FRACTURE RESISTANCE OF OCCLUSAL CERAMIC AND COMPOSITE MOLAR ONLAY COMPARING TO LITHIUM DISILICATE MOLAR CROWN

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Esthetic Restorative and Implant Dentistry
Common Course
Faculty of Dentistry
Chulalongkorn University
Academic Year 2018

การศึกษาความต้านทานต่อการแตกหักของฟันกรามใหญ่บนที่บูรณะด้วยเซรามิกออนเลและคอมโพสิตออนเล เปรียบเทียบกับครอบฟันลิเทียมไดซิลิเกตเซรามิก

น.ส.จตุพร ลือเกียรติไพศาล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
สาขาวิชาทันตกรรมบูรณะเพื่อความสวยงามและทันตกรรมรากเทียม ไม่สังกัดภาควิชา/เทียบเท่า
คณะทันตแพทยศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2561

Thesis Title	FRACTURE RESISTANCE OF OCCLUSAL CERAMIC AND COMPOSITE MOLAR ONLAY COMPARING TO LITHIUM DISILICATE MOLAR CROWN
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Field of Study	Esthetic Restorative and Implant Dentistry
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จตุพร ลือเกียรติไพศาล : การศึกษาความต้านทานต่อการแตกหักของฟันกรามใหญ่บนที่บูรณะด้วยเซรามิกออนเลและคอมโพสิตออนเล เปรียบเทียบกับครอบฟันลิเทียมไดซิลิเกตเซรามิก. (FRACTURE RESISTANCE OF OCCLUSAL CERAMIC AND COMPOSITE MOLAR ONLAY COMPARING TO LITHIUM DISILICATE MOLAR CROWN) อ.ที่ปรึกษาหลัก : รศ. ทพ.เฉลิมพล ลี้ไวโรจน์

วัตถุประสงค์: งานวิจัยนี้มีวัตถุประสงค์เพื่อประเมินความต้านทานต่อการแตกหักและรูปแบบการแตกหักของออนเลชนิดบางที่ขึ้นรูป 3 วิธี คือจากการอุดด้วยวัสดุเรซินคอมโพสิต จากบล็อก 2 ชนิด ได้แก่ วีตาอีนามิกบล็อก และไอพีเอสอีแมกซ์แคดบล็อก

วิธีการและเครื่องมือ: ฟันกรามใหญ่บนจำนวน 40 ซี่ ถูกเตรียมผิวฟันฟันด้านบดเคี้ยวโดยการกรอผิวเคลือบฟันและเนื้อฟันออกบางส่วน โดยฟัน 30 ซี่ถูกบูรณะด้วยออนเลชนิดบางขึ้นรูปจากการอุดด้วยวัสดุเรซินคอมโพสิต วีตาอีนามิกบล็อก และไอพีเอสอีแมกซ์แคดบล็อก (กลุ่มละ 10 ซี่) และฟัน 10 ซี่ถูกเตรียมผิวฟันเพิ่มเติมและบูรณะด้วยครอบฟันที่ขึ้นรูปจากไอพีเอสอีแมกซ์แคดบล็อก ฟันที่บูรณะแล้วทั้งหมดถูกนำไปทดสอบความแข็งแรงโดยใช้แรงกดในแนวดิ่ง บันทึกค่าแรงกดที่ทำให้เกิดการแตกหักและนำไปวิเคราะห์ความแปรปรวนแบบทางเดียวและเปรียบเทียบภายหลังโดยใช้สถิติเกมส์โฮเวลที่ระดับความเชื่อมั่นร้อยละ 95 และเปียบเทียบความสัมพันธ์ของค่าความต้านทานการแตกหักและรูปแบบการแตกหักโดยใช้สถิติสหสัมพันธ์เชิงอันดับของของสเปียร์แมน

ผลการวิจัย: ค่าเฉลี่ยความต้านทานต่อการแตกหักของฟันที่บูรณะทั้ง 4 กลุ่มเรียงตามลำดับจากน้อยไปมากดังนี้ 1,949.59, 2,358.86, 2,438.66 และ 2,870.44 นิวตัน สำหรับครอบฟันไอพีเอสอีแมกซ์แคด วีตาอีนามิกออนเล เรซินคอมโพสิตออนเล ไอพีเอสอีแมกซ์แคดออนเล ตามลำดับ โดยไอพีเอสอีแมกซ์แคดออนเลมีค่าความต้านทานต่อการแตกหักมากกว่าครอบฟันไอพีเอสอีแมกซ์แคดอย่างมีนัยสำคัญ ไม่พบความสัมพันธ์ระหว่างค่าความต้านทานต่อการแตกหักและรูปแบบของการแตกหักในทุกกลุ่มการทดลอง

สรุปผลการวิจัย: ค่าความต้านทานต่อการแตกหักของฟันที่บูรณะด้วยออนเลมีค่าใกล้เคียงกัน โดยทุกกลุ่มการทดลองมีค่าความต้านทานต่อการแตกหักสูงกว่าค่าแรงบดเคี้ยวเฉลี่ยของมนุษย์

สาขาวิชา ทันตกรรมบูรณะเพื่อความสวยงามและทันตกรรมรากเทียม ลายมือชื่อนิสิต ....

ปีการศึกษา 2561 ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

5875807732 : MAJOR ESTHETIC RESTORATIVE AND IMPLANT DENTISTRY

KEYWORD: Thin occlusal onlay; polymer-infiltrated ceramic network; hybrid ceramic; lithium-disilicate glass ceramic; CAD/CAM; strength.

Jatuporn Luekiatpaisarn : FRACTURE RESISTANCE OF OCCLUSAL CERAMIC AND COMPOSITE MOLAR ONLAY COMPARING TO LITHIUM DISILICATE MOLAR CROWN. Advisor: Assoc. Prof. Chalermpol Leevailoj

Purpose: This in vitro study evaluated fracture strengths and failure modes of thin occlusal onlays fabricated from direct resin composite, CAD/CAM polymer-infiltrated ceramic-network, and CAD/CAM lithium-disilicate glass ceramic under compressive loading.

Materials and Methods: Forty extracted maxillary molars were prepared, including occlusal enamel and dentin removal, leaving two dentin slopes with peripheral enamel. Thirty teeth were restored with 0.6-mm-thick occlusal onlays using direct resin composite (Premise), CAD/CAM polymer-infiltrated ceramic-network (Vita Enamic), and CAD/CAM lithium-disilicate glass ceramic (IPS e.max CAD). Others were restored with IPS e.max CAD crowns. All restored teeth were loaded vertically by means of a universal testing machine. Fracture loading data were recorded in Newtons (N) and statistically analyzed by one-way analysis of variance and Games-Howell post hoc test ($\alpha = 0.05$). The failure modes were classified, and correlations between fracture strength and failure mode were analyzed by Spearman's rank-order test.

Results: The fracture strengths (mean ± SD) were 1,949.59, 2,358.86, 2,438.66 and 2,870.44 N for IPS e.max CAD crowns, Vita Enamic occlusal onlay, Premise occlusal onlay and IPS e.max CAD onlays respectively. The IPS e.max CAD onlays showed significantly higher fracture strength than the IPS e.max CAD crowns ($p < 0.05$). No correlation between fracture strength and failure modes was found within each material.

Conclusion: The fracture strength of all thin occlusal onlays were comparable. However, all restorations demonstrated higher fracture resistance than average force of mastication.

Field of Study:	Esthetic Restorative and Implant Dentistry	Student's Signature ....
Academic Year:	2018	Advisor's Signature ....

ACKNOWLEDGEMENTS

This thesis would not have been completed and succeeded without the assistance and support of following people.

First, and foremost, I would like to express my appreciation and special thanks to my advisor, Assoc. Prof. Chalermpol Leevailoj for providing me the opportunity and guidance throughout this research. His expertise, creative suggestion, kindly support and encouragement are valuable for me not only for this research, but also during the whole period of my master's degree study.

I would like to thank my thesis supervisory committee, including Assoc. Prof. Pattapon Asavanant for giving advice and assistance all along my research.

I am grateful to Assoc. Prof. Chanchai Hosanguan for his guidance in the statistical analysis.

Also, I would like to thank all staffs of the Dental Material Research Center for their assistance. Moreover, my thanks are extend to staffs and dental assistants of Esthetic Restorative and Implant Dentistry Clinic for their assistance throughout my graduate program.

Thank you my friends who have been together through thick and thin. Their sincere friendship and support encourage me to finish this research and my graduate program.

Finally, I would like to acknowledge my family, the most essential people who always beside me all the time. This achievement would not possible without their real love.

Jatuporn Luekiatpaisarn

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CHAPTER I INTRODUCTION

Background and rationale

Noncarious tooth surface loss is a normal physiological process occurring throughout life, but it usually becomes a problem affecting function and esthetics or causes sensitivity and pain. This loss of tooth structure or wear is commonly classified as abrasion, attrition, erosion, and abfraction.[1, 2] It is the accumulation of a small amount of structure loss each year over time due to multifactorial etiology, including the aging process.[1, 3] However, the premature and accelerated loss of enamel by gastroesophageal reflux disease (GERD) or erosion caused by bulimia nervosa may occur in adolescence or childhood.[4, 5]

This occlusal tooth structure loss in posterior teeth affects mastication capacity, occlusal stability, vertical dimension, and overall patient satisfaction with esthetic appearance, pain, and oral comfort.[6] Early diagnosis and treatment are critical to the cessation of tooth structure loss that leads to tooth sensitivity or pulp pathology. In the past, treatment of advanced occlusal tooth structure loss was by conventional full-coverage crowns, which offer an acceptable esthetic outcome and improved mechanical properties but require significant tooth reduction. Currently, the use of adhesive techniques combined with improved restorative materials properties allows for advanced occlusal tooth surface loss to be restored with thin occlusal onlays, not only following the strategy of minimal reduction of sound tooth structure but also achieving acceptable esthetic, mechanical, functional, and biological outcomes.[7-11]

Dental CAD/CAM (computer-aided design/computer-aided manufacturing) technology was first developed in 1971[12] and has been developed over time with many advantages, including speed, ease of use, and quality control.[13-15] Digital scanning, CAD software design, as well as milling processes can be faster than conventional processes because some steps have been eliminated. Quality is constant, because prefabricated blocks from manufacturers are controlled to be free from internal defects.[14] In addition, this dramatically improved technology enhances fabrication of thin restorations. According to previous studies, CAD/CAM restorations with thickness less than 1 mm demonstrated success in the milling process without defects and with acceptable mechanical strength.[7, 8, 10, 11] The first chairside CAD/CAM system, CEREC (Sirona Dental Systems GmbH, Bensheim, Germany), was introduced in 1987. This system combines a digital scanner with design software and a milling machine. It allows dentists to provide indirect restorations fabricated from commercially available blocks in a single visit.[13, 14]

Several materials can be fabricated with CAD/CAM technology, including a lithium-disilicate glass ceramic such as IPS e.max CAD (Ivoclar Vivadent, Schaan, Liechtenstein) and a polymer-infiltrated ceramic-network/hybrid ceramic such as Vita Enamic (Vita Zahnfabrik, Bad Säckingen, Germany). Vita Enamic, a new hybrid ceramic, is comprised of a structure-sintered ceramic matrix with space between ceramic substrates filled with resin material to form a double-network hybrid.[16] It offers the combined benefits of ceramic and composite. The inorganic portion (86 wt%) provides stability, and the infiltrated organic copolymer portion (14 wt%) provides elasticity.[16-21] This material is claimed to absorb masticatory forces and stop crack formation.[22-26] Characterization of this hybrid material was derived from a feldspathic ceramic network interconnected with a polymer-based network, resulting in properties between those of glass ceramics and resin composites.[17] Moreover, this hybrid material can be milled at relatively thin thicknesses to achieve conservative tooth preparations.[7] Therefore, a polymer-infiltrated ceramic network is a potential candidate for thin occlusal onlays utilized for the reconstruction of lost occlusal tooth surface.

The fracture strength of thin occlusal onlays fabricated with a polymer-infiltrated ceramic network, direct resin composite, and lithium disilicate ceramic compared with that of a lithium disilicate full-coverage crown has not been clarified. This study aimed to evaluate the fracture strengths and failure modes of thin (0.6-mm) occlusal onlays fabricated from direct resin composite or CAD/CAM hybrid ceramic blocks or CAD/CAM lithium disilicate ceramic blocks compared with those of conventional full-coverage crowns under vertical compressive loading.

Research question

Do types of restorations (thin occlusal onlay, full coverage crown) influence the fracture resistance of molar tooth?

Do types of materials (Resin composite, Vita Enamic and e.max CAD) influence on the fracture resistance of molar tooth?

Statement of hypothesis

Null hypothesis

1.There is no statistically significant difference in fracture resistance value among different type of restorations.

2. There is no statistically significant difference in fracture resistance value among different materials used to fabricate thin occlusal onlay.

Alternative hypothesis

1.There is statistically significant difference in fracture resistance value among different type of restorations.

2. There is statistically significant difference in fracture resistance value among different materials used to fabricate thin occlusal onlay.

Conceptual framework

Population : 40 extracted human maxillary molar teeth with caries-free

Intervention : two types of restoration (full coverage crown and thin occlusal onlay) and three types of materials of thin occlusal onlay (Premise resin composite, Vita Enamic and IPS e.max CAD)

Outcome measurement :

- primary outcome : fracture strength (N)
- secondary outcome : mode of failure

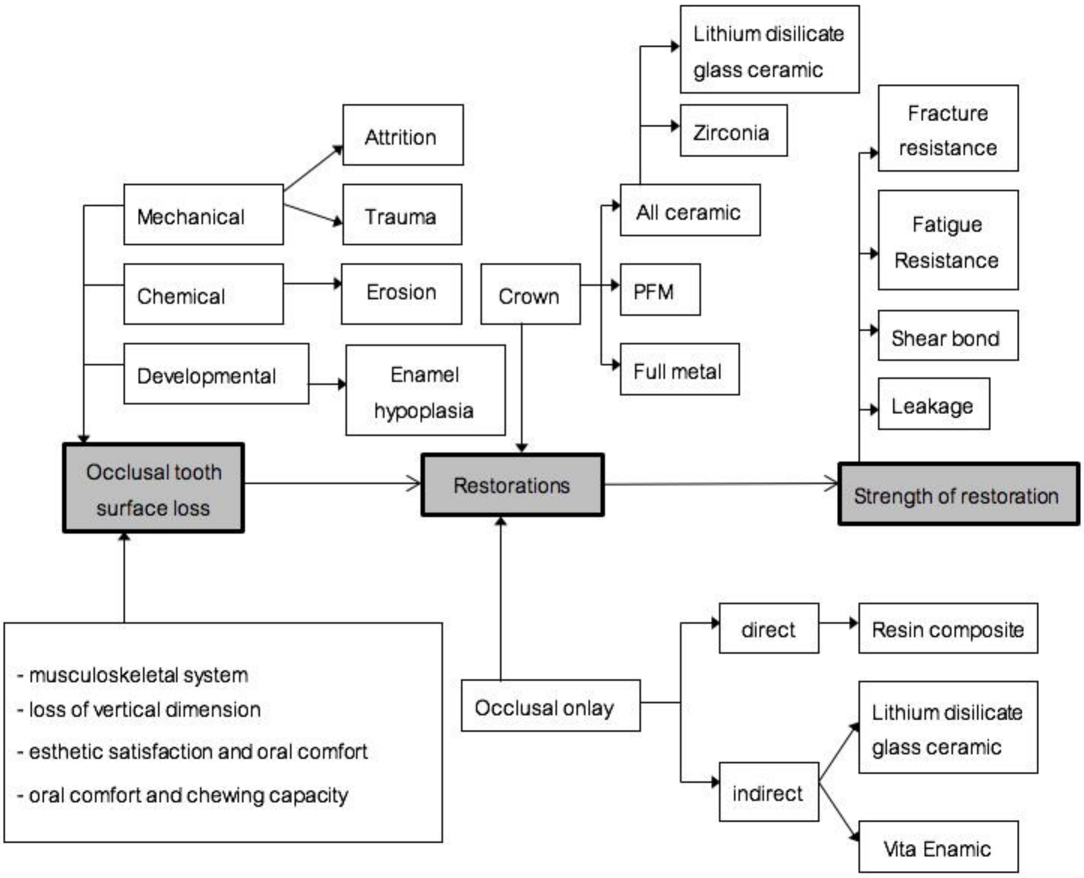

Figure 1 Conceptual framework

Study limitation

This in vitro study was designed to use extracted human molar teeth which may vary in size, dimension and morphology. The minimal thickness of thin occlusal onlay was defined as 0.6 mm-thick. In addition, our study was designed to determine only static compressive strength testing which could not replicate either the long-term effect of occlusal force on the restoration-tooth system, or the forces generated by most patients who exhibit occlusal wear. Thus, to eliminate this controversy, further studies regarding aging processes and dynamic strength testing should be undertaken.

Keywords

Thin occlusal onlay; polymer-infiltrated ceramic network; hybrid ceramic; lithium-disilicate glass ceramic; CAD/CAM; strength.

Expected benefit of the study

The results from this study will assist clinicians to make a proper decision of choosing proper restoration with suitable materials to restore occlusal tooth structure loss. Not only obtain acceptable esthetic outcome and improved mechanical properties, but also follow the strategy of minimal intervention. In addition, these findings offer further support for the utilization of thin occlusal onlays as functional and predictable means of posterior tooth reconstruction.

CHAPTER II REVIEW OF LITERATURES

The literatures in these following topics were reviewed.

- Noncarious tooth surface loss or tooth wear
    - Classification and Etiology
    - Clinical appearance of molar tooth wear
    - Management
- Dental Ceramic classification
- Resin composite restoration
    - Composition
    - Classification of resin composite
- Review of materials used in this study
    - IPS e.max CAD
    - Vita Enamic
    - Premise
- CAD/CAM technology
    - History
    - Dental Chair-side CAD/CAM : CEREC System
    - Advantages and disadvantages
- Fracture strength testing

Noncarious tooth surface loss or tooth wear

Classification and etiology

1. Erosion : The loss of tooth structure caused by acids without bacteria involvement. There are two major causes of dental erosion; intrinsic and extrinsic cause.[1, 3] The most common cause is the frequent consumption of acids (extrinsic acids). Strong acids with low pH will cause demineralization of the hydroxyapatite in the tooth structure. Common examples of foods which contain strong dietary acids are soft drinks, citrus fruits such as lemons, grapefruit, oranges, limes as well as food prickled with vinegar.[1, 27] Medications, vitamin C, iron preparations, and aspirin are acidic in nature.[28] Some dietary habits such as sipping acidic drinks or snacking on fruits result in prolonged drops in oral pH, when combined with other forms of wear such as attrition or abrasion, cause tooth wear. Intrinsic causes are mostly of gastric reflux and include vomiting in case of anorexia, bulimia nervosa, and rumination.[3] Anorexia and bulimia nervosa are relatively uncommon disorders predominantly affecting females between the ages of 13 and 20 years old. Sufferers use dietary restriction or vomiting to control their body image. The outcome on teeth is palatal dental erosion which is often severe. However, damage caused to the permanent teeth due to erosion that occurs during the childhood may compromise the growing dentition for their entire lifespan, and thus, may require increasingly complex restorations which may have to be repeated also. Evidence also suggests that that erosive wear also predisposes to attrition, and that the two mechanisms very often act together causing tooth surface loss.[2]

2. Attrition: It describes the wear from tooth to tooth contact without any foreign substance intervention. It may also describe as physiological wearing off process. [1-4] It is a common finding with well-defined wear facets. Attrition occurs either on occlusal or incisal surfaces. The more severe attrition occurs with habits such as bruxism because continual and prolonged loading on teeth causes significant occlusal wear. The causal factors for attrition are parafunctional habits, bruxism, clenching [1, 2, 4], coarse diet, and natural teeth opposing porcelain.[3, 29] In class III incisal relationship and lack of posterior support also lead to attrition of anterior teeth.[30]

3. Abrasion : It describes the pathologic wear of dental hard tissue via mechanical processes by foreign objects, which were repeatedly introduced in the mouth. Depending on the etiology, the patterns may vary from localized to diffuse.[31] Both patient and material are related factors influences the prevalence of abrasion. The brushing technique, brushing frequency, and the force applied while brushing are common patient-related factors. The type of bristle material of toothbrush, stiffness of toothbrush bristles, the abrasiveness, and pH of dentifrice used are factors related to material.[32] If excessive force is applied the mechanical action from the tooth brushing may result in wear and this normally appears on the cervical margins of premolar and canine teeth.[32] This lesion usually appear as V-shaped defect, associated with intensive horizontal brushing technique. Cervical areas are susceptible to toothbrush abrasion, particularly cuspids and first premolars. Habits involving other intraoral objects, for example pipe smoking, toothpick use, and thread biting can cause incisal and occlusal defects.[2]

4. Abfraction : It describes a wedge-shaped defect at the cementoenamel junction of a tooth. Lesions due to abfraction are also called 'cervical stress lesions' in the literature.[33] These lesions are usually located subgingivally, where the influence of tooth brushing abrasion is unusual. Laboratory studies using finite element analysis have hypothesized that abfraction might occur based on excessive lateral occlusal forces on teeth causing microscopic flexure, leading to cyclic stress concentration in the cervical area, resulted in loss of tooth tissue. Weakening of the hydroxyapatite present near the cervical region of the teeth is weakened due to tensile stresses, which produces the classical wedge-shaped defects having sharp edges near to the cementoenamel junction.[33]

Clinical appearance of molar tooth wear

In the early stages disconnected circular cavities may appear on the occlusal surfaces of molar and premolar teeth. These cavities are hard and have whitened peripheral enamel surrounding the deeper yellow dentine. The cause of these lesions is normally associated with erosion or abrasion. This is often referred as 'cupping out' of the cusp tips. If the process become worsen, the disconnected cavities join resulted in size increase. If the erosion is rapid and severe, the cusp tips or incisal edges of one or more opposing teeth may not contact into the intercuspal position. If the cause of the wear is predominantly attrition, the occlusal surfaces of either anterior or posterior teeth from both dental arches demonstrate paired wear facets. But in more severe cases, the flat area of opposing cusps or incisal edges meet and closely interdigitate in the intercuspal position. Typically in severe cases fractured restorations are found following the excessive occlusal loading from the opposing teeth.[1]

Management recommendation

Initial management of tooth surface loss depends on the accurate diagnosis, the identification of the etiology and frequent monitoring of the successive changes. Early detection and prevention are the most important steps. Avoid all etiologic factors and monitor the condition twice a year. The extent of the tooth wear may compromise the longevity of the tooth. However, the slow progression in ageing patients, for example a 70-year-old patient, may be regarded as normal ‘wear and tear’; however, if the same amount of wear was seen in a 20-year-old patient, might be a serious problem. For many patients, monitoring is an effective and acceptable procedure even though there is no attempt to restore the shape and appearance of the teeth. But other patients may complaint in poor appearance, poor function, intractable tooth sensitivity as well as concerns about continued wear and esthetics.[1] With these reasons, they need some management or restorative procedures. This management usually involves adjustments of the incisal edge and sharp cusps of teeth and the application of a desensitizing agent or glass ionomer cements over those exposed dentine. Pulp extirpation or dental extraction may be required in severe cases. In those cases where esthetics has been severely compromised, composite restorations, porcelain veneers and occlusal onlays may be provided to the patients.[3] If the defects (on posterior teeth) extent over two or more tooth surfaces, then reconstruction with full ceramic overlays is required. In patients with severe tooth surface loss on more than two surfaces per tooth and massive loss of vertical dimension, a complex reconstruction with conventional full coverage ceramic crowns is often required following the guidelines for conventional oral rehabilitation concepts.[34] The main disadvantage of doing crown coverage is removal of remaining tooth structure of the clinical crown when placing the margins at the gingival level to provide the required vertical path of insertion for crown.[35]

Ceramic restorative materials

Ceramics are nonmetallic inorganic materials. Although they are strong in compression but they are weak in tension. The main advantage of using this material is esthetic reason. Many different ceramic systems have been introduced to use as indirect restorative materials in different type of restoration, depending on their physical, mechanical and optical properties.

For the fabrication of ceramic restorations, several different techniques have been developed. However, the physical properties of ceramic restorations are strongly influenced not only by the manufacturing procedure, but also by the degree of skill and precision of individual dental technicians.[36] To reduce the discrepancies of dental technicians' skills and experience, computer-aided design/computer-aided manufacturing (CAD/CAM) technology became the new alternative.

Ceramic classification based on microstructure

According to the review of McLean and Giordano in 2010, they classified dental ceramic in 4 categories.[37]

Category 1: Glass-based systems (mainly silica)

Glass-based systems contain mainly silicon dioxide (silica or quartz) and various amounts of alumina (Al_2O_3). The mechanical properties are low flexural strength, ranging from 60–70 MPa. Thus, they are used as veneering materials for metal or ceramic substructures, as well as for veneers.[37]

Category 2: Glass-based systems (mainly silica) with crystalline (typically leucite or a different high-fusing glass)

The glass composition is similar to the pure glass of category 1, however, various amounts and types of crystals added in the glass matrix. The primary crystal types are leucite, lithium disilicate and fluorapatite. This category can be subdivide into three subcategories.

Subcategory 2.1: Low to moderate leucite-containing feldspathic glass ceramics

Leucite is created by increasing the potassium oxide (K_2O) content of the aluminosilicate glass. Leucite crystals may alter the coefficient of thermal expansion (CTE) of material, and inhibit crack propagation, which improves the strength of this material. These materials are the typical powder/liquid materials that are used for veneering core systems and are the ideal materials for porcelain veneers.

The original materials had a large crystals size (several hundred microns) and random distribution, contributing to low fracture resistance and abrasive to enamel. Newer generations have been developed with finer leucite crystals (10–20 microns) and even particle distribution. These materials have much higher flexural strengths and less abrasiveness.[38]

Subcategory 2.2: High leucite-containing (approximately 50 %) glass ceramics

This material starts as a homogeneous glass. A secondary heat treatment nucleates and grows the crystals that lead to improved mechanical and physical properties, such as increased fracture resistance, improved thermal shock resistance, and resistance to erosion. Their improved properties are depend on the interaction between the crystals and glass matrix, as well as on the crystal size and amount. Generally, finer crystals produce stronger materials. In addition, they may be opaque or translucent, depending on the percentage of crystal and chemical composition. The crystal part acts as blocks to stop crack propagation. A crack spreading from a defect must go through or around the crystal, which takes some energy away from the propagating crack and may stop its progress. Thus, the restoration may continue to function instead of being half cracked.[37]

Subcategory 2.3: Lithium disilicate glass ceramics

Lithium disilicate crystals are created by adding lithium oxide (Li_2O) to the aluminosilicate glass. It also acts as a flux, that lowering the melting temperature of material. The glass matrix consists of a lithium silicate with micron-size lithium disilicate crystals in between submicron lithium orthophosphate crystals. This creates a highly filled glass matrix. This material originally introduced by Ivoclar Vivadent as IPS Empress II (and later in form of IPS e.max Press and IPS e.max CAD). Increasing the crystal content to about 70 % and refining the crystal size resulted in improvement in flexural strength.[37]

The shape and volume of crystals increase the flexural strength to around 360 MPa, or about three times that of IPS Empress.[39-41] This material can be very translucent even with high crystalline content because of the relatively low refractive index of the lithium disilicate crystals. Their translucency is high enough that it can be used for full contour restorations in the highest esthetic area.

Fluorapatite, a fluoride containing calcium phosphate ($Ca_5(PO_4)_3F$), is a veneering porcelain. It consists of fluorapatite crystals in an aluminosilicate glass and may be layered on to the lithium disilicate core in order to create the final morphology and shade of restoration. The fluorapatite crystals have appropriate optical properties and CTE, so that, it matches the lithium disilicate pressable or machinable material. Both the veneering material and the lithium disilicate material are etchable due to their glassy phase. Initial clinical data for single restorations with this material is excellent, especially if it is bonded.[41]

Category 3: Crystalline-based systems with glass fillers (mainly alumina)

VITA In-Ceram (VITA Zahnfabrik) consists of a family of all-ceramic restorative materials based on the same principle introduced in 1988. It belongs to an interpenetrating phase composites [42] consisting of at least two phases, that are intertwined and extend continuously from the internal to the external surface, resulted in improved mechanical and physical properties.[37] The interpenetrating phase materials are generally fabricated by first creating a porous matrix, called a ceramic sponge. The pores are then filled by a second-phase material, a lanthanum aluminosilicate glass, using capillary action to draw a molten glass into all pores to produce dense interpenetrating material.

This family includes a range of strengths, translucencies and fabrication methodologies designed to cover the wide scope of all-ceramic restorations. VITA In-Ceram SPINELL (alumina and magnesia matrix) is the most translucent, moderate strength and ideally used for anterior crowns. Flexural strength is about 350 MPa. VITA In-Ceram ALUMINA (alumina matrix) has high strength and moderate translucency, and it is used for anterior and posterior crowns. Flexural strength around 450 MPa. VITA In-Ceram ZIRCONIA (alumina and zirconia matrix) has a very high strength and low translucency, and it is used primarily for three-unit posterior bridges. Flexural strength ranges up to 650 MPa.[37]

Category 4: Polycrystalline solids (alumina and zirconia)

These ceramics are formed by directly sintering crystals together without any matrix to form a dense, air-free, glass-free polycrystalline structure. There are several different processing techniques that allow the fabrication of solid sintered alumina or zirconia frameworks. The first fully dense polycrystalline material for dental applications was Procera AllCeram alumina (Nobel Biocare) with a strength of about 600 MPa[43] and 20 % shrinkage approximately.

Zirconia (or zirconium dioxide: ZrO_2) may consist of several crystal phases, depending on the metal oxide added, such as calcia (CaO), magnesia (MgO), yttria (Y_2O_3), and ceria (CeO_2). Typically for dental applications, about 3 wt% of yttria is added to the pure zirconia in order to stabilize tetragonal phase at room temperature. Zirconia has twice as strong and tough as alumina-based ceramics. The flexural strength ranges from 900-1,100 MPa.[44, 45] Another important physical property is fracture toughness, which has been reported between 8 and 10 MPa $m^{1/2}$ for zirconia.[45]

Resin composite restoration

Composition

1. *Organic part (resin matrix)*

The resin matrix consists mainly of Bis-GMA (bisphenol-A-glycidyldimethacrylate).[46] Because Bis-GMA itself is highly viscous, it is mixed with other short-chain monomers such as TEGDMA (triethylenglycol-dimethacrylate) or UDMA (urethane dimethacrylate). The lower Bis-GMA content and the higher proportion of TEGDMA, the higher polymerization shrinkage.[47] Replacing Bis-GMA with TEGDMA increases the tensile but reduces the flexural strength of material.[48] Other mnomers such as glycol dimethacrylate, urethane dimethacrylateethoxylated bisphenol-A-dimethacrylate (Bis-EMA), decanediol dimethacrylate (D3MA) are also often used in various proportions.[46] Longer light polymerization improves the rate of conversion (chain-linking of the individual monomers) and leads to less monomer release from the material.[49]

Once initiated, the chemical reaction of these dimethacrylate monomers produces a rigid, heavy cross-linked polymer network around the fillers, and thus, the hardening of the dental composite occurs.[50] Due to the formation of covalent bonds, the polymerization reaction leads to volumetric polymerization shrinkage. If not managed correctly, this shrinkage can result in catastrophic negative results.

2. *Inorganic part (fillers)*

The fillers are made of quartz or silica. With increasing filler content, the polymerization shrinkage, the linear expansion coefficient and water absorption are reduced. In addition, with increasing filler content, the compressive and tensile strength, the modulus of elasticity and wear resistance are generally increased.[51] The filler content of composite is sometimes determined by the shape of filler. In a study with different types of composite, those materials containing pre-polymerized composite fillers were shown to have the lowest filler content and the lowest flexural strength and hardness. Composites with round fillers had the highest filler content, which was associated with higher hardness and higher flexural strength. For mixed filler particles (hybrid composites) there was no linear relationship between filler content and flexural strength.[51]

3. *Silane coupling agent*

The organic matrix and inorganic fillers are bonded covalently and this strong bond is essential in order to achieve the desired mechanical properties as well as the clinical predictability. The silane coupling agent have a silane group at one end and a methacrylate group at the other end. These bifunctional molecules can bond to both the hydroxyl groups of silica filler particles and copolymerize into the polymer methacrylate matrix.[46] A typical used bifunctional coupling agent is 3-methacryloxypropyltrimethoxysilane (MPTS). Salinization of the filler is important for material strength.[52] The stable bond between the filler and matrix has influences on the material properties. The quality of the bond affects the abrasion resistance of the restorative material.[53]

4. *Photo-initiator systems*

The polymerization reaction of resin composites can be activated chemically, via light or via a combination of these two methods. In light activated resin composite, the most common photo-initiator system used is camphoroquinone, a diketone photoactivator accelerated by an aromatic tertiary amine.[54, 55] Inhibitors are also added to prevent spontaneous polymerization during storage.

Classification of resin composites

Ferracane summarized the classification of resin composites in his 2010 review.[50] He classified resin composite as :

- Conventional "macrofills" dental composites had average filler (usually be quartz) sizes exceed 1 micron. These materials were very strong, but difficult to polish and impossible to retain surface smoothness.
- "Microfills" composites, containing microscopic particles (usually be colloidal silica), were later called truly nanofills composites, because the average size of the amorphous spherical silica reinforcing particles was approximately 40 nm. The filler level in these materials was low, but could be increased by incorporating highly filled, pre-polymerized resin fillers (PPRF) within the resin

matrix seeming that the micron-sized microfill particles were added. These composites were polishable but generally weak due to their relatively low filler content.

- "Midifills (small particle hybrid) composites contain average particle size slightly greater than 1 micron but also containing a portion of the 40 nm-sized fumed silica microfillers.
- "Minifills" composites contain sub-micron, typically average about 0.4–1.0 micron and ultimately came to be referred as "microhybrids." These materials are generally considered to be universal composites as they can be used for most anterior and posterior applications based on their combination of strength and polishability.
- The most recent innovation has been the development of the "nanofills" composites, containing only nanoscale particles. Furthermore, the modified microhybrids by including nanoparticles and possibly pre-polymerized resin fillers, have named "nanohybrids".

Review of materials used in this study

IPS e.max CAD

IPS e.max CAD is a lithium disilicate glass ceramic for CAD/CAM applications introduced by Ivoclar Vivadent in 2006 as a chair-side monolithic restorative material.

This new-technology blocks use optimized processing techniques, which prevent the formation of defects (pores, accumulation of pigments, etc.) in the bulk of block.[56] The blocks are manufactured in a process based on the pressure-casting procedure as use in the glass industry. Their flexure strengths range between 350-450 MPa, which is higher than that of leucite-reinforced dental ceramics.[57] IPS e.max CAD is available in A–D and Bleach shades with 3 translucencies. The least translucent blocks are used primarily as a framework material and the higher translucency blocks are used for full-contour restorations.[37] These CAD/CAM blocks are supplied in a pre-crystallized or blue state. The blue ceramic contains metasilicate and lithium disilicate nuclei and exhibits a flexural strength of 130 ± 30 MPa. At this state, the block can be easily milled. After that, the restoration is re-crystallized in a chair-side ceramic oven at 850 °C in vacuum for 20–25 min. During this heat treatment, the metasilicates are dissolved, lithium disilicate crystallizes and the ceramic is glazed at the same time. The block also changes from blue to the chosen tooth-colored shade and translucency as well as reaches desired mechanical properties. In this state, called full crystalized state, the ceramic contains 70 vol% of crystals and the strength increases dramatically to desired 360 MPa.[56-59]

Laboratory studies have shown that fully anatomical IPS e.max CAD crowns may be resistant to fatigue in cyclic loading and its fracture load is significantly higher than the ProCAD and Empress CAD.[60] The material has been recommended by the manufacturer for use in fabricating inlays, onlays, veneers, anterior and posterior crowns and implant supported crowns.[25] Guess et al.(2010) tested monolithic CAD/CAM lithium disilicate and hand layer-veneered zirconia all-ceramic crowns and found that using IPS e.max CAD crowns resulted in higher fatigue resistance, while hand layer-veneered zirconia crowns showed early veneer failure.[56] Reports from short term clinical trials on IPS e.max CAD single crowns showed survival rates between 97.4% and 100% after two years.[61, 62]

Vita Enamic

Vita Enamic (Vita Zahnfabrik) was recently introduced in 2013 as a polymer-infiltrated- ceramic-network material. This material is claimed to be a hybrid ceramic material comprising a structure-sintered ceramic matrix with space in between ceramic substrates filled with resin material to form a double network hybrid.[16] Although the processing is not disclosed by the manufacturer, the mass percentage of the inorganic ceramic part (porous feldspathic ceramic matrix) is stated to be 86 wt% and the rest 14 wt% is infiltrated organic copolymer part (urethane dimethacrylate and triethylene glycol dimethacrylate). As claimed by the manufacturer, the dominant basic ceramic network provides stability, and the polymer network provides elasticity.[16-21] This material is claimed to absorb masticatory forces and stop crack formation.[22-26] Characterization of this hybrid material was derived from a feldspathic ceramic network interconnected with a polymer-based network, resulting in properties between those of glass ceramics and resin composites.[17] This material is indicated for veneers, inlay/onlay, anterior and posterior single crowns, as well as implant prosthesis.[25] Studies suggest this material is strong in thin layers and suitable for treating young patients, or patients with bruxism or dental erosion. However, long-term in vivo studies are still lacking.

Premise composite

Premise is a universal light-cured resin-based nanofilled composite, which is designed for direct placement. The resin matrix is made of ethoxylated Bis-GMA and TEGDMA. The inorganic part contains 84% by weight of three different filler types: non-agglomerated silica nanoparticles (0.02 μm), pre-polymerized filler;PPF (30 μm to 50 μm) and barium silicate glass (0.4 μm). The resin matrix also has photo-initiators and stabilizers. The incorporation of PPF leads to high filler loading. Their advantages have been claimed to have ultra-low polymerization shrinkage with high filler loading, high polishability, increased wear resistance, high mechanical strength, excellent handling with non-sticky manipulation, superior esthetics and universal application.[63] Because camphorquinone has been use as a photo-initiator which activates in the approximate 465 nm range, so that, it is recommended by the manufacturer that this composite should be cured with a reliable, high-power, visible light source.

Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) technology

CAD/CAM for dentistry was developed in 1971.[12] These systems use machinable ceramic materials and allow automated manufacturing of all-ceramic restorations, hence achieving advantages of reduced manufacturing time and technical inaccuracies. For chair side fabrication of all-ceramic restorations, the CEREC CAD/CAM system (Sirona Dental Systems GmbH, Bensheim, Germany) allows dentists to create well-fitting and esthetically pleasing ceramic restorations within one visit.[13, 14]

History

The pioneer of dental CAD/CAM was Francois Duret who built an optical scanner that would make a digital impression of an abutment tooth, which was then transferred to a computer to design and then milled in a controlled machine.[12] Subsequently, Werner Mormann and Marco Brandestini further improved the capability to take chairside optical impression and link with chairside milling machine to produce a single-visit ceramic restoration, named CEREC (Chairside Economical Restorations of Esthetic Ceramics).[64]

The advancements of CEREC and other CAD/CAM systems are involved in either the optical capture of the prepared teeth or the milling process. In terms of optical capture, CEREC Blue Cam utilizes an LED blue light camera and a three dimensional reconstruction is made.[65] Typical accuracies of this system has been reported ranging between17-50 µm depending on the investigated system.[65] This precision is easily comparable to the accuracy reported from conventional impression. The advancements made in the milling machine specifically relate to the number of milling axes. All chairside milling machines are limited to three axes (X, Y and Z), resulting in limiting the accuracy and precision of the restorations, however, short milling time is consumed.[13] Five axes milling systems are able to rotate the milling spindle, hence, permit the ability of milling more complex structures with increased accuracy, fit and precision.[13]

Dental Chair-side CAD/CAM : CEREC System

CEREC, introduced by Dr. Momann in 1987, was the first dental system which combine digital scanning with a milling unit.[66] The system allows dentists to provide restorations made from commercially available blocks in a single visit.[13, 14]

This system has been continually improved in terms of both hardware and software. The earliest models produced only inlays and onlays.[64] The later model, known as CEREC AC powered by BlueCam (Sirona, Charlotte, NC, USA),had been introduced in 2009. It also has ability to take half-arch or full-arch impressions and create crowns, veneers, and bridges. This system uses intense blue light from light-emitting diodes (LEDs). To use this system, the entire tooth preparation to be scanned is coated with a layer of special titanium dioxide powder, which makes translucent areas of the teeth opaque and permits the camera to register all tissues. Several optical impressions are then taken from occlusal surface, being sure to obtain images of the tooth to be restored as well as the adjacent and opposing teeth. This scanner is able to focus automatically.[14]

The latest generation of CEREC came up with CEREC Omnicam scanner, a small powder-free color camera, recording continuous video for precise 3D images in natural color. In addition, the CEREC Omnicam allows clinicians to determine the color of the scanned teeth in the software. After the digital impression is completed, a 3-D rendering image of the tooth to be restored appears on the monitor. The clinician is able to mark where the die should begin and end based on this image. The margin of restoration is marked and the path of insertion is allocated. The software program then generates a proposed restoration based on the adjacent and opposing teeth, which can then be adjusted manually as needed. After the design is approved, the milling process can begin.[14] A block of ceramic or composite material is simply inserted into the milling unit. Typically, 4-12 minutes is taken to mill a single restoration, depending on the indication and material used. Alternatively, the dentist can obtain a digital impression and send the data to a dental laboratory. The laboratory can design and mill the restoration using CAD/CAM technology. They can also use the digital image to fabricate a hard resin model based on the data and fabricate the restoration in the conventional manner.[14]

Advantage

Davidowicz and Kotick summarized advantages of CAD/CAM in dentistry as speed, ease of use and increase in constant quality because prefabricated blocks from manufacturers are controlled to be free from internal defects.[14] In addition, chairside milling units allow for the convenience of producing indirect restorations for patients in one visit, thus saving chair time, laboratory time and patient time.[14]

Miyazaki stated the advantages of CAD/CAM in dentistry as reduced labor time, cost effectiveness and quality control[15], for example, the control of thickness and anatomy of restorations during fabrication, as well as manufacturer-regulated mechanical properties of the restorative materials. Many confounding operator factors can be avoided, such as dental laboratory technicians' skills and accuracy involved in the fabrication process. Moreover, the clinical benefit of the ability to accurately and quickly reproduce prostheses on demand because design and milling processing data can be saved electronically. If lab based CAD/CAM systems are preferred, reduced production time is still possible due to the ability to mill multiple works in one machine at one time. Furthermore, errors are often detected in advance and can be immediately corrected prior to milling, thus minimizing the number of remakes and waste.[15] Santos also adds minimization of human error and patient satisfaction.[67]

Disadvantage

There are some disadvantages as well with CAD/CAM dentistry. The initial cost of the equipment and software is high, and the practitioner needs to spend time and money on training.[13, 66] Santos et al. reported that marginal adaptation, postoperative sensitivity and opposing tooth wear were concerned.[67] In addition, material surface damage or chipping, occurred due to machining, can reduce the accuracy of fit and contribute to decreased mechanical properties over time.[68] In a review of Denry et al., they concluded that milling ceramics with a diamond bur, as done in CAD/CAM milling, is directly correlated to increasing in failure-inducing flaws.[69]

Fracture strength testing

The fracture resistance testing of teeth is the simplest way to perform. However, this destructive test may not always simulate in vivo conditions, because the forces required to fracture specimens in vitro may not occur in the oral cavity.[70] The application of static force does not simulate actual intraoral loading.[71] However the clinical loading of teeth is a dynamic process, in which loading force, frequency and direction are vary.

In general, crosshead speeds, which commonly in the range of 1mm/min or 2mm/min, have been used by different researchers, but this does not seem to be a critical factor.[72, 73] Espevik et al. stated that lower speeds are accompanied by greater plastic deformation as a result higher fracture resistance measurements will be recorded.[74]

The direction of forces on the tooth cusps during excursive jaw movements is complex, and is influenced by different factors such as cuspal morphology and intermaxillary occlusal relationships. The direction of load may affect the fracture resistance of teeth. Loney et al. demonstrated significant differences in fracture resistance of maxillary central incisor between specimens tested at the different load angles (110, 130, 150 degrees). Mean failure loads increased when the load angle became more parallel to the long axis of the teeth.[75] Teeth are more prone to fracture when eccentric forces are applied. Different angles of loading had been used varying between 30 degrees, 45 degrees and parallel to the long axis of the tooth.[70, 76] Vertical forces are better tolerated because they are directly against the dense bone around the tooth apex, while lateral forces are more destructive as they are directly against the thinner and weaker buccal, lingual and interproximal walls of the alveolar bone.[77]

CHAPTER III MATERIALS AND METHODS

Research Design : The experimental (in vitro) study will be conducted.

Research Methodology :

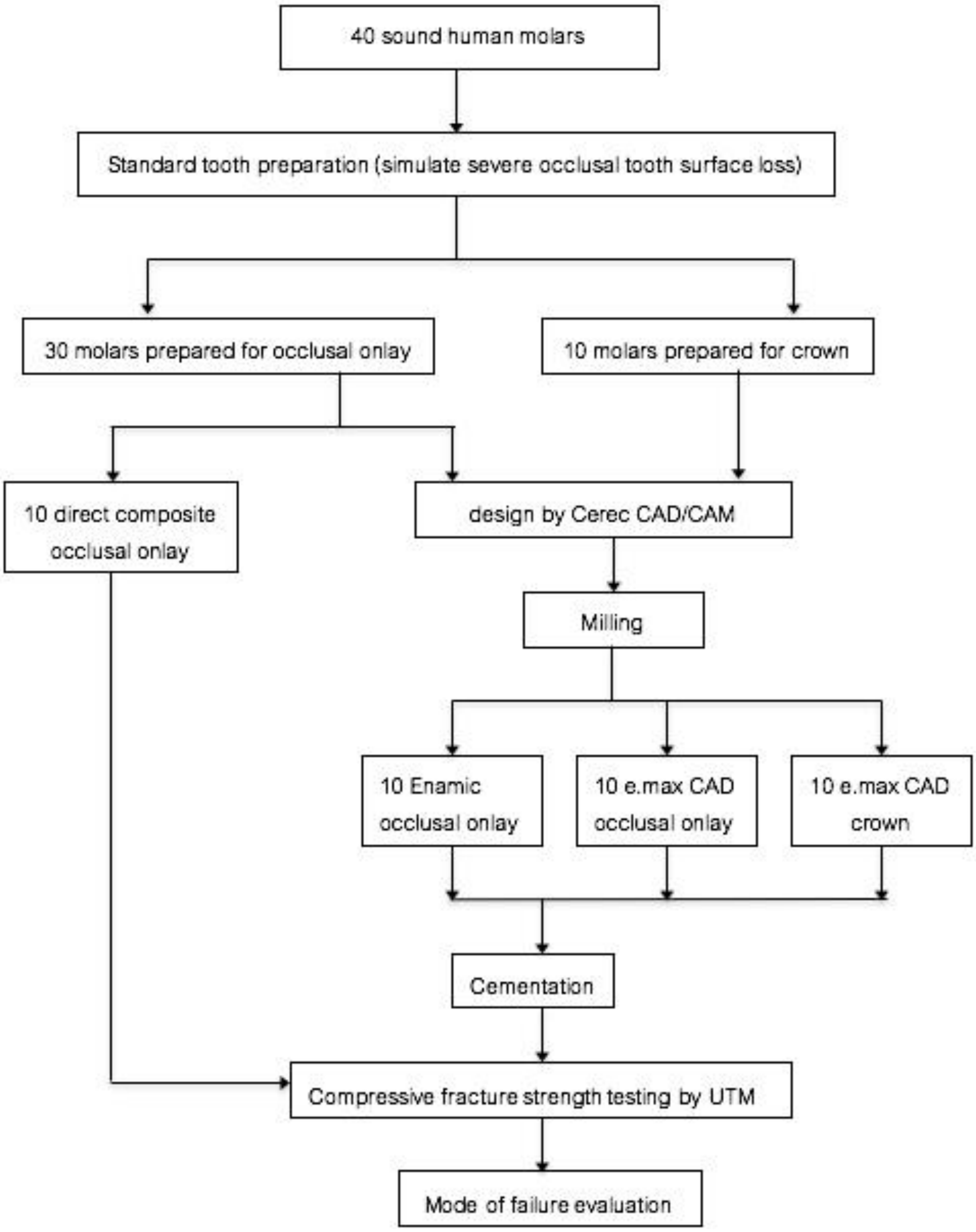

Figure 2 Design of the study

Dental Materials

Table 1 Materials used in the study

Materials	Manufacturer
Vita Enamic block 2M2 HT	Vita Zahnfabrik, Bad Säckingen, Germany
IPS e.max CAD block A1 LT	Ivoclar Vivadent, Schann, Liechtenstein
Premise, syringe type A2	Kerr, Orange, CA
NX3 Nexus(clear) 3rd Generation	Kerr, Orange, CA
Gel Etchant : 37.5% H3(PO)4	Kerr, Orange, CA
OptiBond FL Primer and Adhesive	Kerr, Orange, CA
OptiBond Solo Plus	Kerr, Orange, CA
Silane Primer	Kerr, Orange, CA
Porcelain Etch : 9% HF	Ultradent, South Jordan, UT

Table 2 Equipments used in the study

Equipment	Manufacturer
Periodontal probe 23/UNC 15	Hu-Friedy, Chicago, IL
Cerec AC Omnicam	Sirona Dental Systems GmbH
Cerec 4 CAD/CAM system	Sirona Dental Systems GmbH
vernier caliper	Hu-Friedy CLP1, Frankfurt am Main, Germany
Ceramic fernance : Programat P700	Ivoclar Vivadent, Schann, Liechtenstein
Universal Testing Machine (Instron model 5566)	Instron, Canton, MA
LED light Curing Unit : Demi	Kerr, Orange, CA

Methodology

The Ethical Committee, Faculty of Dentistry, Chulalongkorn University, approved the research protocol involving the collection of human teeth due to non-occlusion (approval number: HREC-DCU 2017-014). Teeth were collected and selected according to the following criteria: (1) permanent human maxillary molars with similar shapes and mesio-distal dimensions of 9 ± 0.5 mm; (2) no dental caries, previous root canal treatment, or cracks; (3) minimal coronal height of 5 mm; and (4) no previous extractions in the preceding 3 months. Exclusion criteria were as follows: (1) irregularly shaped maxillary molars; and (2) maxillary molars with incomplete root formation. From previous studies, 10 samples were determined for each group.[8, 9, 11]

Tooth preparation

Forty extracted sound human maxillary molars with similar dimensions (mesio-distal width = 9 ± 0.5 mm) were collected, cleaned, and stored in 0.1% thymol solution for no longer than 3 months. Then, they were inserted into a polyvinyl chloride (PVC) mold with 18 mm internal diameter, 22 mm external diameter, and 40 mm height. The molds were filled with auto-polymerizing acrylic resin (Palapress; Heraeus Kulzer GmbH, Hanau, Germany). Teeth were embedded up to 3 mm below the cemento-enamel junction (CEJ), controlled by a dental surveyor.[9, 11]

All teeth were subjected to standardized preparation to simulate advanced occlusal tooth surface loss by means of round-ended tapered diamond rotary cutting instruments (D8; Intensiv, Montagnol, Switzerland). The entire coronal tooth structure, 5 mm occlusal to the CEJ, was sectioned axially, leaving 5-mm height of a flat area of exposed dentin and peripheral enamel. Then, the central groove was deepened by 2 mm, and two slopes from buccal and palatal margins were created, smoothed, and ended at the central groove. (Fig 3) Only minimal finishing steps were performed.

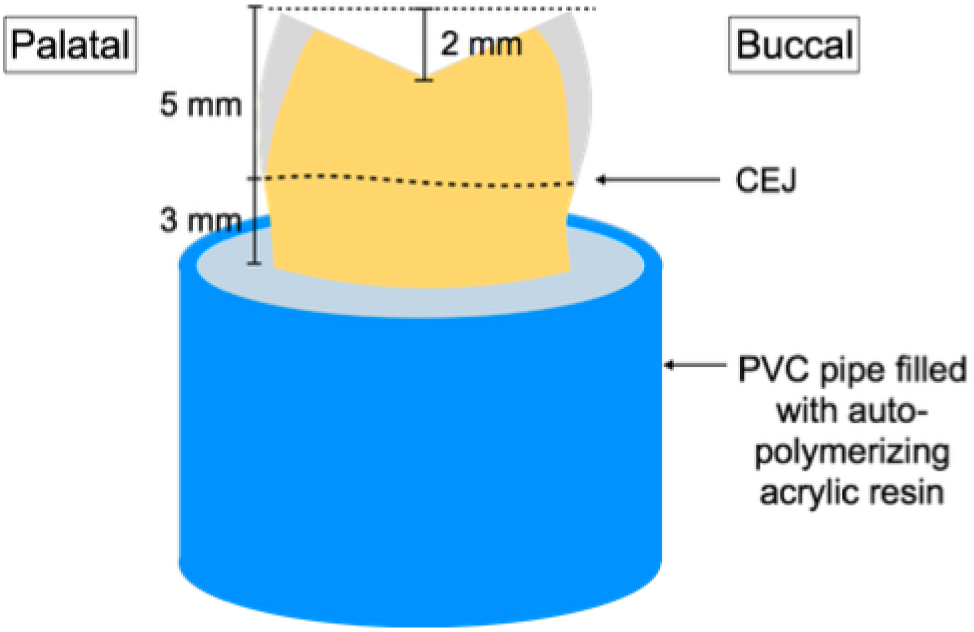

Figure 3 Tooth preparation for occlusal onlay

Then, all prepared teeth were randomly divided among four groups (n = 10) according to the type of restoration and material used:

Group 1 (O-CF): Teeth were restored with direct resin composite (Premise, Kerr Corp., Orange, CA) for thin occlusal onlays.

Group 2 (O-ENM): Teeth were restored with polymer-infiltrated ceramic network (Vita Enamic, Vita Zahnfabrik) for thin occlusal onlays.

Group 3 (O-EMX): Teeth were restored with lithium disilicate ceramic (IPS e.max CAD, Ivoclar Vivadent) for thin occlusal onlays.

Group 4 (Cr-EMX): Teeth were restored with lithium disilicate ceramic (IPS e.max CAD, Ivoclar Vivadent) for full-coverage crowns.

All teeth in the Cr-EMX group were then additionally prepared for all-ceramic crowns by means of round-ended tapered diamond rotary cutting instruments (D8; Intensiv). Dimensions of preparation were done according to the manufacturer's instructions as follows: 1.0-1.5 mm buccal and lingual reduction, total occlusal convergence angle around 6°, and 0.8- to 1.0-mm-deep chamfer margin with 0.5 mm above the CEJ. (Fig 4)

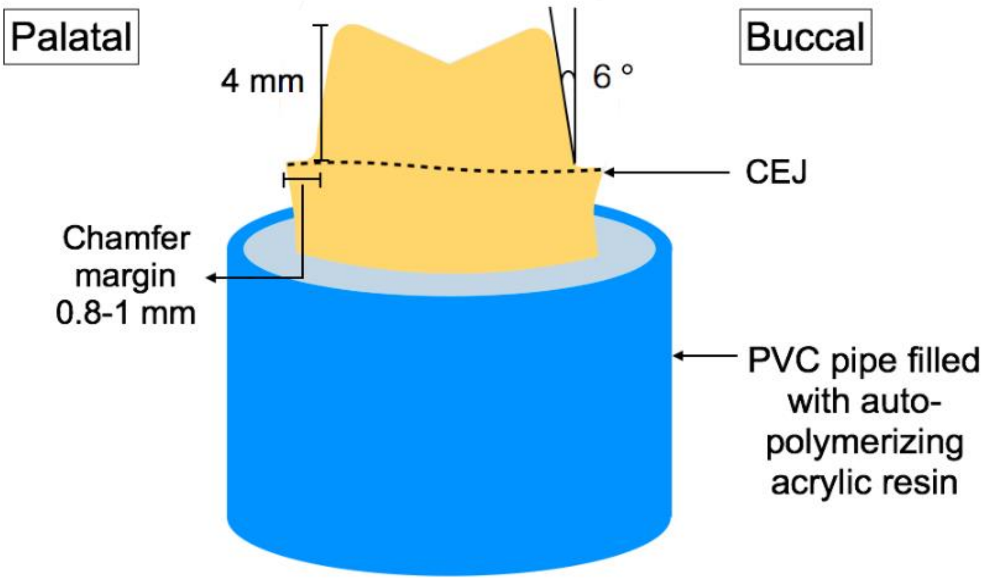

Figure 4 Tooth preparation for crown

All angles were rounded, and all prepared surfaces were refined by means of fine and superfine diamond rotary cutting instruments (40D7 and 50D7; Intensiv), then stored in distilled water at room temperature for 24 hours. All preparations were done by one dentist

Restoration design and fabrication

After 24-hour storage in distilled water at room temperature, teeth in the O-CF, O-ENM, and O-EMX groups were scanned with an Omnicam scanner (Cerec AC Omnicam; Sirona Dental Systems) and designed for thin occlusal onlays with the Cerec4 CAD/CAM system (Sirona Dental Systems). The occlusal onlay design was created by means of the software’s design tools (Cerec SW v. 4.5.2; Sirona Dental Systems) set in Biogeneric Individual Mode with a minimum thickness of 0.6 mm at the central groove, a maximum thickness of 1.3 mm at cusp tips, and 1.0 mm at the internal cusp slope.[11] For standardized form and anatomy, the design of the restoration was begun with the use of position tools (translation and rotation), and then manual adjustment of the original shape produced by the software was performed as needed.

Teeth in the Cr-EMX group were scanned with the Omnicam scanner and designed for all-ceramic full-coverage crowns in the Cerec4 CAD/CAM system. The crown design was created by the software's design tools set in Biogeneric Individual Mode, with an average uniform thickness of 1-1.5 mm.

All restorations in the O-CF, O-ENM, O-EMX, and Cr-EMX groups were milled in a wet-milling machine (Cerec MC XL; Sirona Dental Systems) with Vita CAD Temp Block (Vita Zahnfabrik), Vita Enamic block, and an IPS e.max CAD block for thin occlusal onlays and an IPS e.max CAD block for full-coverage crowns. Then, they were inspected under a dental loupe at 2.5x magnification (Kerr Corp.) for the detection of possible milling cracks. If cracks were present, a new, identical, restoration would be milled. Thickness of restorations was measured with a vernier caliper (Hu-Friedy CLP1, Frankfurt am Main, Germany). The tip of the caliper was positioned at the central pit, mesial pit, and distal pit to ensure the thickness of the occlusal onlay at the center fossa, which was designed to be 0.6 mm. All cusp tips and inclined planes of occlusal onlays were measured to ensure the assigned thicknesses of 1.3 mm and approximately 1 mm, respectively. Crown thickness was measured and corrected until the desired thickness of 1-1.5 mm was uniformly achieved.

Lithium disilicate ceramic restorations (O-EMX and Cr-EMX groups) were crystallized in a ceramic furnace (Programat P700; Ivoclar Vivadent) in which firing parameters for Crystallization LT, MT, and HT were set as recommended by the manufacturer (Ivoclar Vivadent). The outer surfaces of lithium disilicate restorations (O-EMX and Cr-EMX groups) were polished mechanically with an all-ceramic polisher (Jota set 1358; Jota, Switzerland), while polymer-infiltrated ceramic-network onlays (O-ENM group) were finished and polished with the Vita Enamic polishing set (Vita Zahnfabrik).

In the O-CF group, each Vita CAD Temp onlay was temporarily cemented with temporary cement (Temp Bond NE; Kerr Corp.) onto its corresponding prepared tooth to stabilize itself while a transparent shell was fabricated in the next step. After that, the teeth restored with Vita CAD Temp onlays were scanned with the Omnicam scanner and prepared for a 1-mm-thick transparent shell to be placed on top of the thin occlusal onlay, with the software's design tools set in Biogeneric Individual Mode with an average uniform thickness of 1 mm. The margin of the transparent shell was set at the height of the contour level. Subsequently, the transparent shells were milled in the wet-milling machine with clear PMMA blocks (CEREC Guide Bloc, Dentsply Sirona). These transparent shells, which replicated the occlusal anatomy and dimensions of the thin occlusal onlay, were used to standardize the direct composite-restoration procedure. (Fig 5A, 5B, 5C, 5D)

After removal of those Vita CAD Temp occlusal onlays, and tooth-cleaning with pumice, transparent shells were tried-in on corresponding teeth. If the transparent shells were perfectly seated, they were removed to begin the direct composite-restoration procedure. Tooth surfaces were prepared with the three-step etch-and-rinse dentin bonding system, following manufacturer's instructions: etched with 37.5% phosphoric acid (Gel Etchant; Kerr Corp.) for 15 seconds, rinsed thoroughly for 10 seconds until etchant had been completely removed, and air-dried gently for 3-5 seconds with no desiccation on the dentin surface. Then primer was applied over enamel and dentin surfaces (Optibond FL primer; Kerr Corp.) with a light scrubbing motion for 15 seconds, after which teeth were gently air-dried for 3-5 seconds. At this point, the dentin surfaces were expected to have a slightly shiny appearance. The adhesive resin (Optibond FL adhesive; Kerr Corp.) was then applied uniformly over the enamel and dentin, creating a thin coating, thinned with a light application of air and light-polymerized for 20 seconds (Demi Light Curing Unit; Kerr Corp.). After resin composite (Premise A2; Kerr Corp.) was applied directly to the tooth surface, the transparent shell was placed and seated on top of the occlusal surface, excess materials were removed, and the tooth was light-polymerized for 40 seconds. (Fig 5E, 5F, 5G, 5H) All direct composite restorations were finished by means of rugby-ball-shaped superfine diamond rotary cutting instruments

(Intensiv) and polished with an aluminum oxide polisher and diamond polisher (HiLuster PLUS Polishing system; Kerr Corp.).

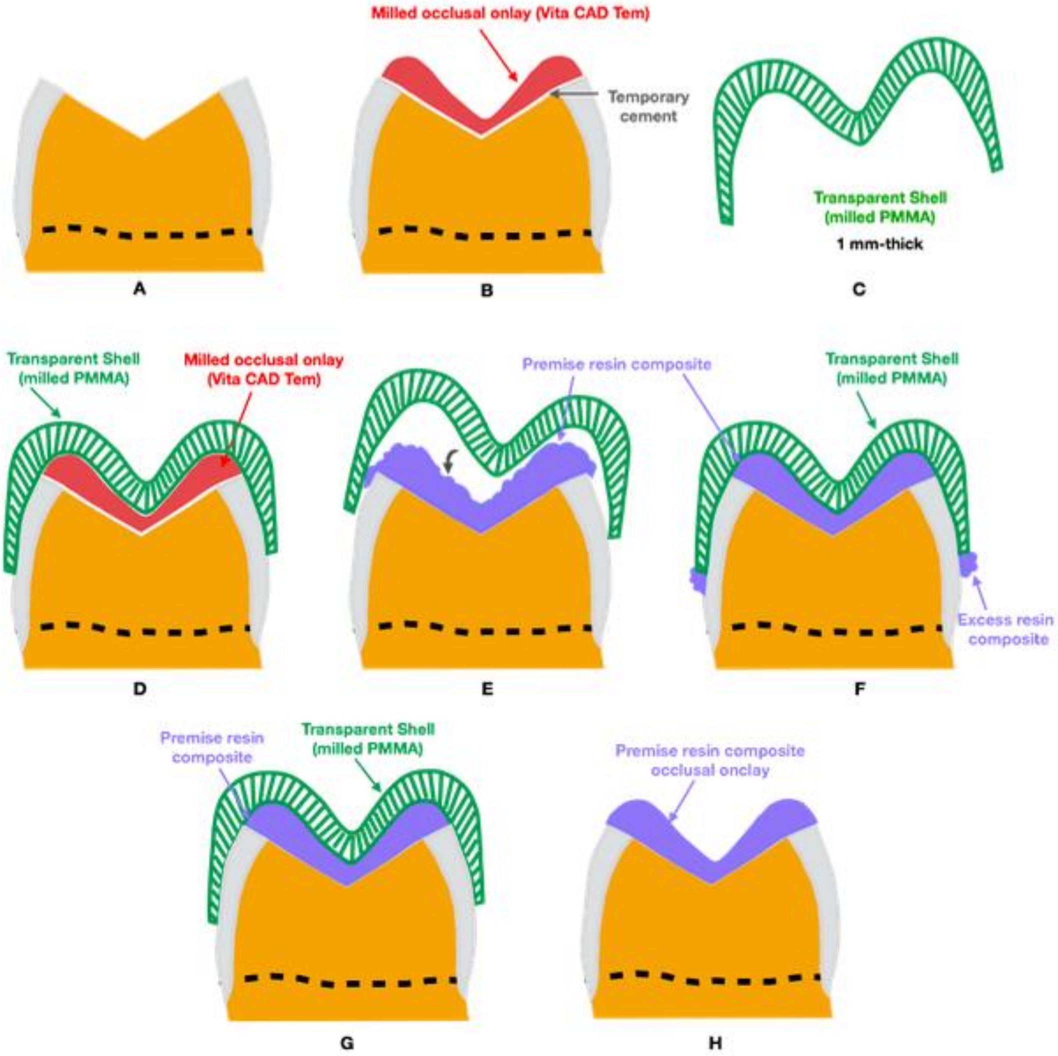

Figure 5 Steps for direct composite thin occlusal onlay restoration

(A) Completed tooth preparation for onlay, (B) First milled thin occlusal onlay, (C) Second milled transparent shell, (D) Try-in transparent shell on their correspond teeth, (E) Apply resin composite and seat the transparent shell on top, (F,G) Remove excess resin composite and light cured, (H) Completed direct resin composite thin occlusal onlay

Cementation of indirect restorations

The inner surfaces of IPS e.max CAD restorations in the O-EMX and Cr-EMX groups were etched with 9% hydrofluoric acid (Porcelain Etch; Ultradent, South Jordan, UT) for 20 seconds in accordance with the manufacturer’s instructions, then thoroughly rinsed for 20 seconds, immersed in distilled water in an ultrasonic bath for 3 minutes, and air-dried. Then, Silane Primer (Kerr Corp.) was applied to the etched surfaces, left for 1 minute, and hot-air-dried for 5 minutes. The self-priming adhesive resin (Optibond Solo adhesive; Kerr Corp.) was applied to the intaglio surfaces of restorations with a dipped microbrush and thinned with a dry microbrush. After the surface treatment and before insertion, the restorations were kept unpolymerized. The same protocol was used for Vita Enamic restorations (O-ENM group), except that the time for the hydrofluoric etching step was extended to 60 seconds.

Concurrently, prepared tooth surfaces in the O-ENM, O-EMX, and Cr-EMX groups were etched with 37.5% phosphoric acid for 15 seconds, rinsed thoroughly for 10-15 seconds until all acid was removed, and gently air-dried for 5 seconds with no desiccation on dentin surfaces. Then, self-priming adhesive resin (Optibond Solo adhesive; Kerr Corp.) was applied over enamel and dentin with a light brushing motion for 15 seconds, thinned with a light application of air for 3 seconds, and light-polymerized for 20 seconds.

The dual-cured adhesive resin cement (NX3 Nexus Third Generation; Kerr Corp.) was applied to intaglio surfaces of the restorations, which were then seated on their corresponding prepared teeth with finger pressure, and residual cement was removed. Buccal, lingual, mesial, distal, and occlusal surfaces were light-polymerized for 20 seconds each. The restored teeth were stored in distilled water at room temperature for 7 days prior to being tested.

Fracture resistance testing

All restored teeth were subjected to static vertical loading at a crosshead speed of 0.5 mm/min in a universal testing machine (Instron model 5566; Instron Corp., Canton, MA). Compressive force was applied with a 3.5-mm-diameter steel tip to stimulate opposing cusps. The tip was positioned along the cuspal inclines over the central fossa to achieve tripodization of contacts. The automatic cut-off was set at 60% loss of peak load. As soon as the crack or fracture occurred, resulting in the discontinuity of the chart recording, the testing machine stopped. The compressive fracture load or fracture strength was recorded in Newtons (N).

Failure mode evaluation

After fracture, the specimens were examined under a dental loupe at 2.5x magnification. Modes of failure were categorized as follows: Mode FrR, fracture in the restoration only; Mode FrRE, fracture of the restoration and enamel; Mode FrRED, fracture of the restoration, enamel, and dentin; and Mode FrREDP, fracture of the restoration, enamel, dentin, and exposed pulp.[7] Mode FrR, FrRE and FrRED were grouped and considered as non-biological failure. Fracture in mode FrREDP was considered as biological failure.

Statistical analysis of data

Data on fracture load and modes of failure were collected by the author and analyzed with statistical software (IBM SPSS Statistics, version 20.0).

The data on fracture load were heterogeneous and normally distributed. One-way ANOVA and Games-Howell post hoc test were used to analyze the differences in failure load among groups (significance level 0.05). The correlation between the fracture load and mode of failure within each group was tested by Spearman's rank-order correlation (significance level 0.05). Pearson Chi-square was used to analyze the difference of biological failure in each group.

CHAPTER IV RESULTS

The fracture strengths of all groups were analyzed (Table 3, Fig 6). The results demonstrated that all restorations exhibited fracture at average loads ranging from 1,949.59 N for Cr-EMX to 2,870.44 N for O-EMX. Restorations in the O-EMX group showed higher fracture strength than those in the O-CF, O-ENM, and Cr-EMX groups. However, one-way ANOVA and Games-Howell post hoc test showed statistically significant differences between the O-EMX and Cr-EMX groups (one-way ANOVA, *p* = 0.001). No statistically significant differences in fracture load were found among the O-CF, O-ENM, and O-EMX groups.

The analysis of failure modes indicated that 2, 1, 2, and 5 specimens in the O-CF group fractured in the FrR, FrRE, FrRED, and FrREDP modes, respectively. Seven, 2, and 1 specimens in the O-ENM group fractured in the FrRE, FrRED, and FrREDP modes, respectively. No specimen in this group fractured in the RrE mode. For the O-EMX group, 1, 4, 2, and 3 specimens exhibited the fracture modes FrR, FrRE, FrRED, and FrREDP, respectively. For the Cr-EMX group, there were 8 and 2 specimens exhibiting the fracture modes FrR and FrREDP, respectively; however, no specimen fractured in the FrRE and FrRED modes. (Fig 7,8)

According to Hinkle's criteria [78], the analysis of correlation between fracture load and mode of failure found that Spearman's rank-order correlation coefficient was categorized as “little if any positive correlation”, “little if any negative correlation”, and “low positive correlation” for the O-CF and O-EMX groups (r_s = 0.254 and 0.108), the Cr-EMX group (r_s = -0.152), and the O-ENM group (r_s = 0.315), respectively.[78] However, with a 95% confidence interval (α = 0.05), all groups presented no statistically significant differences in correlation between the fracture load and mode of failure (Table 3). Pearson Chi-square showed no statistically significant differences in biological failure among groups (p = 0.222).

Table 3 Average fracture strength and mode of failure

Group	Fracture strength (Mean ± SD)	Mode of failure					
		FrR	FrRE	FrRED	FrREDP	r_s	p
O-CF	2,438.66 ± 678.25 ^{a,b}	2	1	2	5	0.254	0.497
O-ENM	2,358.86 ± 396.17 ^{a,b}	0	7	2	1	0.315	0.376
O-EMX	2,870.44 ± 414.95 ^{a}	1	4	2	3	0.108	0.766
Cr-EMX	1,949.59 ± 215.15 ^{b}	8	0	0	2	-0.152	0.675

Different letters indicate significant differences in fracture strength between groups (Games-Howell post hoc test; $p < 0.05$).

r_s = Spearman’s rank-order correlation

p = p value

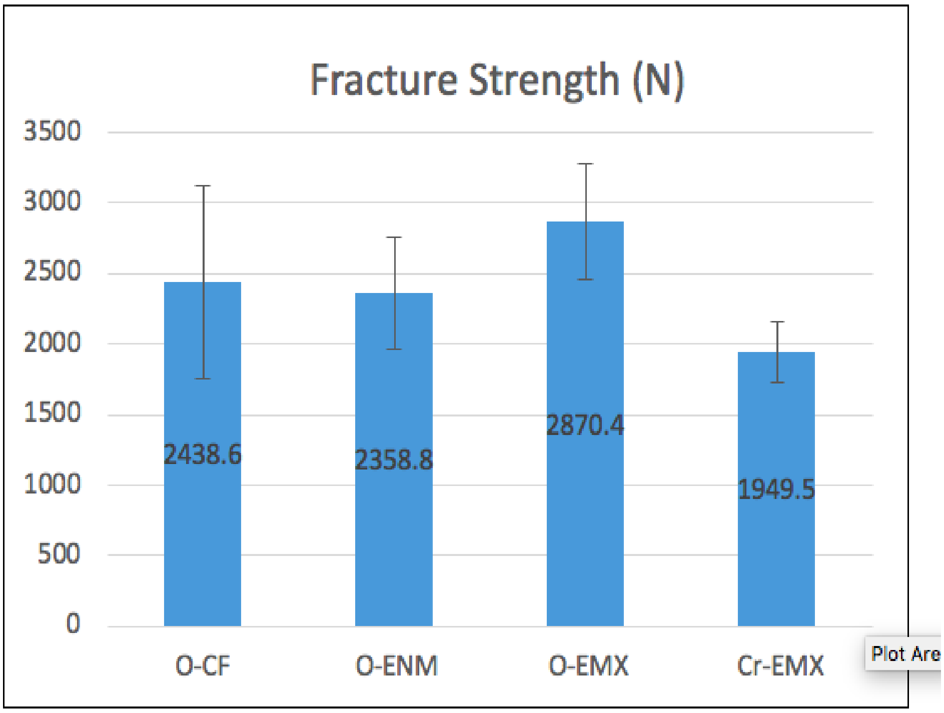

Figure 6 Average fracture strength of each group

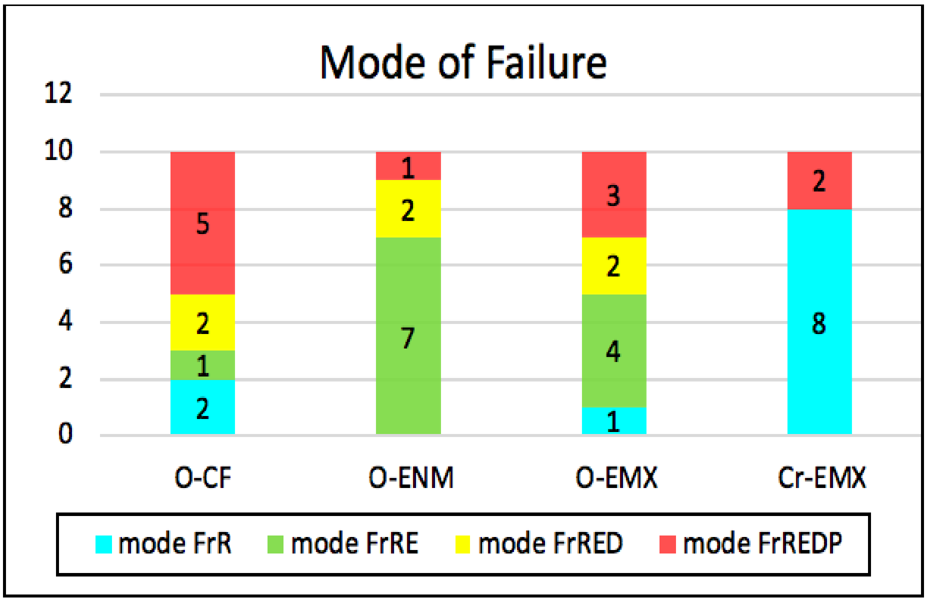

Figure 7 Modes of failure of each group

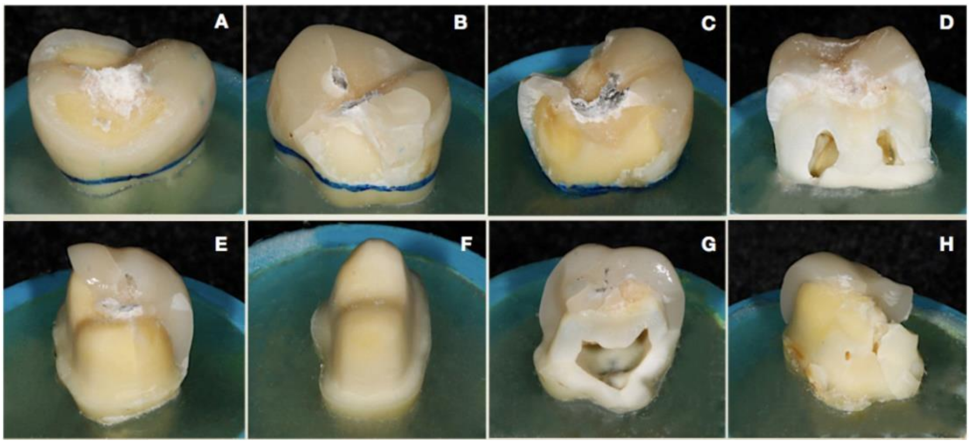

Figure 8 Fracture of onlay and crown specimens

(A-D) onlays, (E-H) crowns, (A) mode FrR, (B) mode FrRE, (C) mode FrRED, (D) mode FrREDP, (E,F) mode FrR, (G,H) mode FrREDP

CHAPTER V DISCUSSIONS

The thin occlusal onlay is a treatment option with a minimally invasive strategy. It has been used to restore occlusal tooth surface loss that occurred for physical and chemical reasons. Compared with conventional full-coverage crowns, use of the thin occlusal onlay decreases the amount of tooth preparation. This study aimed to evaluate the fracture strengths and failure modes of thin occlusal onlays (0.6-mm) fabricated from direct resin composite (Premise) or a polymer-infiltrated ceramic-network block (Vita Enamic) or a CAD/CAM lithium disilicate ceramic block (IPS e.max CAD) compared with those of conventional full-coverage crowns (IPS e.max CAD crown) under vertical compressive loading. We found that lithium disilicate ceramic (IPS e.max CAD) onlays exhibited significantly higher fracture resistance than did lithium disilicate ceramic (IPS e.max CAD) crowns, indicating that a lithium disilicate ceramic (IPS e.max CAD) onlay could effectively withstand higher static loads. These findings offer further support for the utilization of thin occlusal onlays as functional and predictable means of posterior tooth reconstruction.

The results of this study showed fracture strengths in descending order: lithium disilicate ceramic (IPS e.max CAD) onlay, direct resin composite (Premise) onlay, polymer-infiltrated ceramic-network (Vita Enamic) onlay, and lithium disilicate ceramic (IPS e.max CAD) crown. However, one-way ANOVA and Games-Howell post hoc test showed statistically significant differences between lithium disilicate ceramic (IPS e.max

CAD) onlays and lithium disilicate ceramic (IPS e.max CAD) crowns. Due to different means of tooth preparation, less tooth reduction was achieved with the thin occlusal onlay cemented onto both dentin and peripheral enamel, whereas more tooth preparation was achieved with crowns mostly cemented onto dentin, resulting in increased susceptibility to static compressive load for crowns. It can be said that the larger the degree of tooth preparation, the weaker the remaining tooth structure. In contrast to our study, Fennis et al. (2004) demonstrated that fatigue resistance of cuspal-coverage restorations on premolars was increased when reduced tooth structure was replaced with thicker restorative material. However, in terms of failure mode, the higher tooth-structure loss could cause more dramatic irreversible failure.[79] In a study by Wittneben et al. (2009), who determined long-term clinical survival rates of single-tooth CAD/CAM restorations, similar 5-year survival rates of full crowns (92.3%) and inlay/onlays (92.9%) were reported.[80]

Fractures that are limited to the restorative material and do not involve the tooth structure improve the longevity of a restored tooth because it can be easily replaced by an identical milled restoration, without damage to natural tooth structure. Fractures that involve pulpal tissue are called “biological damage” or “biological failure”, which are also considered severe situations. Such biological failure may force the patient to elect endodontic procedures or extraction, leading to further compromise of the patient’s dental health. Our results showed that 50% of direct resin composite (Premise) onlays exhibited fracture in the FrREDP mode or biological failure, whereas less biological failure occurred in other groups. However, Pearson Chi-square showed no statistically significant difference in number of tooth fracture in biological failure between groups.

Ninety percent of onlay restorations exhibited fracture involving tooth structure (enamel, dentin, or pulp), and only 10% (3 of 30) exhibited fracture in restorative material. It could be inferred that the majority of onlays required more aggressive or complicated treatment when fractures arose. Compared with crowns, most (80%) fractured in restorative material and only 20% fractured in tooth structure. Regarding failure mode, 50% of samples in the direct composite group in the current study tended to fail in the FrREDP mode. This was in agreement with the results of a previous study by Kois et al. (2013), who evaluated fracture resistance of 2-mm-thick occlusal onlays. They found that lithium disilicate ceramic had significantly higher fracture resistance than leucite-reinforced ceramic, feldspathic ceramic, and indirect resin composite. Ceramic occlusal onlays tended to fracture in restorative material itself, but when composite occlusal onlays fractured, they exposed tooth structure, with 74% of pulp exposed.[81]

Several studies have determined the mechanical properties and reported the superior mechanical strength of lithium disilicate ceramic (IPS e.max CAD) compared with polymer-infiltrated ceramic-network (Vita Enamic) and other CAD/CAM composite blocks.[19, 82-85] Stawarczyk et al. (2015) reported flexural strengths of 356 and 146

MPa for IPS e.max CAD and Vita Enamic, respectively.[19] They also reported similar flexural strengths for Lava Ultimate, Shofu Block, and other composite blocks. Similar results were found in other studies of the flexural strength of IPS e.max CAD and Vita Enamic.[83-85] In addition, Lawson et al. (2016) reported comparable flexural strength between Paradigm MZ100 and Vita Enamic.[85] Albero et al. (2015) also reported higher values of fracture load and flexural strength for IPS e.max CAD (0.44 kN and 2716 MPa) than for Vita Enamic (0.25 kN and 1809 MPa) and Lava Ultimate (0.26 kN and 1643 MPa).[82] We hypothesized that IPS e.max CAD thin occlusal onlays would provide higher fracture strength than Vita Enamic thin occlusal onlays. However, different results were found in the current study compared with the other studies mentioned above. The present study found no difference in fracture strength among IPS e.max CAD, Vita Enamic, and composite when thin occlusal onlays were fabricated.

Today's CAD/CAM technologies are being continuously improved. This technology allows for quality control, for example, the control of thickness and anatomy of restorations during fabrication, as well as manufacturer-regulated mechanical properties of the restorative materials. They have also achieved standardization of the internal fit of restorations.[13, 14] Many confounding operator factors can be avoided, such as dental laboratory technicians' skills and accuracy involved in the fabrication process. In addition, labor and processing time can be reduced, and design and processing data can be saved and reproduced.[13, 15]

There have been numerous studies regarding the feasibility of fabricating CAD/CAM thin occlusal onlays with thicknesses of 1 mm or less.[7, 8, 10, 11] First, Egbert et al. (2015) compared fracture strengths and modes of failure of 0.3-mm occlusal onlays fabricated from CAD/CAM composite (Paradigm MZ100), resin nanoceramic (Lava Ultimate), and hybrid ceramic (Vita Enamic). All restorations could be fabricated successfully and showed fracture strengths ranging from 1727 N (for Vita Enamic) to 2415 N (for Lava Ultimate); most restorations exhibited fracture in the restoration only.[7] Second, Johnson et al. (2014) determined the effects of material type and restoration thickness (0.3, 0.6, and 1.0 mm) on the fracture strength of posterior occlusal onlays made from CAD/CAM composite (Paradigm MZ100) and composite-ceramic (Lava Ultimate) materials. All restorations could be milled successfully. Lava Ultimate fractured at higher loads than Paradigm MZ100 onlay without the effect of thickness.[8] Third, Sasse et al. (2015) evaluated fracture resistance of non-retentive full-coverage onlays made from lithium disilicate ceramic with various thickness (0.3-0.6, 0.5-0.8, and 0.7-1.0 mm) and different types of bonding surface (enamel, enamel + dentin, and enamel + dentin + composite). They found that fracture resistance was influenced by thickness and that only the thickest occlusal onlay (0.7-1.0 mm) survived cyclic loading without damage. Restorations bonded to dentin or composite surfaces provided higher fracture resistance than those bonded to enamel,[10] which was in contrast to the results of the current study. The assumed reason for this contrast is the different adhesive bonding systems involved. In the study mentioned, self-etching primer was used, leading to higher bond strength to dentin, while total-etch adhesive systems were used in the current study. Fourth, Schlichting et al. (2011) assessed the fatigue resistance of CAD/CAM ceramic (IPS Empress CAD and IPS e.max CAD) and composite (Paradigm MZ100 and XR) thin occlusal onlays with 0.6-mm thickness. All restorations could be milled successfully. Both composite occlusal onlays had higher fatigue resistance than ceramic occlusal onlays.[11] Similar to the present study, in which tooth preparation was performed, exposing dentin and peripheral enamel, thin occlusal onlays (0.6 mm at the central groove, maximum 1.3 mm at the cusp tip, and 1.0 mm at the internal cusp slope) could be milled successfully with all the materials tested. However, no difference in fracture strengths of thin occlusal onlays was observed among the different materials used in the current study.

In contrast, Tsitrou et al. (2008) investigated the ability of the CAD/CAM system to produce minimal preparation designs: 0.6-mm occlusal reduction and 0.4-mm chamfer margin, for crowns with resin composite (Paradigm MZ100) and two ceramic materials (ProCAD and VITA Mark II). They found that only the composite block could fabricate acceptable crowns without marginal defect, while the ceramic block could not. The ceramic materials required more aggressive preparation design to produce clinically acceptable crowns,[86] implying that their ability to mill thin restorations may be influenced by the type of preparation (crown vs non-retentive occlusal onlay). We hope that further development of oral scanners, together with improved CAD design software and CAM milling machines, as well as the excellent mechanical properties of prefabricated blocks, can enhance the fabrication of thinner restorations.

Due to time limitations, our study was designed to determine only static compressive strength testing. It was known that static loading could not replicate either the long-term effect of occlusal force on the restoration-tooth system, or the forces generated by most patients who exhibit occlusal wear.9 Occlusal force generated by such patients is multidirectional and non-tripodized. Nevertheless, the tripodization of contact we used in this study is considered the 'gold standard' in restoring patients with fixed restorations,[87] and the static load value could be the maximum strength for such restorations. Environmental effects and cyclic loading (mechanical and thermal fatigue) are likely to reduce this maximum strength value over time. Therefore, many studies have been designed to determine dynamic strength testing instead, and the results found higher fatigue resistance of composite compared with ceramic onlays.[9, 11] Although the same configuration of tooth preparation was performed, different results of fracture strength were found in the current study compared with the studies mentioned above. Thus, to eliminate this controversy, further studies regarding aging processes and dynamic strength testing should be undertaken.

The high fracture strengths of thin occlusal onlays reported from this study may support various useful clinical applications for patients with lost occlusal tooth structure.

The author proposes the use of thin occlusal onlays made from CAD/CAM technology because of its ability to control thickness and reduce treatment time. Both the CAD/CAM hybrid ceramic onlay and the lithium disilicate ceramic onlay provided comparable strength. Compared with crowns, the thin occlusal onlay required less tooth structure removal. With patients suffering from bruxism or clenching, with the concomitant loss of surrounding tooth structure, crowns would be a reasonable option that provides a preferable manner of fracture. However, all groups of restorations in the present study exhibited fracture strengths exceeding average human masticatory force, ranging between 433 and 906 N.[88-91]

CHAPTER VI CONCLUSIONS

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

1. Higher fracture strength was shown in IPS e.max CAD occlusal onlays compared with IPS e.max CAD crowns.
2. Fracture strength of Vita Enamic occlusal onlays was comparable with that of Premise occlusal onlays and IPS e.max CAD onlays.
3. All restorations (onlays and crowns) demonstrated fracture resistance higher than the average force of mastication.

REFERENCES

1. Bartlett, D., *Chapter 4 - Tooth wear*, in *Advanced Operative Dentistry*. 2011, Churchill Livingstone: Edinburgh. p. 45-54.
2. Grippo, J.O., M. Simring, and S. Schreiner, *Attrition, abrasion, corrosion and abfraction revisited: a new perspective on tooth surface lesions.* J Am Dent Assoc, 2004. **135**(8): p. 1109-18.
3. Baloch, H., A. Hanif, and M. Naseem, *Tooth surface loss revisited: Classification, etiology, and management.* J Res Dent, 2015. **3**(2): p. 37-43.
4. Lopez-Frias, F.J., et al., *Clinical measurement of tooth wear: Tooth wear indices.* J Clin Exp Dent, 2012. **4**(1): p. 48-53.
5. Lussi, A., et al., *Buonocore Memorial Lecture. Dental erosion.* Oper Dent, 2009. **34**(3): p. 251-62.
6. Al-Omiri, M., P.-J. Lamey, and T. Clifford, *Impact of tooth wear on daily living.* Int J Prosthodont, 2006. **19**(6): p. 601-5.
7. Egbert, J.S., et al., *Fracture strength of ultrathin occlusal veneer restorations made from CAD/CAM composite or hybrid ceramic materials.* Oral Science International, 2015. **12**(2): p. 53-58.
8. Johnson, A.C., et al., *Fracture strength of CAD/CAM composite and composite-ceramic occlusal veneers*. J Prosthodont Res, 2014. **58**(2): p. 107-14.
9. Magne, P., et al., *In vitro fatigue resistance of CAD/CAM composite resin and ceramic posterior occlusal veneers.* J Prosthet Dent, 2010. **104**(3): p. 149-57.
10. Sasse, M., et al., *Influence of restoration thickness and dental bonding surface on the fracture resistance of full-coverage occlusal veneers made from lithium disilicate ceramic.* Dental Materials, 2015. **31**(8): p. 907-15.
11. Schlichting, L.H., et al., *Novel-design ultra-thin CAD/CAM composite resin and ceramic occlusal veneers for the treatment of severe dental erosion.* J Prosthet Dent, 2011. **105**(4): p. 217-26.
12. Duret, F., J.-L. Blouin, and B. Duret, *CAD-CAM in dentistry.* Journal Of The

American Dental Association, 1988. **117**(6): p. 715-720.

13. Beuer, F., J. Schweiger, and D. Edelhoff, *Digital dentistry: an overview of recent developments for CAD/CAM generated restorations.* Br Dent J, 2008. **204**(9): p. 505-11.
14. Davidowitz, G. and P.G. Kotick, *The Use of CAD/CAM in Dentistry.* Dental Clinics of North America, 2011. **55**(3): p. 559-570.
15. Miyazaki, T., et al., *A review of dental CAD/CAM: current status and future perspectives from 20 years of experience.* Dent Mater J, 2009. **28**(1): p. 44-56.
16. Coldea, A., M.V. Swain, and N. Thiel, *Mechanical properties of polymer-infiltrated-ceramic-network materials.* Dent Mater, 2013. **29**(4): p. 419-26.
17. Della Bona, A., P.H. Corazza, and Y. Zhang, *Characterization of a polymer-infiltrated ceramic-network material.* Dent Mater, 2014. **30**(5): p. 564-9.
18. Sieper, K., S. Wille, and M. Kern, *Fracture strength of lithium disilicate crowns compared to polymer-infiltrated ceramic-network and zirconia reinforced lithium silicate crowns.* J Mech Behav Biomed Mater, 2017. **74**: p. 342-348.
19. Stawarczyk, B., et al., *Evaluation of mechanical and optical behavior of current esthetic dental restorative CAD/CAM composites.* J Mech Behav Biomed Mater, 2015. **55**: p. 1-11.
20. El Zhawi, H., et al., *Polymer infiltrated ceramic network structures for resistance to fatigue fracture and wear.* Dental Materials, 2016. **32**(11): p. 1352-1361.
21. Elsaka, S.E., *Repair bond strength of resin composite to a novel CAD/CAM hybrid ceramic using different repair systems.* Dental Materials Journal, 2015. **34**(2): p. 161-167.
22. Coldea, A., M.V. Swain, and N. Thiel, *Hertzian contact response and damage tolerance of dental ceramics.* J Mech Behav Biomed Mater, 2014. **34**: p. 124-33.
23. Ramos Nde, C., et al., *Microstructure characterization and SCG of newly engineered dental ceramics.* Dent Mater, 2016. **32**(7): p. 870-8.
24. Swain, M.V., et al., *Interpenetrating network ceramic-resin composite dental restorative materials.* Dent Mater, 2016. **32**(1): p. 34-42.

25. Lambert, H., et al., *Dental biomaterials for chairside CAD/CAM: State of the art.* J Adv Prosthodont, 2017. **9**(6): p. 486-495.

26. Min, J., et al., *Comparison of human enamel and polymer-infiltrated-ceramic-network material “ENAMIC” through micro- and nano-mechanical testing.* Ceramics International, 2016. **42**(9): p. 10631-10637.

27. Gilmour, A.G. and H.A. Beckett, *The voluntary reflux phenomenon*. Vol. 175. 1993. 368-72.

28. Milosevic, A., P. J Young, and M.A. Lennon, *The prevalence of tooth wear in 14-year-old school children in Liverpool*. Vol. 11. 1994. 83-6.

29. Lee, A., et al., *Tooth wear and wear investigations in dentistry.* Journal of Oral Rehabilitation, 2011. **39**(3): p. 217-225.

30. Chu, F.C.S., et al., *Restorative Management of the Worn Dentition: 1. Aetiology and Diagnosis.* Dental Update, 2002. **29**(4): p. 162-168.

31. Addy, M., *Tooth brushing, tooth wear and dentine hypersensitivity — are they associated?* International Dental Journal, 2010. **55**(S4): p. 261-267.

32. Bizhang, M., et al., *Toothbrush abrasivity in a long-term simulation on human dentin depends on brushing mode and bristle arrangement.* PLOS ONE, 2017. **12**(2): p. e0172060.

33. Sarode, G. and S. Sarode, *Abfraction: A review*. Vol. 17. 2013. 222-227.

34. Peutzfeldt, A., T. Jaeggi, and A. Lussi, *Restorative Therapy of Erosive Lesions.* Monographs in Oral Science, 2014. **25**: p. 253-261.

35. Vailati, F. and U.C. Belser, *Classification and treatment of the anterior maxillary dentition affected by dental erosion: the ACE classification.* Int J Periodontics Restorative Dent, 2010. **30**(6): p. 559-71.

36. Hondrum, S.O., *A review of the strength properties of dental ceramics.* Journal of Prosthetic Dentistry, 1992. **67**(6): p. 859-865.

37. Giordano, R. and E.A. McLaren, *Ceramics overview: classification by microstructure and processing methods.* Compend Contin Educ Dent, 2010. **31**(9): p. 682-688.

38. McLaren, E. and R. Giordano, *Zirconia-Based Ceramics: Material Properties, Esthetics, and Layering Techniques of a New Veneering Porcelain, VM9.* Quintessence Dent Technol, 2005. **28**: p. 99-111.

39. Albakry, M., M. Guazzato, and M.V. Swain, *Biaxial flexural strength, elastic moduli, and x-ray diffraction characterization of three pressable all-ceramic materials.* Journal of Prosthetic Dentistry, 2003. **89**(4): p. 374-380.

40. Höland, W., et al., *A comparison of the microstructure and properties of the IPS Empress®2 and the IPS Empress® glass-ceramics.* Journal of Biomedical Materials Research, 2002. **53**(4): p. 297-303.

41. Piwowarczyk, A., H.-C. Lauer, and J.A. Sorensen, *In vitro shear bond strength of cementing agents to fixed prosthodontic restorative materials.* Journal of Prosthetic Dentistry, 2004. **92**(3): p. 265-273.

42. Clarke, D.R., *Interpenetrating Phase Composites.* Journal of the American Ceramic Society, 1992. **75**(4): p. 739-758.

43. Andersson, M., et al., *Procera: a new way to achieve an all-ceramic crown.* Quintessence Int, 1998. **29**(5): p. 285-96.

44. Papanagiotou, H.P., et al., *In vitro evaluation of low-temperature aging effects and finishing procedures on the flexural strength and structural stability of Y-TZP dental ceramics.* Journal of Prosthetic Dentistry, 2006. **96**(3): p. 154-164.

45. Piwowarczyk, A., et al., *A Clinical Report and Overview of Scientific Studies and Clinical Procedures Conducted on the 3M ESPE Lava™ All-Ceramic System.* Journal of Prosthodontics, 2005. **14**(1): p. 39-45.

46. Chen, M.H., *Update on dental nanocomposites.* J Dent Res, 2010. **89**(6): p. 549-60.

47. Goncalves, F., et al., *Contraction stress determinants in dimethacrylate composites.* J Dent Res, 2008. **87**(4): p. 367-71.

48. Asmussen, E. and A. Peutzfeldt, *Influence of UEDMA, BisGMA and TEGDMA on selected mechanical properties of experimental resin composites.* Dental Materials, 1998. **14**(1): p. 51-56.

49. Sideridou, I.D. and D.S. Achilias, *Elution study of unreacted Bis-GMA, TEGDMA, UDMA, and Bis-EMA from light-cured dental resins and resin composites using HPLC.* J Biomed Mater Res B, 2005. **74**(1): p. 617-626.

50. Ferracane, J.L., *Resin composite—State of the art.* Dental Materials, 2011. **27**(1): p. 29-38.

51. Kim, K.-H., J.L. Ong, and O. Okuno, *The effect of filler loading and morphology on the mechanical properties of contemporary composites.* Journal of Prosthetic Dentistry, 2002. **87**(6): p. 642-649.

52. Ikejima, I., R. Nomoto, and J.F. McCabe, *Shear punch strength and flexural strength of model composites with varying filler volume fraction, particle size and silanation.* Dental Materials, 2003. **19**(3): p. 206-211.

53. Manhart, J., et al., *Mechanical properties of new composite restorative materials.* Journal of Biomedical Materials Research, 2000. **53**(4): p. 353-361.

54. Stansbury, J.W., *Curing Dental Resins and Composites by Photopolymerization.* J Esthet Restor Dent, 2000. **12**(6): p. 300-308.

55. Azzopardi, N., et al., *Effect of resin matrix composition on the translucency of experimental dental composite resins.* Dental Materials, 2009. **25**(12): p. 1564-1568.

56. Guess, P.C., et al., *Monolithic CAD/CAM lithium disilicate versus veneered Y-TZP crowns: comparison of failure modes and reliability after fatigue.* Int J Prosthodont, 2010. **23**(5): p. 434–442.

57. Li, R.W.K., T.W. Chow, and J.P. Matinlinna, *Ceramic dental biomaterials and CAD/CAM technology: State of the art.* Journal of prosthodontic research, 2014. **58**(4): p. 208-216.

58. Culp, L. and E.A. McLaren, *Lithium disilicate: the restorative material of multiple options.* Compend Contin Educ Dent Suppl, 2010. **31**(9): p. 716-20, 722, 724-5.

59. Sadowsky, S.J., *An overview of treatment considerations for esthetic restorations: A review of the literature.* Journal of Prosthetic Dentistry, 2006. **96**(6): p. 433-442.

60. Asai, T., et al., *Effect of overglazed and polished surface finishes on the*

compressive fracture strength of machinable ceramic materials. Dental Materials Journal, 2010. **29**(6): p. 661-667.

61. Fasbinder, D.J., et al., *A Clinical Evaluation of Chairside Lithium Disilicate CAD/CAM Crowns.* Journal Of The American Dental Association, 2010. **141**: p. 10S-14S.

62. Reich, S., et al., *A preliminary study on the short-term efficacy of chairside computer-aided design/computer-assisted manufacturing- generated posterior lithium disilicate crowns.* Int J Prosthodont. , 2010. **23**(3): p. 214-6.

63. Blackham, J.T., K.S. Vandewalle, and W. Lien, *Properties of Hybrid Resin Composite Systems Containing Prepolymerized Filler Particles.* Operative Dentistry, 2009. **34**(6): p. 697-702.

64. Moörmann, W.H., *The evolution of the CEREC system.* Journal Of The American Dental Association, 2006. **137**: p. 7S-13S.

65. Galhano, G.Á.P., E.P. Pellizzer, and J.V.Q. Mazaro, *Optical Impression Systems for CAD-CAM Restorations.* Journal of Craniofacial Surgery, 2012. **23**(6): p. 575-9.

66. Mormann Wh Fau - Brandestini, M., et al., *Chairside computer-aided direct ceramic inlays.* Quintessence Int, 1989. **20**(5): p. 329-39.

67. Santos Gc Jr Fau - Santos, M.J.M.C., Jr., et al., *Overview of CEREC CAD/CAM chairside system.* Gen Dent, 2013. **61**(1): p. 36-40.

68. Tsitrou, E.A., S.E. Northeast, and R. van Noort, *Brittleness index of machinable dental materials and its relation to the marginal chipping factor.* Journal of Dentistry, 2007. **35**(12): p. 897-902.

69. Denry, I., *How and when does fabrication damage adversely affect the clinical performance of ceramic restorations?* Dental Materials, 2013. **29**(1): p. 85-96.

70. Mondelli, R.F.L., et al., *Fracture resistance of weakened teeth restored with condensable resin with and without cusp coverage.* J Appl Oral Sci, 2009. **17**(3): p. 161-165.

71. Kelly, J.R., *Clinically relevant approach to failure testing of all-ceramic restorations.* Journal of Prosthetic Dentistry, 1999. **81**(6): p. 652-661.

72. Al-Wahadni, A. and D.L. Gutteridge, *An in vitro investigation into the effects of retained coronal dentine on the strength of a tooth restored with a cemented post and partial core restoration.* International Endodontic Journal, 2002. **35**(11): p. 913-8.

73. Zandbiglari, T., H. Davids, and E. Schäfer, *Influence of instrument taper on the resistance to fracture of endodontically treated roots.* Oral Surg Oral Med Oral Pathol Oral Radiol Endod, 2006. **101**(1): p. 126-131.

74. Espevik, S., *Stress/strain behavior of dental amalgams.* Acta Odontologica Scandinavica, 1978. **36**(2): p. 103-111.

75. Loney, R.W., R.G. Moulding Mb Fau - Ritsco, and R.G. Ritsco, *The effect of load angulation on fracture resistance of teeth restored with cast post and cores and crowns.* Int J Prosthodont., 1995. **8**(3): p. 247-51.

76. Salameh, Z., et al., *Fracture Resistance and Failure Patterns of Endodontically Treated Mandibular Molars Restored Using Resin Composite With or Without Translucent Glass Fiber Posts.* Journal of Endodontics, 2006. **32**(8): p. 752-755.

77. Ross, I.F., *Occlusal contacts of the natural teeth.* Journal of Prosthetic Dentistry, 1974. **32**(6): p. 660-667.

78. Hinkle, D.E., W. Wiersma, and S.G. Jurs, *Applied Statistics for the Behavioral Sciences*. Applied Statistics for the Behavioral Sciences. 2003: Houghton Mifflin. 756.

79. Fennis, W.M., et al., *Fatigue resistance of teeth restored with cuspal-coverage composite restorations.* Int J Prosthodont, 2004. **17**(3): p. 313-7.

80. Wittneben, J.G., et al., *A systematic review of the clinical performance of CAD/CAM single-tooth restorations.* Int J Prosthodont, 2009. **22**(5): p. 466-71.

81. Kois, D.E., et al., *Evaluation of fracture resistance and failure risks of posterior partial coverage restorations.* J Esthet Restor Dent, 2013. **25**(2): p. 110-22.

82. Albero, A., et al., *Comparative characterization of a novel cad-cam polymer-infiltrated-ceramic-network.* J Clin Exp Dent, 2015. **7**(4): p. 495-500.

83. Goujat, A., et al., *Mechanical properties and internal fit of 4 CAD-CAM block*

materials. J Prosthet Dent, 2018. **119**(3): p. 384-389.

84. Homaei, E., et al., *Static and fatigue mechanical behavior of three dental CAD/CAM ceramics.* J Mech Behav Biomed Mater, 2016. **59**: p. 304-313.

85. Lawson, N.C., R. Bansal, and J.O. Burgess, *Wear, strength, modulus and hardness of CAD/CAM restorative materials.* Dent Mater, 2016. **32**(11): p. e275-e283.

86. Tsitrou, E.A. and R. van Noort, *Minimal preparation designs for single posterior indirect prostheses with the use of the Cerec system.* International journal of computerized dentistry, 2008. **11**: p. 227-240.

87. McHorris, W.H., *Occlusion with particular emphasis on the functional and parafunctional role of anterior teeth. Part 2.* (0022-3875 (Print)).

88. Abu Alhaija, E.S., et al., *Maximum occlusal bite forces in Jordanian individuals with different dentofacial vertical skeletal patterns.* Eur J Orthod, 2010. **32**(1): p. 71-7.

89. Gibbs, C.H., et al., *Occlusal forces during chewing—Influences of biting strength and food consistency.* Journal of Prosthetic Dentistry, 1981. **46**(5): p. 561-567.

90. Varga, S., et al., *Maximum voluntary molar bite force in subjects with normal occlusion.* Eur J Orthod, 2011. **33**(4): p. 427-33.

91. Waltimo, A. and M. Kononen, *A novel bite force recorder and maximal isometric bite force values for healthy young adults.* Scand J Dent Res., 1993. **101**(3): p. 171-5.

APPENDIX

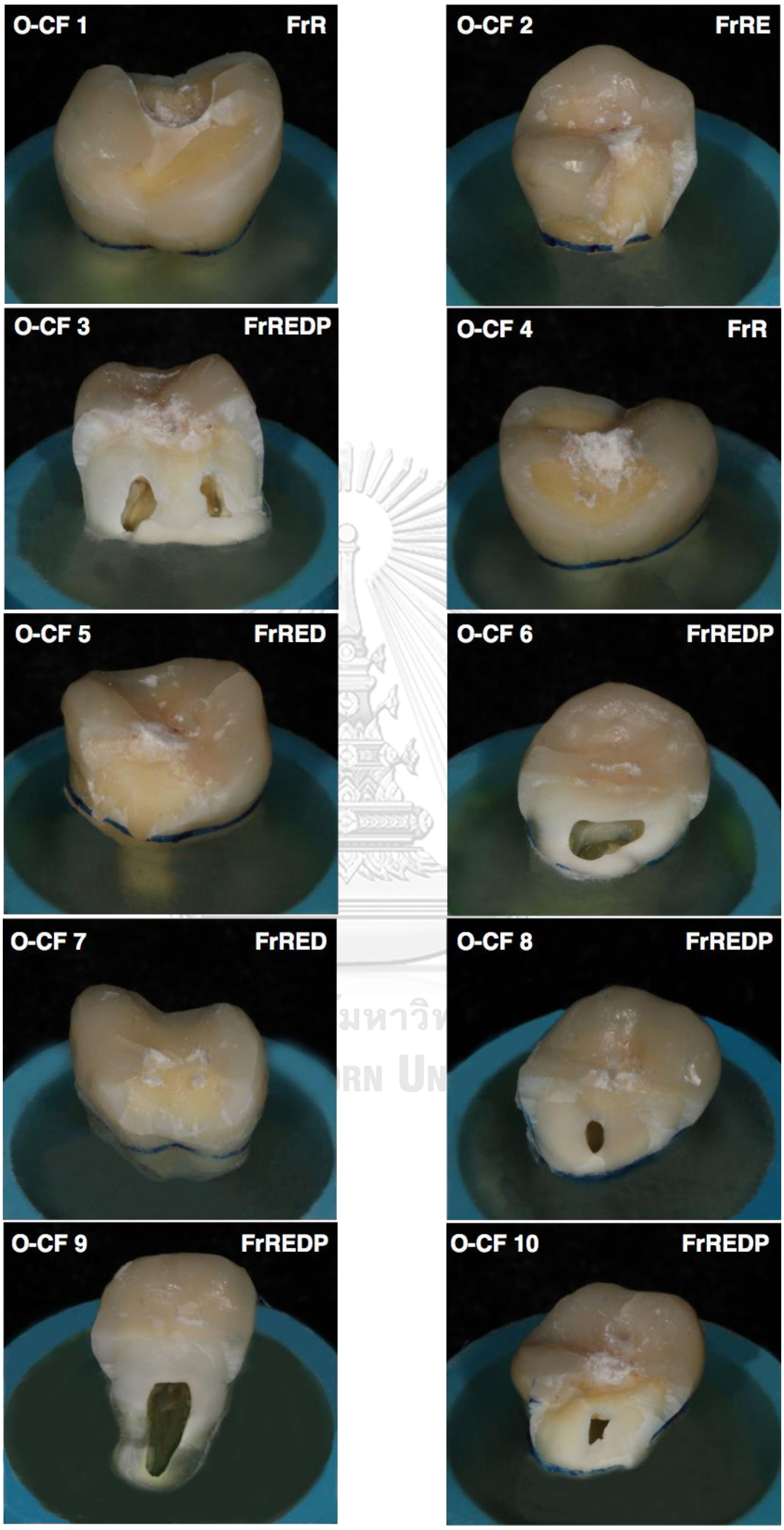

Figure 9 Fracture of specimens in O-CF group

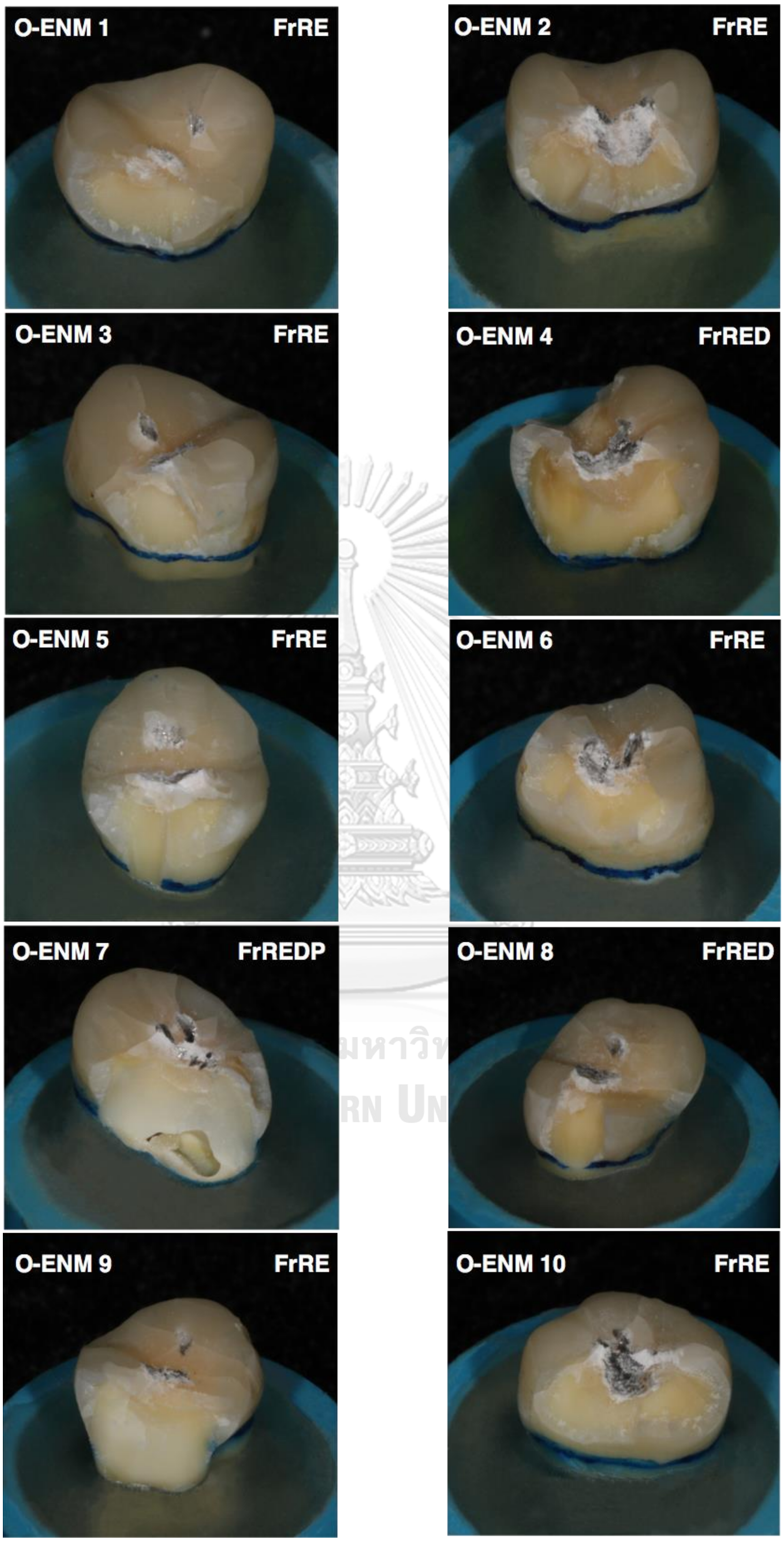

Figure 10 Fracture of specimens in O-ENM group

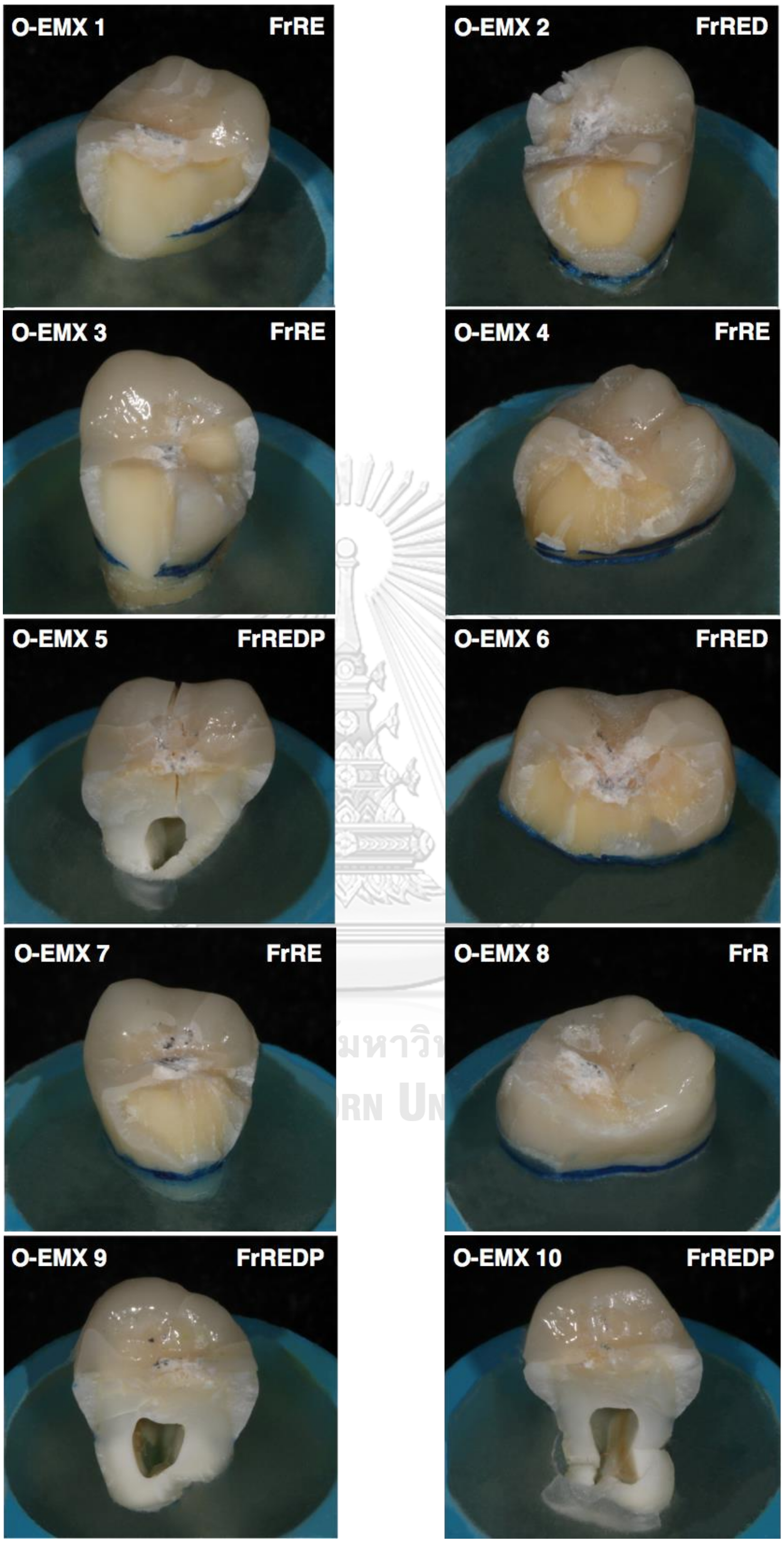

Figure 11 Fracture of specimens in O-EMX group

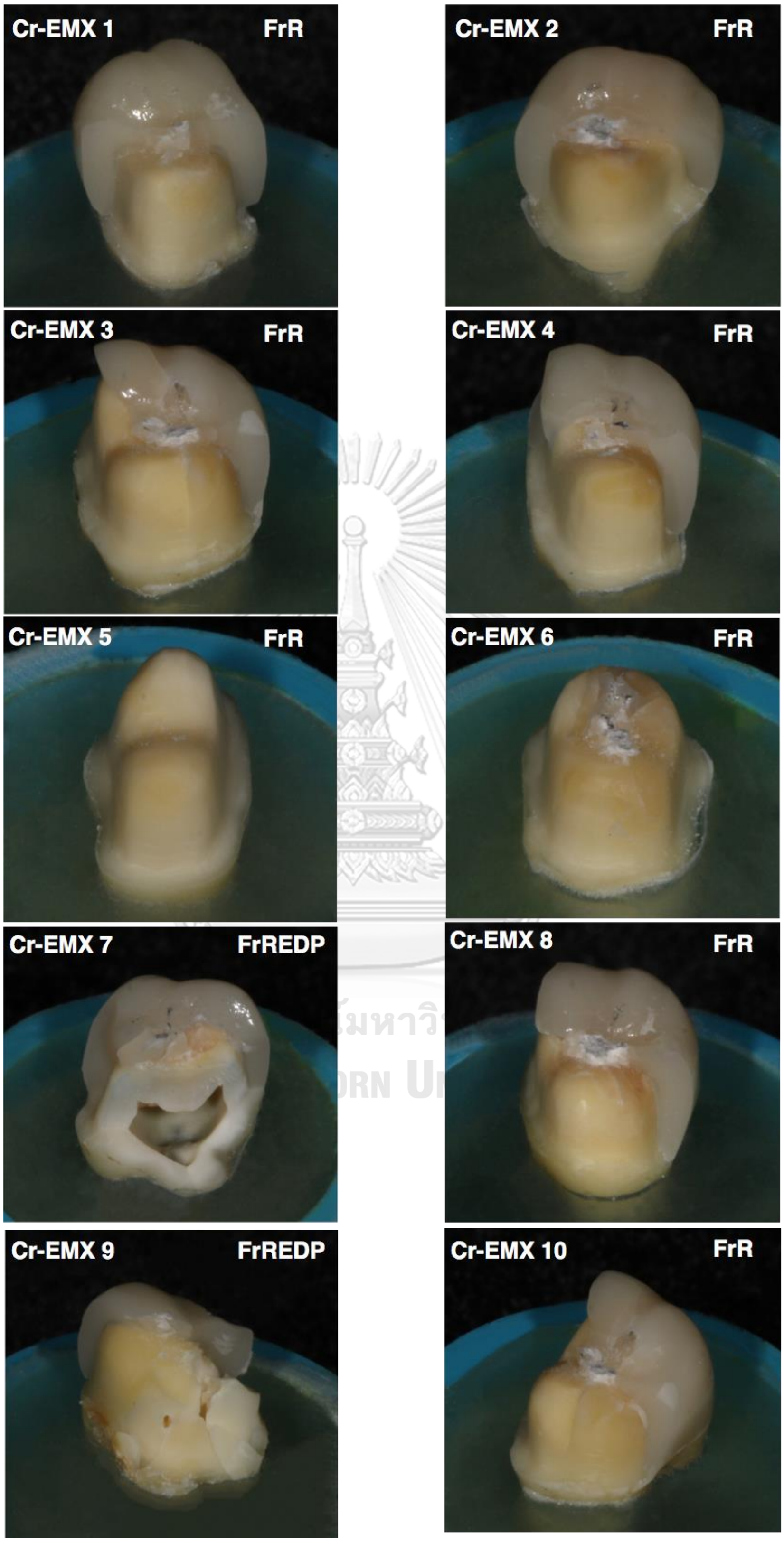

Figure 12 Fracture of specimens in Cr-EMX group

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