of the mouth. [31, 32, 123]

The biocompatibility of all-ceramic restorations [112] has elevated the in-
terest in metal-free restorations, especially that metal hypersensitivity has been a concern to some people. Gold allergy, although rare, had been documented in the literature [65]. Population prevalence of metal contact allergy was reported to be 0.78-9.5% for gold [107, 69], 1.6% for silver [63], 9% for cobalt [69], 8.2% for tin [41], 8% for palladium [63], 8% for chromium [102], and 29% for nickel [102]. Namikoshi reported a case that developed a hypersensitivity reaction resulting in lichen planus due to the release of palladium from a dental metal alloy [84]. Contact allergy to metal dental restorations may even be a risk factor for development of intra-oral squamous cell carcinoma [51]. The highest percentage of metal allergic reactions occurred in patients with lichenoid tissue reactions, lichen planus, burning mouth syndrome, stomatitis, gingivitis, and peri-oral dermatitis. [118]

The combination of advancements in dental material, computer technology, and equipments has made it possible to fabricate an indirect esthetic restoration in one appointment. The CAD/CAM CEREC system is used for electronical designing and milling of restorations. Using this system, the dentist can manufacture a restoration without the need for lab assistance and without impressions nor temporary restorations [66]. The restoration can be designed in less than five minutes and then milled in 10 to 12 minutes [119]. Hence, only one appointment is needed to prepare and insert the restoration. After preparing the tooth, the dentist sprays tin oxide powder on the preparation. Then, he/she aligns the intra-oral camera’s angle of vision for the scan along the insertion axis of the preparation while checking the image on
the monitor. After the camera is stabilized, the preparation is scanned and the optical impression is completed. The restoration is designed, milled and polished to prepare it for insertion.

1.2 Porcelain-Fused-to-Metal Restorations

1.2.1 Advantages of Porcelain-Fused-to-Metal Restorations

- Clinically-proven longevity and fracture resistance: fracture rate of porcelain-fused-to-metal crowns and bridges were reported to be as low as 2.3% after 7.5 years. [5]

- Combines the esthetics of porcelain with the strength, marginal adaptation, and accuracy of cast metal restorations. [103]

- More resistant to fracture than conventional all-ceramic crowns. The slight difference in the coefficient of thermal expansion between the metal and ceramic causes the ceramic to undergo residual compressive stresses following the cooling process during crown fabrication. This constant residual compressive stresses resists the tensile stresses the crown is subjected to rendering the crown stronger and more fracture resistant. [6]

- A more conservative preparation provides adequate thickness for porcelain-
fused-to-metal crowns when compared to all-ceramic crowns. [5]

- No wear of ceramic by abrasion or attrition. [5]
- No change of color due to no microleakage between the veneer and the metal. [5]

1.2.2 Limitations of Porcelain-Fused-to-Metal Restorations

- Non-ideal esthetics since:
  - the metal at the gingival margin may cause gingival discoloration [131]
  - the dark metal core may show through in areas with minimal porcelain thickness especially at the gingival third
  - the metal margin may become visible if gingival recession occurs
- Metal hypersensitivity

1.3 History of the CEREC technology

Advances in computer technology have made it possible to develop the CAD/CAM technology (Computer-assisted Design/Computer-aided Manufacturing). The CEREC system (computer-assisted CERamic REConstruction) was the first operational CAD/CAM system to be used in the dental office [49]. The
design was produced by Dr. Brandestini and the software versions were developed by the CEREC teams at Siemens and Sirona (Bensheim, Germany) [78]. In 1980, the basic concept was developed by Mormann (University of Zurich) and Brandestini (Brandestini Instruments, Zurich). Dr. Alain Ferru, a young French software engineer, was approached by Dr. Mormann to design the CEREC software. In 1985, the first chair-side inlay was fabricated using the CEREC I by Mormann and Brandestini (Brains, Zurich). In 1988, onlays and veneers capabilities were added to the unit. Full and partial crowns and copings were made possible by introducing the CEREC 2 in 1994 by Siemens (Munich, Germany). In 2000, the Cerec 3 was introduced and the three dimensional capability was added in 2003. In 2005, the new software enabled the automatic virtual occlusal adjustment. [78]

Several studies criticized the marginal fit of the CEREC restorations [121, 106]. However, the improvement in the CEREC unit and software made it possible to produce more clinically acceptable marginal fit of the milled restorations. [52, 81, 12, 53, 54, 44, 26]

1.3.1 CEREC I

The CEREC I prototype was available in 1983 [78]. The first unit had a water turbine drive. The modified version with E-drive and CEREC Operating System 2.0 was launched in 1991. In this system a ceramic block is fed against a grinding wheel along the mesio-distal axis of the restoration with a different distance from the inlay axis at each feed step [78]. This system was
limited only to inlays, onlays, and veneers [49]. The two dimensional software capability did not provide the restoration with any occlusal anatomy or contact. Hence, the dentist had to carve and finish the restoration’s occlusal anatomy and contacts him/herself after the unit milled the adapted surface of the restoration which made this unit impractical to use. [78]

1.3.2 CEREC II

CEREC II was developed in 1994 to try to overcome the limitations of the CEREC I unit. The team at Siemens (Munich, Germany) added a cylinder diamond to the system which enabled the CEREC II unit to grind full and partial crowns and copings [78]. The display was two-dimensional and the design of the occlusion was introduced in three modes: extrapolation, correlation and function. Bindl and Mormann [15] compared margin adaptation of Vitablocs Mark II partial crowns fabricated with CEREC-I and CEREC-II and found significantly improved margin adaptation for CEREC-II manufactured partial crowns (207 ± 63µm) compared to those manufactured by CEREC-I (308 ± 95µm). Mormann and Schug [82] also compared both systems in regards to precision of fit of the milled restorations. They found a 30% improvement in the accuracy fit of CEREC-II manufactured restorations, with marginal gap of 56±27µm, compared to that of CEREC I, which equals 84 ± 38µm.
1.3.3 CEREC III

The CEREC III was launched in 2000 (Figure 1.1). The system consists of an acquisition unit containing a portable computer, design software and an optical imaging system, and a milling chamber with two diamonds for milling the final restoration from a prefabricated ceramic or composite resin block [38]. The software was upgraded to its three-dimensional capability in 2003. The CEREC-3D software is much easier to handle compared to the previous versions. Automatic virtual occlusal and proximal contact adjustment of a
selected digital full-crown anatomy was added in 2005. This enabled the
dentist to control the vertical dimension of the restoration prior to milling
[37]. In the CEREC III unit, a two-bur system, a cylindrical diamond and
a tapered bur, was introduced instead of the grinding wheel (Figure 1.2).
In 2006, the “step bur”, which has a smaller diameter at the top one-third
of the cylindrical bur, made it possible for the unit to fabricate restorations
with higher precision (Figure 1.3). [78]

The marginal fit of CEREC III milled inlays exceeded that of CEREC II,
although both were within the clinically acceptable range of 50-100 microns.
[30]
1.4 Advantages and Limitations of the CEREC technology

1.4.1 Advantages of the CEREC technology

- CEREC restorations have demonstrated documented clinical success and longevity [90]. Restoration size, tooth vitality, and tooth location did not significantly affect the prognosis. Posselt and Kerschbaum [90] reported a survival probability of 95.5% over 9 years.

- The CAD/CAM blocks are fabricated under optimum controlled conditions. This provides a restoration with higher intrinsic strength eliminating the material variation found in lab-fabricated restorations. [79]

- Utilizing the CAD/CAM technology, the computer controlled fabrica-
tion diminishes the potential inaccuracies resulting from human error and is able to generate a restoration within a clinically acceptable fit of about 50 micrometers as established by the American Dental Association. [30]

- Only one appointment is needed to complete the restoration and hence,
  - the patient is subjected to only one administration of local anesthetic.
  - no need to fabricate a temporary restoration [24], this is an advantage because:
    - the temporary restoration is subject to loss, breakage or leakage which may lead to contamination of the dentinal tubules and/or sensitivity. [119]
    - requires time to fabricate. [119]
    - may be difficult to clean during the temporization period which may lead to gingival irritation. [119]
    - when removing the temporary restoration, pulpal stress may occur as a result of excessive cleaning, drying or trauma. [119]
    - veneer temporaries are time-consuming, difficult to fabricate, and can easily be displaced. [119]
  - Decreased second-appointment set-up costs which is inevitable with conventional laboratory-fabricated restoration, as the patient needs to come back for a separate appointment to insert
the restoration. This leads to fewer instruments needing sterilization, less need for chair time set-up/breakdown, and improved office efficiency. [119]

- Elimination of the cost of some disposable supplies that are needed for conventional restorations such as impression materials, wax, stone, temporary resin material, and temporary cement. [119]

- The clinician has complete control over the final result and esthetics of the restoration since the software delivers a restoration that may only need some characterization by staining or glazing. [119]

- Minimal reported post-operative sensitivity due to: [38]
  
  - use of rubber dam isolation in the clinical trials which ensures a clean, isolated tooth surface for adhesion bonding.

  - insertion of the restoration at the same appointment of the preparation which prevents possible tooth contamination during the temporization phase.

  - the use of factory manufactured composite and ceramic blocks which minimizes the polymerization shrinkage since it is only limited to the resin cement interface.

- No laboratory fee involved. [119]
1.4.2 Limitations of the CEREC technology

- Cost of the equipment, which is approximately $100,000 plus tax, is a factor especially for dentists in solo practices. To overcome this problem, several offices may form a team and use one centrally located CEREC machine. Thus, the cost can be shared among several dentists. [24]

- Color of the finished restoration is not ideal since the restoration is milled from a monochromatic block. However, multicolor blocks have been developed to overcome this limitation. Also, superficial stains can be placed by the dentist to mimic any shade variability of the patient’s tooth, but this requires the acquisition of a glazing oven. [24]

- Significant time is required for the dentist to become proficient enough in use of the system to be financially successful [24]. However, in one study, CEREC 3D was introduced to dental students in their last semester and they were able to produce clinically acceptable inlays with high short-term success rate (2 years). [127]

- A well-trained, dedicated staff is essential for a successful cost-efficient restoration. Staff members could make the restoration after the dentist has prepared the tooth. This saves time which adds to the financial viability of the CEREC technology. [24]

- In severely broken down teeth, it is difficult to digitally capture sub-
gingivally placed margins. Gingival retraction methods are needed in such cases [24]. However, gingival retraction methods are also needed in conventional restorations with sub-gingival margins.

- CAD/CAM technology in the dental office is limited to single units only. A system that can mill several unit restorations is needed to overcome this problem. [24]

- The time needed to fit, polish and insert the CEREC restoration is longer than that needed for a lab manufactured restoration. However, with more experience, the dentist may become faster and more efficient in performing these tasks. [24]

1.5 Materials Used for Chair-side CEREC

For a material to be considered appropriate to be used by the CEREC system it must exhibit the following properties:

- can be milled rapidly. [42]

- can withstand the harshness of the milling process. [34]

- can be easily finished (polished, stained, or glazed). [42]

- provide a clinically acceptable restoration once cemented. [34]
All CEREC blocks have fine particle-sized micro-structure which leads to improved machining damage resistance, faster polishability, improved mechanical properties, and decreased wear of the opposing dentition. [42]

1.5.1 Ceramics

Feldspathic porcelain-based ceramics:

- Vitablocs Mark II (Vita Zahnfabrik, Bad Sackingen, Germany):
  
  - Introduced in 1991. [34]
  
  - Is a fine-grained feldspathic ceramic [34] manufactured using fine-grained powders producing fine crystal, pore-free ceramic which leads to better polishability, lower enamel wear and higher strength [42]. The strength of this ceramic material when polished is approximately 130 MPa and it could reach 160 MPa or higher if glazed. This is about twice as strong as conventional feldspathic ceramics and slightly higher than many pressable ceramics. [101, 43]
  
  - The average particle size is approximately 4µm. [34]
  
  - It can be etched using hydrofluoric acid or abraded with Aluminum Oxide particles creating a retentive surface that provides micro-mechanical retention to the adhesive resin cement. [34]

- CEREC Bloks (Vita Zahnfabrik, Bad Sackingen, Germany).
Leucite-reinforced Ceramics:

- ProCAD (Ivoclar Vivadent, Schaan, Lichtenstein) blocks:
  - Introduced in 1998. [34]
  - They can be etched. [34]
  - A leucite-reinforced ceramic [34] with leucite crystals ranging from 5 to 10 micrometers in size. Strength properties are similar to those of Vitablocs Mark II. [42]

- Empress CAD (Ivoclar Vivadent, Schaan, Lichtenstein) blocks:
  - The new generation of ProCAD

Advantages of Ceramics

- It is possible to produce a ceramic restoration with natural appearance [9] in terms of color, translucency, and surface texture [95, 104] due to the wide range of shades and translucency - opacity combinations that can be customized to each case. The surface can also be characterized by add-on stains for improved shade match to the adjacent tooth. [42]

- Ceramics are inert and highly biocompatible [109, 112] due to their glass-like properties. Dental plaque adherence is minimized when the ceramic restoration is polished and glazed [59]. A supra-gingival or at-the-gingiva margin can produce an esthetically pleasing result with
all-ceramic restorations. This promotes a healthy periodontium since, with these margins, the gingival involvement during tooth preparation, impression, and function is minimized. [59]

- Machined ceramics demonstrated less wear rate when compared to type I gold alloys, base-metal alloys, cobalt chromium alloys and composite resin. [128]

- Ceramics have also shown better color stability compared to composite resin restorations. [106]

**Disadvantages of Ceramics**

- Low tensile strength. [75]

- Higher yield stress response than enamel. [47]

- Crack propagation that may lead to catastrophic fracture [9]. Cracks may initiate from two types of defects: fabrication defects (which are introduced during processing or that exist as micro-structural features) or surface micro-cracks (which are introduced during the machining stage) [96]. The interaction of applied loads with those defects may lead to microscopic damage which may cause restoration failure [28]. Failure can also occur as a result of sub-critical crack growth [31, 32] which is facilitated by the surrounding aqueous environment.

- Excessive brittleness. [75, 98]
• Difficult to repair if fracture occurs. [23, 98]

• Difficult to adjust chair-side. [98]

• Technique sensitivity.

• Require firing for glazing and stain characterization [98]. Glazing is required for ceramics to attain optimum strength. [98]

• Firing shrinkage. [73]

• Wear of opposing natural dentition. [124, 98]

• Inadequate marginal fit which may lead to microleakage [9]. New ceramic formulations and processing techniques were developed to overcome such limitation. Also, the improvement of bonding systems and the use of computed technology have resulted in all-ceramic restorations with improved marginal adaptation and decreased microleakage. The use of resin cement with ceramic restorations demonstrated improved marginal fit and decreased microleakage. [97]

However, dental ceramics have been improved over the past two decades to overcome the fore-mentioned limitations. Among these improved ceramics is the injection molded Empress glass ceramic (Vivident, Schaan, Liechtenstein), a leucite-reinforced material that has improved fracture resistance.
1.5.2 Composite Resin

- Paradigm MZ100 (3M ESPE, St. Paul, Minn.)
  
  - First introduced to the market in 2000. [34]
  - Paradigm MZ100 is a bisphenol A-diglycidyldimethacrylate/triethylene glycol dimethacrylate resin-based composite with filler composed of nanocrystalline zirconia in an amorphous silica matrix [98]. The inorganic filler is radio-opaque and its loading is 85% by weight with mean particle size of 0.6 micrometers. Paradigm MZ100 is a factory processed version of Z100 Restorative (3M ESPE) resin. It has superior physical properties comparing to conventional Z100 resin due to controlled manufacturing conditions which lead to a dense, pore-free material that is completely cured throughout. This processing technique maximizes the degree of cross-linking [34]. The degree of conversion of the methacrylate groups in the Paradigm MZ100 is approximately 84% which is higher than that for Z100 direct restorative composite resin material (74%). This provides both dependable physical properties and sufficient amount of unreacted monomers for bonding. [98]

Advantages of Composite Resin

- According to the manufacturers, a more conservative chamfer or bevel preparation is acceptable with resin compared to ceramics which require
a shoulder or a broad chamfer. [121]

- Easier finishing and polishing than ceramics. [42]

- Can be easily adjusted and/or polished intra-orally. [34]

- Kinder to opposing teeth in regards to wear relative to ceramics. [42, 98]

- Easier to add on adjustments if necessary which is difficult in ceramic restorations [132]. The surface can be air-abraded using $50\mu m$ silicon dioxide particles then bonded to hybrid resin. [34]

- Color characterization can be easily accomplished by internal or external resin tints and color modifiers, which are light-cured rather than oven-fired. [34]

- Using Paradigm MZ100 blocks can elongate the life of the milling diamond and increase the number of composite resin restorations milled by each milling diamond before requiring replacement [34]. Rusin et al [99] observed that ceramic materials required milling diamond replacement at significantly earlier stage than the Paradigm MZ100 material. This leads to reduced operating cost and fewer delays from diamond bur exchange. [99]
1.6 Concerns of the current CEREC materials

1.6.1 Strength

The blocks used for CEREC are fabricated under ideal manufacturing conditions in a reproducible constant manner eliminating human error. This results in a dense, defect-free, high-quality material. On the other hand, conventionally fabricated restorations are made by hand which may introduce human error that could affect its mechanical and esthetic properties. [42]

In one study [117], it was concluded that industrially prepared ceramics are more structurally reliable than conventional lab-fabricated ceramics although CAD-CAM procedures may introduce surface and subsurface flaws that may adversely affect this property. However, the strength can be gained back by polishing using rubber wheels and diamond paste. Further enhancement of strength of about 160 MPa can be acquired using a combination of polishing and glazing. [42]

Attia concluded that the fracture resistance of teeth restored with CEREC manufactured crowns was equivalent to that of unprepared natural teeth, but was significantly higher than that of teeth restored by conventional low-fusing ceramic crowns. [9]
1.6.2 Esthetics

Esthetics have been a concern in CEREC materials due to the monochromatic nature of the blocks. However, the porcelain restoration can be stained and glazed after milling. Color modifiers and internal and external tints can be easily added to composite restorations then cured [34]. Also, the blocks come in a large variety of shades to match the adjacent natural dentition. Vitablocs TriLuxe (Vita Zahnfabrik) contain three shades in a graded variation in which the middle layer has a regular chroma, the top layer has a translucent, low intense chroma, and the lower layer has low translucency and an intense chroma. This makes it possible to imitate the optical characteristics of the natural tooth and hence make the restoration more blendable with the adjacent teeth. [42]

Herrguth et al. conducted a clinical study to compare the esthetics of individually stained CEREC-manufactured crowns to Cergogold crowns (Degussa Dental GmbH, Hanau, Germany) which is fabricated by the layering technique [48]. They concluded that regardless of the type of crown used, the restorations were esthetically acceptable to all patients with no statistically significant difference in the esthetic ratings between the two crowns. In a clinical study of 109 inlays in 46 patients over 7 years, Cerutti et al. [21] reported an initial good shade match of 88 % Alfa which decreased to 62.4 % Alfa and 33 % Bravo after 7 years. Several studies reported that the degree of color mismatch increased over time [76, 39]. In a series of studies by Sjogren et al. [108, 110, 111] of 66 Vitablocs Mark II inlays, the color mismatch
increased from 16% to 38% after 10 years. The observed increase in color mismatch was due to a color change of the tooth rather than the color shift of the milled restoration [39]. In a different clinical study, Fasbinder et al. reported that the color match of Paradigm composite inlays was significantly better than Vitablocs Mark II ceramic inlays at three years. This was due to the fact that composite resin appeared to reflect the surrounding tooth color to a better degree than did the ceramic inlays. [38]

In conclusion, CEREC-manufactured restorations can provide an esthetically acceptable restoration when polished and an esthetically optimum one when stained and glazed. The decrease in color match over time can be attributed to a change in tooth shade and translucency, rather than a change in the color of the CEREC-manufactured restoration. [36]

1.6.3 Post-operative Sensitivity

Significant level of post-operative sensitivity was reported in early clinical studies addressing CEREC-manufactured restorations. Magnuson et al. [67] reported 9% immediate post-operative sensitivity in a study of 301 CEREC-manufactured inlays. Most of these cases involving post-operative sensitivity resolved within one month. However, three cases remained problematic for six months and which necessitated endodontic therapy. In a different study by Sjogren et al. [108], 13.8% of patients with Vitablocs Mark I or II inlays complained of post-operative hypersensitivity. In a three-year clinical study by Fasbinder et al. [40], 13% of 92 Vitablocs Mark II onlays were slightly
sensitive after one week, and 4 % were slightly sensitive in two weeks. All post-operative sensitivity resolved after one month, and no post-operative sensitivity was reported in the three-year period of observation. Otto and De Nisco [87] observed 13 % immediate post-operative sensitivity in 200 CEREC-manufactured inlays that were caused by premature occlusal contact. Out of the 17 cases reported, 12 resolved within three weeks and the rest resolved in seven months. The majority of post-operative sensitivity can be attributed to occlusal interference since the CEREC-manufactured restorations are inserted in a single appointment. Hence, it is advisable to equilibrate the occlusal contacts after the effects of the local anesthetic have worn away. [36]

More recent studies have reported less post operative sensitivity which could be attributed to the significant improvement of the adhesive materials. In a study of 20 CEREC-generated Vitablocs Mark I inlays, Molin and Karlsson reported no post-operative sensitivity throughout the observation period of 5 years [76]. The same results were observed by Heymann et al. in their four-year clinical trial of fifty CEREC-generated inlays [49]. Fasbinder et al. reported only one sensitive restoration at one week in their randomized clinical trial of 80 Vitablocs Mark II and Paradigm inlays. However, it was resolved in two weeks and no sensitivity was reported in the remainder of the observation period of three years. [38]

The lack of significant post-operative sensitivity in CEREC-manufactured restorations can be attributed to several factors. The optical imaging of the
preparation requires careful isolation. This ensures that optimum fluid control is possible which maximizes the adhesive cementation predictability [36]. The fact that CEREC-manufactured restorations eliminate the need of temporization contributes to the lack of post-operative sensitivity, as it prevents the possible contamination of the dentin tubules during the temporization period if the temporary restoration is lost, fractured, or leaked. [38]

### 1.6.4 Margin Adaptation

Nakamura et al. [83] studied the effect of abutment occlusal conversion angle and the computer luting space setting on the internal fit and marginal adaptation of the ceramic CEREC III milled restoration. They found that when the computer luting space was set to 30 to 50 micrometers, the marginal gap ranged from 53 to 67 micrometers and was not influenced by the abutment angle of occlusal conversion. Other researchers measured margins of about 50 micrometers [30, 91] which suggested that the marginal fit of CAD/CAM generated restorations is adequate for clinical use. Denissen et al. [26] reported a margin gap of 85μm for CEREC III manufactured onlays, this is not significantly different from that of the laboratory-fabricated onlays. These recorded gaps are well within the reported maximum clinically accepted gap of 120 μm. [74]

In a study of CEREC-manufactured restorations, Fasbinder reported less detectable margins in resin-based composite inlays (Paradigm) compared to ceramic inlays (Vitablocs Mark II) after 1 year [38]. However, in 3 years, no
significant difference in margin adaptation between the ceramic and resin-based composite inlays was detected. The nature of the tooth antagonist to the restoration did not affect the amount of margin ditching [11]. Posselt and Kerschbaum [90] reported 47.4% of underfilled margins of 44 CEREC I and CEREC II-manufactured restorations after 9 years.

A well-fitting margin is expected to maximize the longevity of a restoration. In almost all the clinical studies of CEREC-manufactured restorations, ditching due to wear of the composite resin cement at the margin was reported. However, this ditching was not associated with margin discoloration or recurrent decay. In a clinical study of 121 Vitablocs Mark II and Dicor inlays cemented with microfill or hybrid resin-based composite luting agent, a linear wear rate was reported in the first year but then it decreased by approximately 50% [54]. They found that the vertical loss of cement at the margin stopped when it reached 50% of the margin width. No microleakage or secondary decay was reported at the margin. Heymann et al. [49] reported an increase in the wear of the adhesive luting agent at the occlusal margin of inlays over the first 3 years, and then a decrease of that wear after 3 years. No enamel or porcelain inlay margin chipping or margin staining was identified as the adhesive cement started to wear. In a study comparing Vitablocs Mark I and Dicor MGC porcelain inlays and P-50 resin-based composite inlays, no significant difference in margin adaptation was reported [44]. No marginal staining or recurrent decay was noted either. In Otto and De Nisco’s study [87], a 74% occurrence of underfilled margins after 10 years
was not associated with clinical failure.

These studies agree to the fact that the margin wear is just a surface phenomenon that is not associated with a deterioration in the adhesive bond to the tooth. Also, the wear tends to localize at the margin of the occlusal surface of the restoration rather than the margins of the proximal surfaces. Microfill resin cements demonstrated better wear pattern compared to hybrid resin cements. [57, 133]

### 1.6.5 Enamel Wear

Enamel wear is always a concern when ceramics are used as a restorative material. Several factors may influence the harshness of ceramics against enamel tooth structure. It is possible to minimize enamel wear by using fine-grained ceramics and by polishing or glazing the ceramic surface [42]. Several studies have demonstrated that the wear of enamel against polished or glazed ceramic restorations was essentially the same of that against enamel [61, 72, 71, 1]. Researchers measured the amount of tooth structure lost when in function with different dental materials and normalized the data relative to enamel versus enamel. They found that Vitablocs Mark II and ProCAD blocks behaved much like enamel, whereas Paradigm MZ100 exhibited slightly higher resin material loss, i.e. gentler on enamel than porcelains. [42]
1.6.6 Longevity

CEREC manufactured restorations have proven their success and longevity through several studies. The first clinical trial was conducted by Mormann et al. [80] who evaluated 94 CEREC I-manufactured Vitablocs Mark I inlays between September 1985 and August 1987 and reported two fractured inlays. This low level of failure was repeatedly reproduced by a large number of clinical studies. Isenberg et al. [54] observed 121 CEREC I-generated inlays and reported a 94.2% success rate over three years. All the fractures of the failed restorations (3 out of 121 inlays) occurred through the occlusal isthmus and the thickness of ceramic at fracture site was less than 2 millimeters. In a clinical study over a 5-year period, Berg and Derand [11] reported 3 fractures in 115 Vitablocs Mark I inlays. A systemic review by Martin and Jedynakiewicz undertook a comprehensive literature search from 1986 to 1997 to identify the survival rate of such restorations and their causes of failure [70]. It determined that the mean survival rate of CEREC manufactured restorations was 97.4% over a period of 4.2 years. Causes of failure included fracture of ceramic, fracture of supporting tooth, post-operative sensitivity, and wear of the adhesive. Vitablocs Mark II was used in most of these clinical studies but ProCAD was used occasionally. Mormann and Schug studied only Vitablocs Mark II and concluded that the success rate was 95% in 5 years [82]. Brauner and Bieniek [18] reported a survival rate of 88% for 238 Vitablocs Mark II inlays after 5.5 years of clinical service of inlays. In a different study, only one Vitabloc Mark II inlay fractured out
of 16 pairs of CAD/CAM inlays during an eight-year period [88]. During the recall period, no tooth fractures were observed. A 90.4% survival rate for 200 Vitabloc Mark II inlays was observed by Otto and De Nisco after 10 years of clinical service of inlays [87]. The failure was caused by ceramic fractures in 8 cases and by tooth fracture in 3 cases. In an in-vivo study, 18 anterior Vitablocs Mark II crowns were compared to 18 anterior Ceramic core (In-Ceram Spinell) crowns. Survival rate was determined to be 91.7% for In-Ceram Spinell and 94.4% for Vitablocs Mark II over 2-5 years without a statistically significant difference [14]. This raised the interest in evaluating monoceramic Vitablocs Mark II crowns clinically as an alternative to ceramic-core crowns. Bindl et al. compared Vitablocs Mark II crowns in regards to type of preparation and tooth type. They classified type of preparation design to classic crown preparation (preparation wall height of at least 3 mm, 6-8 degree taper, and 1-1.2 mm shoulder), reduced crown preparation (preparation wall height less than 3 mm), and endodontic crown preparation (no clinical crown remaining which used only the pulp chamber for retention). In molars, the survival probability was 94.6% in classic crowns, 92.1% in reduced crown, and 87.1% in endodontic crowns. In premolars, the reported survival probability was 97% in classic crowns, 92.9% in reduced crown, and 68.8% in endodontic crowns. A significant difference was found between the premolar classic crown and endodontic crown. The success of the reduced crown was attributed to the use of the adhesive resin. They concluded that CEREC-manufactured restorations had good prognosis for
classic and reduced crowns on both molars and premolars, and endodontic crowns only for molars.

Another study evaluated 2,328 CEREC fabricated ceramic inlays and onlays in 794 patients and the survival rate was found to be 95.5% at 9 years [90]. The majority of failure was caused by inlay fracture, tooth fracture, tooth extraction, and replacement for occlusal reconstruction. In this study, a successful prognosis was not affected by restoration size, tooth vitality, treatment of caries profunda (CP), type of tooth treated, or whether the restoration was placed in the maxilla or mandible. Reiss and Walther published a series of articles on 1,011 CEREC-manufactured inlays and onlays placed between 1987 and 1990 in 299 patients and evaluated them for up to 18 years. They determined a survival probability of 95% after 5 years, 91.6% after 7 years, and 90.0% at 10 years [93, 94, 92]. Prognosis for inlays in premolars (90%) was more favorable than those in molars (80%). The location of the restoration (maxillary or mandibular) and the number of tooth surfaces restored did not significantly influence the survivability of the inlay. Sjogren et al. [108, 110, 111] published 3 reports on 66 Vitablocs Mark II inlays from 1995 to 2004 and determined a survival probability of 89% after 10 years.

This survival rate is comparable to that of conventional IPS-Empress ceramic restorations which was reported in a literature review to range from 96% at 4.5 years to 91% at 7 years for inlays and onlay and to range from 92% to 99% at 3-3.5 years for crowns [29]. In a separate literature review by
Hickel and Manhart, annual failure rates in posterior stress-bearing restorations were reported to be: 0-7% for amalgam restorations, 0-9% for direct composites, 1.4-14.4% for glass ionomers and derivatives, 0-11.8% for composite inlays, 0-7.5% for ceramic restorations, 0-5.9% for cast gold inlays and onlays, and 0-4.4% for CAD/CAM ceramic restorations [50]. While recurrent decay was the primary cause of failure in direct restorations, fracture of the restoration and tooth fracture were the the most frequent causes of failure in indirect restorations.

In a clinical study, resin-based composite CAD/CAM inlays performed as good as porcelain CAD/CAM inlays after three years of clinical observation [38]. Fasbinder et al. also concluded that porcelain fracture was the primary cause of failure for Vitablocs Mark II inlays, as two of the 40 Vitablocs Mark II inlays and none of the Paradigm inlays fractured over the three year period of study.

A low failure rate of CEREC-manufactured restorations was consistently reported in the literature. This documents the reliability and the clinical predictability of such restorations. Similar to conventional ceramic restorations, the primary cause of failure of CEREC-manufactured restorations is ceramic and tooth fractures. [50]
1.7 Effects of porcelain surface pre-treatment and luting cement on bond strength

Different treatments of the adapted surface of the ceramic have been developed to improve the bonding strength to the resin luting cement [55, 77]. This includes mechanical roughening of the ceramic adapted surface with a coarse diamond bur [2], air abrasion using Alumina particles [126], and etching with hydrofluoric acid [114]. Each technique has some limitations. Mechanical roughening could cause ceramic to chip which may affect the fit of the restoration. Hydrofluoric acid is toxic, caustic, and extremely irritable to the skin and lungs. [55]

Following the micro-roughening of the ceramic surface, a silane coupling agent is applied which has bi-functional molecules capable of reacting with both porcelain surface at one end and the resin luting cement at the other end forming a chemical bond [33]. The use of this method has yielded a high fracture resistance comparable to that of porcelain-fused to metal restorations [27, 116, 55, 129, 56]. The fracture resistance is also affected by the fabrication technique, the restoration’s final surface finish, and the type of luting cement used [22, 58]. Chen et al. [22] concluded that oven-glazing of ProCAD crowns resulted in significantly higher strength and higher resistance to cyclic loading than surface polishing.

Resin-based composites are the material of choice for adhesive luting for all-porcelain restorations. Physical properties and wear behavior of fine par-
ticle hybrid-type resin-based composites exceed those of other materials [62]. Enamel and dentin bonding was proven clinically acceptable when utilize multi-step systems with separate primer and bonding agents, as it provides a perfect internal seal with almost no hypersensitivity. [62]
Chapter 2

The Project

2.1 Rationale, Objectives and Hypothesis

2.1.1 Rationale

The demand for esthetic restorations has increased dramatically over the past 2 decades. The development of CAD/CAM technology has made it possible to fabricate an indirect restoration at one appointment while the patient is waiting. Several machinable materials are currently available to be used for the CEREC chair-side restoration manufacturing. The recent introduction of the composite resin blocks to be used for crowns has raised the question for their strength and durability compared to ceramic blocks. The majority of published CAD/CAM-manufactured restorations long-term clinical studies were based on the CEREC I system. Hence, most of them addressed ceramic inlays and onlays only and very few more recent studies focused on crowns
As a result, CEREC manufactured ceramic restorations were heavily studied and their long term failure rate was reported to be low [68, 92, 111, 87, 88]. However, studies addressing CEREC manufactured composite resin restorations are very limited. Hence, it is crucial to test the mechanical properties such as fracture strength and fatigue resistance of these materials \textit{in-vitro} prior to conducting costly \textit{in-vivo} studies.

Although laboratory studies are valuable to test the physical and mechanical properties of the dental material, clinical studies are still mandatory to test the clinical performance of the restoration in its actual setting in the oral environment under normal function.

2.1.2 Objectives

The objectives of this study were:

1. To measure and compare fracture strength of crowns made with two different materials (ProCAD and Paradigm MZ100) utilizing CAD/CAM CEREC-3D technology.

2. To investigate the effects of mechanical cyclic loading on the fatigue resistance and fracture strength of CAD/CAM manufactured ceramic (ProCAD) and composite resin (Paradigm MZ100) crowns.

2.1.3 Hypothesis

The null hypotheses are:
1. There is no difference between the fracture strength of CEREC manufactured ceramic and composite resin crowns.

2. Cyclic loading has no effect on fracture strength of crowns made with the two different materials (ceramic and composite resin).

3. There is no difference in fatigue resistance between CEREC manufactured ceramic and composite resin crowns.

2.2 Materials and Methods

2.2.1 Sample Size Calculation

Using the following formula \([86]\), the sample size was calculated at \((\alpha = 0.05)\) and \((\beta = 0.1)\):

\[
n = 2[(Z_\alpha + Z_\beta)\delta/\Delta]^2
\]

where:

- \(n\) = sample size per group
- \(Z_\alpha\) = standard score (\(Z\) value) corresponding to alpha error
- \(Z_\beta\) = standard score (\(Z\) value) corresponding to beta error
- \(\delta\) = common standard deviation for both populations
- \(\Delta\) = difference in the mean that is considered to be clinically significant

The values used for sample size calculation were based on a similar previous study [130] where the mean fracture strength of Vitabloc Mark II crowns
was $1272.65 \pm 109.06$. A difference of 15% was set arbitrary for the difference in mean between the samples to be considered clinically significant.

$$n = \frac{2[(1.96 + 1.28) / (109.06/1.15(1272.65) - 1272.65)]^2}{6.85} = 6.85 \text{ (7 samples per group)}$$

Several studies comparing fracture strength of different materials used a sample size of 8-10 per group [130, 10, 9]. Hence, we selected $n = 10$ for the sample size of our study.

### 2.2.2 Preparation

An artificial ivorine mandibular molar replica was prepared to receive an all-ceramic crown following the preparation guidelines suggested for the CEREC 3D system [35]. The tooth received a reduction of 2 mm of the functional cusp and 1.5 mm of the non-functional cusp. Minimal axial reduction was 1.2 mm and the gingival margin was a circumferential shoulder of at least 1 mm width. The lingual and facial surfaces were prepared in two planes and all line angles were rounded to decrease stress concentration. The angle of convergence was 12°. The prepared tooth replica was duplicated to form 40 replicas fabricated from highly filled epoxy resin material (Viade Products Inc., Camarillo, California, USA) (Figure 2.1). This material has a modulus of elasticity equivalent to that of human dentin (12.9 GPa) and responds to 34% phosphoric acid etching by forming micro-roughness for bonding [85].

Using a caliper, the replicas’ dimensions were measured occluso-gingivally, facio-lingually, and mesio-distally to verify accuracy of reproduction (Table
Table 2.1: Epoxy resin die replicas dimensions

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Mesio-distal Dimensions (mm)</th>
<th>Bucco-lingual Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical Occlusal</td>
<td>6.88 6.34</td>
<td>7.51 6.89</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.02 0.01</td>
<td>0.02 0.01</td>
</tr>
</tbody>
</table>

2.1. The CEREC 3D system (Sirona Dental Systems GmbH, Bensheim, Germany) was utilized to fabricate the crowns from two different materials: ProCAD (Ivoclar/Vivadent) and Paradigm MZ100 blocks (3M/ESPE). A complete CEREC 3D system is available on site of the research laboratory.

2.2.3 Optical Impression and Restoration Designing

The Prepared teeth replicas were inserted into a dentoform with mesial and distal adjacent ivorine teeth in place. Both the prepared and adjacent teeth were covered by CEREC Imaging Liquid (Ploysorbate liquid; Vita Zahndfabrik, Bad Sackingen, Germany) to create a sticky surface. Then, the teeth surface was covered with a uniform thin layer of optical reflective powder (Ti-
tanium dioxide; Vita Zahnfabrik, Bad Sackingen, Germany). The CEREC 3D intra-oral camera was used to capture optical impressions of the prepared teeth replicas. An artificial ivorine unprepared mandibular molar was inserted in a dentoform with adjacent teeth and a preoperative occlusal impression was captured. CEREC 3D (Serial number 04996) and CEREC 3D software V3.10 (Sirona Dental Systems GmbH, Bensheim, Germany) were used to design the crown utilizing the correlation mode and the crown copings.

### 2.2.4 Crown Fabrication

In this experiment, 20 ProCAD blocks and 20 Paradigm MZ100, shade A 3.5- Vitapan, 14 mm long were used to fabricate monolithic crowns (Figure 2.2 and Figure 2.3). According to manufacturer’s instructions, burs were replaced after milling each 20 crowns. The Paradigm MZ100 crowns were polished using polishing discs and points. The ProCad crowns were glazed using IPS Empress Universal Glaze Paste (Ivoclar/Vivadent) (Figure 2.4) (Table 2.2 and Table 2.3). Manufacturer’s instructions were followed for the firing cycle. We first pre-dried the crown at $600^\circ C$ for 6 minutes, then increased the temperature at a rate of $58^\circ C/min$ to $950^\circ C$ and held it for 1 minute.
Figure 2.2: Paradigm MZ100 bloc in the milling chamber prior milling

Table 2.2: Physical Properties of some of the materials used in this study (Manufacturer’s Data)

<table>
<thead>
<tr>
<th>Material</th>
<th>Basic Chemical Structure</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Flexural Strength (MPa)</th>
<th>Fracture Toughness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paradigm MZ100</td>
<td>Resin Composite with 85 wt% ultrafine zirconia-silica ceramic particles (0.6 µm), cured</td>
<td>15-20 (more flexible more resilient)</td>
<td>140-160</td>
<td>1.35</td>
</tr>
<tr>
<td>Panavia F 2.0</td>
<td>Adhesive resin cement</td>
<td>9.6</td>
<td>79</td>
<td>-</td>
</tr>
<tr>
<td>Epoxy Resin dies</td>
<td></td>
<td>12.9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 2.3: Paradigm MZ100 crown during milling.

Figure 2.4: Different views of the resulting Composite Resin and Ceramic crowns.
Table 2.3: The composition of some of the materials used in this study (Manufacturer’s Data)

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paradigm MZ100</td>
<td>Polymer matrix of bisGMA (Bisphenol A diglycidyl ether dimethacrylate) and TEGDMA (tri[ethylene glycol] dimethacrylate), Ultrafine zirconia-silica ceramic particles (0.6 µm)(85%)</td>
</tr>
<tr>
<td>ProCAD</td>
<td>Silicon dioxide (SiO₂) (59-63%), Aluminum oxide (Al₂O₃) (16-20%), Potassium oxide (K₂O) (10-14%), Sodium oxide (Na₂O) (3.5-6.5%), Boron oxide (B₂O₃) (0-1.0%), Barium oxide (BaO) (0-1.5%), Calcium oxide (CaO) (0.5-2.5%), Cesium oxide (CeO₂) (0-1.0%), Titanium oxide (TiO₂) (0-0.5%), Pigments (0.2-1.0%)</td>
</tr>
</tbody>
</table>

2.2.5 Cementation

Prior to cementation, each crown was placed in its respective tooth replica to check for fit accuracy. A dental probe with 50 µm tip size was used to check the marginal fit and any crown with a margin gap exceeding 50 µm would have been excluded and remade [62]. No crowns were excluded in this study. The internal surfaces of the ceramic crowns were treated with 9.6% hydrofluoric acid etching gel (Pulpdent Corporation, Watertown, MA, USA) for 2 minutes [17]. The internal surfaces of the composite resin crowns were sandblasted with 50 µm Aluminum oxide particles at 0.20 MPa pressure for 5 seconds [8]. The etched/sandblasted internal surface was rinsed with water spray followed by 60 seconds of ultrasonic cleaning in distilled water (Figure 2.5). Finally, it was dried using oil-free compressed air [8]. A silane coupling agent (Silane, Pulpdent, Watertown, MA, USA) and resin cement containing adhesive phosphate monomer (Clearfil SE bond, Kuraray Medical Inc., Okayama, Japan) were applied to the cleaned internal surface of each
crown and air dried (according to manufacturer’s recommendation).

The surfaces of teeth replicas were etched using 40% phosphoric acid (3M/ESPE) for 1 minute, rinsed, and dried using oil-free compressed air [130]. All crowns were cemented with dual-cured resin cement (Panavia F 2.0; Kuraray) (Figure 2.6 ) according to manufacturer’s recommendations. Equal amounts of ED Primer A&B were mixed and evenly applied to the tooth surfaces of the replicas for 30 seconds then gently dried with compressed air. This initiates the set of the cement. Equal amounts of paste A and B were expressed from the syringe, mixed for 20 seconds, and then applied to the internal surface of the crowns (Table 2.4 ). The crowns were inserted in their corresponding replicas under static pressure of 2.2 kg for 5 minutes.
Figure 2.6: Panavia F 2.0 Dual Cure Dental Adhesive Cement (Kuraray Medical Inc.).

Table 2.4: Materials used in this study

<table>
<thead>
<tr>
<th>Material</th>
<th>Manufacturer</th>
<th>LOT number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paradigm MZ100</td>
<td>3M ESPE, St. Paul, MN, USA</td>
<td>20060718</td>
</tr>
<tr>
<td>ProCAD</td>
<td>Ivoclar Vivadent, Schaan, Liechtenstein</td>
<td>J01294</td>
</tr>
<tr>
<td>Panavia F 2.0</td>
<td>Kuraray Medical Inc., Okayama, Japan</td>
<td>51249</td>
</tr>
<tr>
<td>IPS Empress (Glaze and stain liquid)</td>
<td>Ivoclar Vivadent, Schaan, Liechtenstein</td>
<td>J06718</td>
</tr>
<tr>
<td>Clearfil SE Bond</td>
<td>Kuraray Medical Inc., Okayama, Japan</td>
<td>00719A</td>
</tr>
<tr>
<td>Silane (Porcelain repair kit)</td>
<td>Pulpdent Corporation, Watertown, MA, USA</td>
<td>070516</td>
</tr>
<tr>
<td>9.6% HF Etch Gel (Porcelain repair kit)</td>
<td>Pulpdent Corporation, Watertown, MA, USA</td>
<td>070516</td>
</tr>
</tbody>
</table>
The extruded excess cement was removed and each surface (Buccal, Lingual, and occlusal) was light-cured (Optilux 501, Kerr Demetron, Danbury, CT, USA) for 40 seconds. A layer of Oxyguard II was applied to the margins for 3 minutes according to the manufacturer’s instructions. Using a caliper, the occluso-apical distance of each tooth was recorded before and after cementation to verify the degree of seating (Figure 2.8). Any tooth with more than 50 µm increase in that dimension as a result of cementation would have been excluded and remade [130]. No crowns were excluded in this study due to seating error. One hour following cementation, the crowns were stored in distilled water at a temperature of 37°C for 1 week (Figure 2.9, Figure 2.10, and Figure 2.11). [10]

2.2.6 Cyclic Fatigue and Fracture Test

Each group of 20 crowns was randomly divided into two equal groups. One half was loaded in the Instron machine (Instron, Canton, Mass), a hydraulic driven universal testing machine, using a cross head speed of 1 mm/min (Figure 2.12). The load was applied along the long axis of the replicas with hardened steel bar centered in the central groove (Figure 2.13). The other half was subjected to mechanical cyclic loading in distilled water at room temperature. The cyclic load ranged from 50 N to 600 N for 500,000 cycles at a frequency of 20 Hz (Figure 2.14). The Instron machine was adjusted to stop if the deformation increased to more than 0.15 mm during the mechanical cyclic loading. Those crowns that did not fracture during the
Figure 2.7: Crowns inserted in their corresponding replicas under static pressure of 2.2 kg.
cyclic loading were fractured according to the load-to-failure parameters.

2.2.7 Statistical Analysis

Mean direct fracture load was analyzed using Wilcoxon rank sum test (less sensitive to non-normal data compared to Student’s T test). Failure during cyclic loading was tested with the log-rank test for comparing Kaplan-Meier survival curves. All statistical tests were two-tailed and the level of significance was set at alpha=0.05. The estimate power of this study was 96% based on a 15% effect size between materials. All tests were performed using the R statistical package (www.r-project.org).
Figure 2.9: Composite Resin (Paradigm MZ100) specimens.
Figure 2.10: Ceramic (ProCAD) specimens.
Figure 2.11: Comparison between the resulting Composite Resin and the ceramic crowns.

2.3 Results

2.3.1 Direct Loading Fracture Test Results

During the direct loading fracture test, all crowns exhibited catastrophic fracture in the buccal-lingual plane direction (Figure 2.15). The proximal half of each crown was retained by the adhesive cement while the other proximal half was completely dislodged. In one ceramic specimen, the crown fractured in half while both parts were still retained by the adhesive cement which caused the tooth replica to split down the middle (Figure 2.16).

The mean fracture loads for the composite resin and the ceramic crowns in N were $1,078.64 \pm 283.36$ and $972.28 \pm 256.33$, respectively. No statistically significant difference in mean fracture load was found between the two materials by Wilcoxon rank sum test ($p = 0.42$). Figure 2.17 summarizes the
Figure 2.12: The Instron machine was used to apply load on the crowns.
Figure 2.13: The load was applied along the long axis of the replicas with a hardened steel bar centered at the central groove.
Figure 2.14: Mechanical Cyclic Loading Machine.
Figure 2.15: Fracture patterns following the direct fracture test.

Figure 2.16: Fracture Pattern of one of the Ceramic Crowns where the crown remained cemented and the tooth replica was split in half.
Figure 2.17: Box-plot of Fracture load test before and after cyclic loading (fatigue).

**Non-fatigued**

- Paradigm MZ100
  - ProCAD
- n=10
- p=0.42

**Fatigued**

- Paradigm MZ100
  - ProCAD
- n=9
- n=3
Table 2.5: Changes in the fatigued crowns

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>No evidence of fracture and/or cracks</th>
<th>Fractured</th>
<th>Cracked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paradigm MZ100 (fatigued)</td>
<td>10</td>
<td>10 (100%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ProCAD (fatigued)</td>
<td>10</td>
<td>0</td>
<td>7</td>
<td>3</td>
</tr>
</tbody>
</table>

results in graphical format. Since no statistically significant difference was found between the non-fatigued fracture strength of the two materials, the first null hypothesis cannot be rejected.

### 2.3.2 Compressive Cyclic Loading Test Results

All the composite resin crowns survived the compressive cyclic loading test. However, only 30% of the ceramic crowns survived that test (Table 2.5). The ceramic crowns fractured at a mean of 61,103 cycles which is equivalent to 1.2 years of function (Figure 2.18). The difference in survival of the two materials was statistically significant, $p=0.0012$. Visible cracks were evident on those 3 surviving ceramic crowns. The cracks started to spontaneously propagate following the compressive cyclic loading test and during the following loading fracture test.

Following the compressive cyclic loading test, the mean fracture load for the composite resin crowns was $1,517.56 \pm 231.21$ N. The mean fracture load for the remaining 3 ceramic crowns was found to be $1,023.33 \pm 271.56$ N (Table 2.6).

The fracture strength of the composite resin crown specimens has signif-
Figure 2.18: Kaplan Meier survival curves of failure during cyclic loading (fatigue) test of Paradigm MZ100 and ProCAD.

Log-rank test p-value = 0.0012

Table 2.6: Fracture loads (in N) of the four test groups

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Median</th>
<th>Mean</th>
<th>SD</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paradigm MZ100 (Not fatigued)</td>
<td>10</td>
<td>990.6</td>
<td>1078.6</td>
<td>283.36</td>
<td>1581</td>
<td>702.4</td>
</tr>
<tr>
<td>ProCAD (Not fatigued)</td>
<td>10</td>
<td>955.7</td>
<td>972.3</td>
<td>256.33</td>
<td>1414</td>
<td>595.4</td>
</tr>
<tr>
<td>Paradigm MZ100 (fatigued)</td>
<td>9</td>
<td>1508</td>
<td>1517.56</td>
<td>231.21</td>
<td>1840</td>
<td>1174</td>
</tr>
<tr>
<td>ProCAD (fatigued) *</td>
<td>3</td>
<td>1017</td>
<td>1023.33</td>
<td>271.56</td>
<td>1298</td>
<td>755</td>
</tr>
</tbody>
</table>

* Crowns that fractured during the cyclic loading (fatigue) test were omitted.
icantly increased following the compressive cyclic loading while the fracture strength of the three surviving ceramic crown specimens demonstrated no statistically significant difference to the non-fatigued specimens. Theoretically, this leads to the rejection of the second null hypothesis for the composite resin crown specimens. The second null hypothesis cannot be rejected for the ceramic crown specimens. However, these results should be interpreted cautiously since the conditions of the specimens were not standardized between pre- and post-fatiguing. While the specimens used for direct loading fracture test were tested one week following cementation, those specimens used for the compressive cyclic loading test were tested 3 to 4 months following cementation. In addition, the three surviving fatigued-ceramic crown specimens demonstrated visible cracks prior the fracture test. This may have resulted in inaccuracy of the second fracture test values. Since the difference in survival of the ceramic and composite resin materials was statistically significant, the third null hypothesis can be rejected.

2.4 Discussion

2.4.1 Significance of this research

Improvement in adhesive dentistry has made it possible for all-ceramic restorations to be clinically successful. This encouraged the development of new restorative materials to be used for anterior and posterior crowns, such as ceramic and composite resin blocks that are used with CAD/CAM technol-
ogy. Although these blocks have been improving throughout the past several years, a major disadvantage in this system is the adaptation of the restoration and the surface smoothness following the milling procedure which may lead to failure due to crack propagation and/or poor marginal adaptation. However, we believe that the new CEREC 3D software will prevent or minimize such problems.

This study provides essential information regarding the in-vitro survival of all-ceramic and composite crowns manufactured by CEREC 3D. The most promising material will be selected for subsequent clinical trial supported by industry and/or external funding agencies.

2.4.2 Fracture strength and fatigue resistance of Paradigm MZ100

Since the introduction of composite resin blocks to be used for CEREC-3D full-coverage crowns was fairly recent, studies addressing fracture strength and fatigue resistance of composite resin crowns are very limited. For composite resin crowns, Attia et al. [8] reported that the fracture load in N for Paradigm MZ100 crowns was of 827.1 (86.3), 914.7 (131.7), and 955.9 (130.6) when used zinc phosphate, Fuji CEM, and RelyX ARC, respectively. After subjecting his crowns to 3500 thermal cycles (58°C/4°C) and 600,000 masticatory cycles at 1.2 Hz ranging from 0 N to 49 N, the resulting fracture loads in N of those fatigued composite resin crowns were reported to
be 772.3 (134.7), 923.6 (153.5), and 929.1 (148.5) when used zinc phosphate, Fuji CEM, and RelyX ARC, respectively.

Tsitrou et al. [120] reported a fracture load of 1682 N (315 N) for Paradigm MZ100 composite resin crowns and a fracture load of 1751 N (338 N) for minimally prepared composite resin crowns. Tyan et al. [122] found that the fracture load for composite resin crowns was 2251N (714N) and the fatigued fracture load of those crowns was 1464 N (266 N). In a different study [3], the mean fracture load for Paradigm MZ100 composite resin crowns without fatigue and with 50,000 load cycles was stated to be 1680 N and 1330 N, respectively. In this study, the mean fracture load for of Paradigm MZ100 crowns was 1,078.64 N (283.36 N) which falls within the reported range of the mean fracture strengths (827.1 N to 2251 N).

All of the Paradigm MZ100 crowns subjected to cyclic loading survived the test without any evidence of cracking. None of the previous limited studies reported any failure with Paradigm MZ100 crowns during cyclic loading testing [8, 120, 122, 3]. However, the testing criteria in this study have subjected the specimens to the most extreme testing conditions among the previously reported studies.

The mean fracture load of the fatigued composite resin crowns was found to be 1517.56 N (231.21 N). Most of the literature has reported a decrease in fracture loads following the cyclic loading test [3, 8]. However, these studies used different cements than the one used in this study under different cyclic loading conditions. Attia and Kern [10] found that cyclic loading did not
decrease the median fracture load of crowns cemented with Panavia F. In our study, the mean fracture load increased significantly \((p = 0.003)\). This can be attributed to one or more of the following:

- The cyclic loading test high frequency (20 Hz) and load generated high temperature that caused a higher degree of conversion in the resin cement and hence a more complete resin cure. However, the test was conducted under water which would have acted as coolant and prevented temperature rise.

- The specimens that received cyclic compressive loading were stored for 3 months in water prior testing due to unavailability of the Instron machine for that period. This may have provided the resin cement with more time to fully mature.

- The operator who conducted the direct fracture test is different than that who performed the cyclic loading and the following fracture test. Inter-operator variability may have contributed to such results.

### 2.4.3 Fracture strength and fatigue resistance of Pro-CAD

Attia and Kern [9] measured fracture load of ProCAD crowns to be 715.9 N (105.2 N) when used hydrofluoric acid etching and silane coupling agent (Mirage ABC silane); and 708.4 N (108.7 N) when used phosphoric acid cleaning and Porcelain Liner-M primer. In a different study, Attia and Kern [10]
recorded the fracture resistance of ProCAD crowns cemented with Panavia F to be 960.2 N (211.8 N) and 809.2 N (96.4 N) without and with cyclic loading, respectively. No statistically significant difference was found between the non-fatigued and fatigued ProCAD crowns when Panavia F was used for cementation. Chen et al. [22] reported a fracture load of 2120 N (231 N) and 2254 N (186 N) for polished and oven glazed ProCAD crowns, respectively. For the fatigued ProCAD crowns, Chen et al. reported a fracture load of 1613 (296) N and 2033 (413) N for polished and oven glazed crowns, respectively. They found that prior cyclic loading decreased the fracture resistance of all tested crowns significantly. They also concluded that oven-glazing ProCAD crowns improved their strength and fatigue properties significantly. Stappert et al. [115] studied partial coverage ProCAD crowns and recorded a mean fracture strength of 2134 N (333 N) after subjecting all of the crowns to a load of 49 N for 1.2 million masticatory cycles at 1.2 Hz. All of their Pro-CAD specimens survived mastication simulation. Tyan et al. [122] reported an initial load of 1250 N (255 N) and a fatigue load of 798 N (178 N) for ProCAD crowns. Those crowns were subjected to 10,000 fatigue cycles with a load that varied between the selected maximum value (40% of minimum fracture load = 500 N) and a minimum value of about 1/3 of the maximum load (166 N).

The recorded fracture resistance in this study for the ProCAD crowns was 972.28 (256.33) N which falls within the literature reported means range (715.9 N to 2254 N). The variability in the reported fracture loads can be
attributed to the use of different cements, bonding techniques, abutment types, and testing modalities.

As opposed to the previous studies that reported no ProCAD crown failure during the cyclic loading test, we experienced catastrophic fracture of 70% and cracking of the remaining 30% of our ProCAD specimens. While most of the previous studies [9, 10, 115] used a load of 0-49 N during the compressive cyclic loading test, our study used a range of 50-600 N when fatiguing the specimens. This load falls into the highest range of forces that crowns might be subjected to in the molar area [7]. For a given material, the failure load vs. the no. of cycles required to fracture that material is represented in the following graph (Figure 2.19). If the load applied during the cyclic loading test is too low, the crown may never undergo failure as the number of cycles required for the crown to break reaches infinity. In those fore-mentioned studies, a maximum load of 49 N might have been too low to cause any catastrophic fracture. Tyan [122] used a cyclic load that is 13.3-40% of the minimal load to fracture which corresponds to 166-500 N. However, the number of cycles used was only 10,000 cycle which is 2% of the number of cycles used in this study and believed to be too low to cause any catastrophic fracture of the restorations.
Figure 2.19: Number of cycles required for restoration failure graph.
2.4.4 Fracture strength and fatigue resistance comparison

In our study, Paradigm MZ100 crowns performed as well as ProCAD crowns when subjected to direct fracture loads. There was no significant difference between both crowns in terms of direct fracture strength. All of the previous studies comparing Paradigm MZ100 crowns to CEREC manufactured ceramic crowns have reported no significant difference between the mean fracture loads of both crown systems without cyclic loading [8, 122]. Similarly, the previous studies have reported no failure of composite resin crowns when subjected to compressive cyclic loading. This is consistent with the findings of this study.

Although most clinicians assume that all-ceramic crowns have better mechanical properties when compared to composite resin crowns, we reported no significant difference in the mean direct fracture loads of Paradigm MZ100 and ProCAD crowns. This may be attributed to the optimized manufacturing conditions that CAD-CAM materials undergo eliminating the risk of voids and volume defects [10, 9]. It may also be due to the fact that composite resin crowns have improved elastic properties when compared to all ceramic crowns [64]. As a result, during the process of loading, the composite resin crowns may exhibit higher resiliency with more absorption of load, and thus, the fracture load is increased [8]. Most published literature comparing composite resin to ceramic various restorations reported similar findings.
Gracis et al. [45] concluded that composite resin reduced the impact forces by 57% more than porcelain.

All of our composite resin crowns survived the rigorous compressive cyclic loading test while only 30% of the ceramic crowns survived the test. The surviving 30% ceramic crowns demonstrated visible cracks. When the milled surfaces of the crowns were examined under 500 X magnification with the Scanning Electron Microscope (SEM), a difference in the pattern of material removal was observed. In the composite resin specimen, fine grooves can be seen on the milled surface indicating a plastic deformation mechanism of material removal (Figure 2.20). However, ceramic specimens demonstrated a surface typical of fracture mechanism material removal (Figure 2.21). The 3M Paradigm MZ100 technical product profile reported similar findings. When the margins of milled crowns examined under 60 X SEM magnification, the same broad contours and peaks can be seen in both crown types which is reflective of the margins shape. However, the margin edge appears more sharply defined in the Paradigm MZ100 crown compared to the ProCAD crown which also show chipping (Figure 2.22). While large milling grooves matching the outer shape of the cutting bur can be seen in both, smaller grooves corresponding to individual diamond grains can only be seen on the Paradigm MZ100 material.

The fracture mechanism of material removal in the ProCAD crowns may have introduced micro-cracks in the material during milling. Cyclic loading, especially under wet conditions, results in propagation of micro-cracks that
Figure 2.20: SEM (500 X) image of milled surface of the Paradigm MZ100 crown showing fine grooves which is indicative of a plastic deformation mechanism of material removal.
Figure 2.21: SEM (500 X) image of the milled surface of the ceramic crown showing a fracture mechanism of material removal.

Figure 2.22: SEM (60 X) comparison between the margin edge of the composite resin vs. the ceramic crown.
may have initiated from the milling process. These cracks propagate to form an advancing fissure that weakens the crown [22, 113] and hence leads to catastrophic fracture during cyclic loading.

In addition, Zohairy et al. [132] stated that “CAD/CAM restorations fabricated from resin blocks may have advantage over ceramic blocks with regards to the higher bond strength with resin cements”. This stronger bond strength of composite resin crowns may have contributed to the survival of those crowns when underwent the compressive cyclic loading test.

2.4.5 Clinical relevance of study design

In an *in-vitro* study, it is crucial to mimic the actual oral conditions as closely as possible since this will affect the performance and the outcome of the tested material. The tested *in-vitro* crowns should ideally be subjected to the same forces and force vectors along with thermal changes, the aqueous environment and pH variations that a crown may undergo during its clinical function. Hence, the crown should be tested in an environment that is clinically relevant. [8]

In our study, the master die was prepared according to the CEREC 3D recommendation to receive an all-ceramic crown. This preparation was duplicated using epoxy resin material which has a modulus of elasticity similar to that of dentin (12.9 MPa) and responds to 34% phosphoric acid etching by forming micro-roughness for bonding. An artificial material was used instead of natural tooth to standardize the preparation dimensions since dif-
ferent preparation criteria, such as position of finish line and the amount of tooth structure removed, may influence the fracture load of these non-metallic crowns [8]. This enabled us to compare the different crown materials fracture loads and fatigue resistance while keeping the shape/size variability associated with natural teeth constant. When the dimensions of the epoxy resin dies were measured, a low standard deviation of 10-20 µm was recorded (Table 2.1). A pilot study conducted by Zahran et al. [130] concluded that these epoxy resin dies were susceptible to phosphoric acid-etching and that they bonded well to resin cements. Hence, the risk of these epoxy resin die replicas not bonding to the adhesive resin cement is minimized.

In this study, the crowns were fabricated according to manufacturer’s instructions as in the clinical situation to produce optimum results. The Paradigm MZ100 and the ProCAD crowns’ dimensions were standardized by using the same preoperative optical impression to mill them. The Paradigm MZ100 crowns were polished and the ProCAD crowns were glazed to produce maximum strength according to manufacturer’s recommendation.

It was crucial in this study to obtain an optimum bond between the crown material and the adhesive resin cement to ensure that any differences in fracture strength or fatigue resistance reported in this study were not due to the cementation technique used. The fitted surfaces of the Paradigm MZ100 crowns were sandblasted using \( \text{Al}_2\text{O}_3 \) particles and the fitted surfaces of the ProCAD crowns were etched. Both crown materials were treated with a silane coupling agent (Silane, Pulpdent, Watertown, MA, USA) and resin
cement containing adhesive phosphate monomer (Clearfil SE bond, Kuraray Medical Inc., Okayama, Japan). All crowns were cemented with the same dual-curing phosphate-modified resin cement Panavia F 2.0. No failure was noted to occur between the cement and the crown material.

In the oral environment, non-metallic crowns fail as a result of slow crack propagation that occurs due to fatigue under masticatory stress in a wet environment. The crown specimens in this study were fatigued using a maximum load of 600 N which corresponds to a high level of force a crown might be subjected to in the posterior region. It was reported that the mean masticatory forces during mastication and swallowing in humans to be approximately 40 N. However, the mean maximum posterior masticatory forces may vary from 150 N to 665 N [129, 8]. In our study, the crowns were loaded for 500,000 cycles which represents 10 years of clinical normal mastication function [125], or about half a year of continuous bruxism as suggested by Kelly. [58]

The crack propagation in the oral cavity is accelerated by the presence of saliva. All the compressive cyclic loading in this study was performed in wet environment to simulate the hydrolytic effect of saliva on the crown material “static fatigue: a stress-dependent chemical reaction between water and surface flaws that causes the flaws to grow to a critical dimension, allowing spontaneous crack propagation”. [10, 58]

Kelly [58] recommended several criteria for in-vitro failure testing for all-ceramic crowns to be clinically relevant. Some of these recommendations were followed in this study which includes using die material with elastic
modulus equivalent to that of dentin, preparing the dies according to clinical recommendations, using crowns with dimensions similar to the clinical situation, and using a reliable, commonly used luting cement.

2.4.6 Limitations of study design

1. Teeth replicas were used instead of natural teeth to allow for standardizing teeth sizes, preparation design, and different factors affecting the dentin modulus of elasticity. The dissimilarity in the coefficient of thermal expansion between the teeth replicas and the monolithic crowns prevented thermocycling of the non-metallic crowns. In addition, epoxy resin is not identical to dentine in terms of cellular structure, bonding mechanism to the adhesive resin, and its physical and mechanical properties.

2. In this study, all the forces during the cyclic loading were applied along the vertical axes of the teeth replicas while ignoring all the other force directions due to limitations in the loading machine. Crowns are subjected to non-axial forces that is caused by the elliptical jaw movement and the teeth contact on the cusps’ inclines in the clinical environment [46]. However, the majority of masticatory forces are vertical along the long axis of the teeth in the molar area [46]. Due to the large damage inflicted by the lateral forces [100], the clinical implication of the results of this in-vitro study should be limited only to the vertical loading
3. During the cyclic loading test, the use of high frequency of (20 Hz) compared to a more clinically relevant frequency of (1-2 Hz) was inevitable due to budget limitations. This high frequency may have lead to more heat generation and may have not provided enough time for stress relaxation. In a study by Kelly et al. [60], a frequency of 20 Hz was used for cyclic loading of leucite-reinforced all-ceramic crowns using a staircase approach for loads between 200-800 N with a 100 N step size for 1,000,000 cycles in water. They were able to record fracture loads within reasonable clinical relevance. The high frequency used in this study should not be a concern when comparing the two tested material since both materials were fatigued under identical testing conditions.

4. The use of a stainless steel rounded tip rod would have increased the contact pressure in the crown specimen compared to the clinical contact pressure. This contact pressure is affected by the ratio of the elastic modulus of the ceramic to that of the loading steel rod, and by the radius of the tip of that steel rod. To overcome such limitation, we could have used a loading ball with a modulus of elasticity lower than that of the stainless steel rod to get a clinically relevant contact pressure. However, the increase in the contact pressure due to using the stainless steel rod with high modulus of elasticity and small diameter was applied to both crown material specimens and should not alter the comparison
between them.

5. It is expected that crack initiation occurs at lower forces compared to those needed for complete fracture. If a crack initiates in a crown, there is a high possibility that the crack will propagate leading to catastrophic fracture. In this study, the load needed to initiate cracking was not recorded because the crack initiation was not accompanied by any drop in the load since the loading piston was completely supported by the intact crown. In this study, fracture loads were recorded when a sharp drop in the load-displacement curve occurred. However, the load at catastrophic fracture is not an adequate indicator of the load that the material would withstand prior to crack initiation.

2.4.7 Future projects

According to the results of this study, the following need further investigations:

- *In-vitro* fracture strength and fatigue resistance of Paradigm MZ100 crowns compared to the gold-standard porcelain-fused-to-metal crowns. This will provide significant information regarding the strength and durability of Paradigm MZ100 crowns compared to the clinically proven strength and durability of porcelain-fused-to-metal crowns prior to conducting expensive and time consuming clinical trials.

- If the Paradigm MZ100 crowns showed encouraging results in the pre-
vious in-vitro study, a clinical investigation of those resin composite
crowns should be conducted to test their durability and longevity un-
der the conditions of the oral environment and function.

2.5 Conclusions

Within the limitations of this in-vitro study, the following can be concluded:

1. There was no statistically-significant difference between the in-vitro
   mean compressive fracture loads of the resin composite (Paradigm
   MZ100) and ceramic (ProCAD) molar crowns. However, this finding
   should be cautiously interpreted since the two materials behaved
differently under conditions of cyclic loading.

2. Resin composite crowns sustained compressive cycling load without
   any fractures while 70% of the ceramic crown specimens underwent
   catastrophic fracture.

3. These in-vitro results suggest that resin composite molar crowns (Paradigm
   MZ100) milled with CEREC-3D would be expected to resist fracture
   well under forces of mastication.
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