



**MARGINAL ADAPTATION AND FRACTURE
RESISTANCE OF MILLED AND 3D-PRINTED
CAD/CAM HYBRID MATERIALS OF DENTAL
CROWNS WITH VARIOUS OCCLUSAL THICKNESSES**

BY

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THESIS

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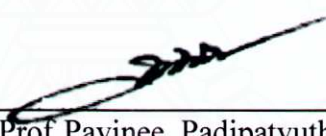
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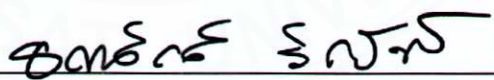
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Thesis Title	MARGIINAL ADAPTATION AND FRACTURE RESISTANCE OF MILLED AND 3D-PRINTED CAD/CAM HYBRID MATERIALS OF DENTAL CROWNS WITH VARIOUS OCCLUSAL THICKNESSES
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ABSTRACT

Purpose

To evaluate the marginal adaptation and fracture resistance of three computer-aided design/computer-assisted manufacturing hybrid dental materials with different occlusal thicknesses.

Methods

Ninety single-molar crowns were digitally fabricated using a milled hybrid nanoceramic (Cerasmart, CE), polymer-infiltrated ceramic network (PICN, Vita Enamic, VE), and 3D-printed materials (Varseosmile, VS) with occlusal thicknesses of 0.8, 1, and 1.5 mm (10 specimens/group). Anatomical 3D-printed resin dies (Rigid 10K) were used as supporting materials. A CEREC MCX milling unit and a DLP-based 3D printer, Freeform Pro 2, were utilized to produce the crown samples. Before and After cementation with self-adhesive resin cement, the marginal adaptation, absolute marginal discrepancy (AMD), and marginal gap (MG) were assessed using micro-CT scanning. Fracture resistance was evaluated using a universal testing machine. The number of fractured crowns and the maximum fracture values (N) were recorded. Data were statistically analyzed using both one- and two-way ANOVA, followed by Tukey's honestly significant difference (HSD) test.

Results

For all occlusal thicknesses, the VS crowns demonstrated the lowest AMD and MG distances, significantly different from those of the other two milling groups ($P < 0.05$), whereas CE and VE did not differ significantly ($P > 0.05$). All VS crowns were fractured using the lowest loading forces (1480.3 ± 226.1 to 1747.2 ± 108.7 N). No CE and 1 and 1.5 mm VE crowns fractured under a 2000 N maximum load.

Conclusions

All hybrid-material crowns demonstrated favorable marginal adaptation within a clinically acceptable range, with 3D printing yielding superior results to milling. All materials could withstand normal occlusal force even with a 0.8 mm occlusal thickness.

Keywords

Hybrid ceramic, Composite resin nanoceramic, Hybrid material, 3D-printing, Marginal adaptation, Fracture resistance

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Pisit Suksuphan



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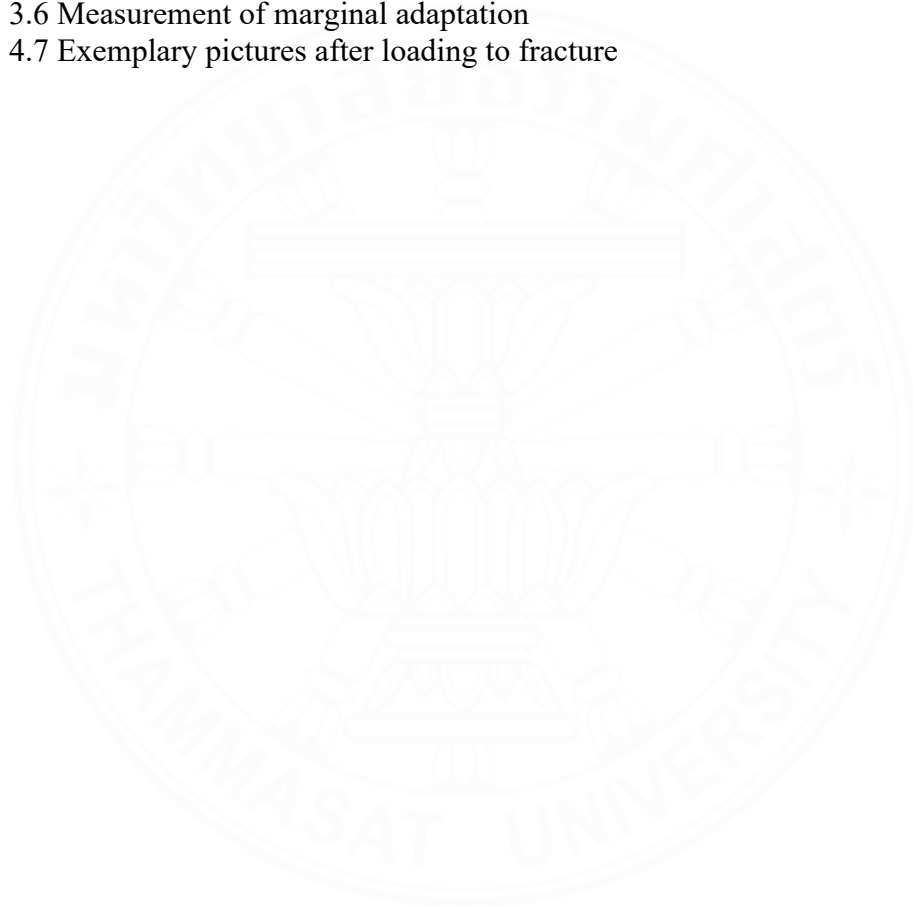


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LIST OF ABBREVIATIONS

Symbols/Abbreviations	Terms
CAD	Computer-aided design
CAM	Computer-assisted manufacturing
3D	Three-dimensional
CE	Cerasmart
VE	Vita Enamic
VS	Varseosmile Crown plus
DLP	Digital light processing
LU	Lava Ultimate
VSU	Vita Suprinity
micro-CT	Microcomputed tomography
mm	Millimeter
N	Newton
BC	Brillilliant Crios
PMMA	Polymethyl methacrylate
rpm	Round per minute
µm	Micron
STL	Standard triangle language
SLA	Stereolithography
LED	Light emitting diode
PICN	Polymer-infiltrated ceramic-network
GPa	Giga pascal
HV	Vickers hardness
ISO	International organization for standardization
USA	United states of America
Zr	Zirconia
hr	Hour
min	Minute
°C	Degree celcius
kV	Kilo volt
µA	Micro ampere
Al	Aluminium
AMD	Absolute marginal discrepancy
MG	Marginal gap
sec	Second
mW/cm ²	Milli watt per square millimetres
SD	Standard deviation

CHAPTER 1 INTRODUCTION

Digital technologies are already ubiquitous in many aspects of the dental workflow(1) due to the improvement of computer-aided design/computer-assisted manufacturing (CAD/CAM). Nowadays, CAD/CAM technology can manufacture many restorations with excellent esthetic properties. The benefits of CAD/CAM generating technique are the access to industrially prefabricated and almost defect-free dental restorations, improvement in precision and planning, as well as increasing quality, reproducibility and efficiency.(2) The current CAD/CAM technique includes both subtractive milling and additive manufacturing known as three-dimensional (3D) printing.(3) The additive manufacturing may provide more benefits than the subtractive milling, lesser material waste and able to produce complex shapes where there are undercuts or locations that can't not be milled.(4) Recently, new hybrid materials have been developed for CAD/CAM system that combines the superiority of ceramics in the esthetic characteristics, durability and color stability with the advantage of resin composites such as high flexural strength, low abrasiveness and intraoral reparability. Recently, most hybrid ceramics for restorative materials are available for the subtractive milling technique.(5) Two examples of the hybrid materials are Cerasmart® (CE) and Vita Enamic® (VE). Cerasmart® is a high-density resin composite material containing 71% filler particles by weight or referred as "Flexible Nano Ceramic".(6) VE or PICN material consists of 86% (by weight) porous feldspathic ceramic matrix, infiltrated with copolymer (urethane dimethacrylate and triethylene glycol dimethacrylate). Both materials are manufactured by a milling process. Only few 3D-printed hybrid materials are acquirable for fixed permanent single restorations. Lately, Varseosmile Crown plus® (VS), a novel 3D-printable hybrid material, additively fabricated by Digital Light Processing (DLP) technology, has launched.(7) The manufacturer claims that this material has high dimensional stability, high flexural strength and modulus with excellent esthetics.(7)

Three basic necessities to determine the favorable outcomes of dental restorations are esthetic perception, adaptation of the margin and fracture resistance.(8) Although key considerations for esthetic success are subjective, the judgement is not universal and depends on various factors. For marginal adaptation, the inadequate adaptation may induce plaque accumulation causing microleakage and potentially increase the risk of caries and may also cause gingival inflammation.(8) Moreover, it could contribute to cement dissolution resulting in compromising the esthetic appearance.(8) Yildirim in 2014 evaluated the marginal and internal adaptation of 3 different materials (VE, Lava Ultimate®; LU and Vita Suprinity®; VSU) compared with lithium disilicate (e.max CAD®, IPS) using microcomputed tomography (micro-CT scan) and found that the hybrid materials demonstrated significantly lower adaption than the lithium disilicate(9) but still within a clinical acceptable range.(10) Contrariwise, a study from Azarbal in 2017 reported that VE crowns fabricated with CEREC system showed a superior marginal adaptation to that of e.max CAD® crowns.(11)

Preserving tooth structure is an important principle of tooth preparation that is related to fracture resistance of the restoration. The thin layer-restorations offer an

alternative treatment for occlusal space-limited patients and for juveniles to avoid pulp exposure. Previous studies have shown the minimum thickness of hybrid ceramic crowns that may survive from fracture load and can be used for a single posterior restoration.(12, 13) Rabeae in 2020(14) studied the fracture load on VE and lithium disilicate restorations with 0.3, 0.6 and 1.0 mm occlusal thicknesses and showed no significant difference between the two materials. The failure load of 0.3 mm thickness was 547-846 N, which is still higher than normal occlusal load (50-300 N), but less than the clenching force (1200 N).(14) However, the study concluded that the 0.3 mm restoration may not survive in the oral environment and instead recommended to use either 0.6 or 1.0 mm thickness in the clinical situation.(14) On the other hand,, Zimmermann in 2019(5) studied the fracture force of 3 types of particle-filled composites (LU, CE, Brillilliant Crios; BC) produced in 3 occlusal thicknesses (0.5, 1.0 and 1.5 mm) and compared with VE and e.max CAD®. The study found that all particle-filled composite crowns with 0.5 mm thickness survived the fatigue testing and that e.max CAD® and VE showed lesser strength than that of CE.(5) However, the minimum thickness of 1.0 mm VE and 1.5 mm CE was recommended by the manufacturers.(15) Thus far, there are only some studies investigating marginal fit and fractural strength of the hybrid materials, as mentioned above.

CAD/CAM hybrid dental materials are mostly categorized as rather weak materials which may be due to the inappropriate evaluation methods.(16) Most of the available *in vitro* studies are mainly investigated the hybrid materials fabricated by milling technique(17, 18) and there is no study investigating the marginal fit and fracture load of the 3D-printed hybrid materials made with different occlusal thicknesses. Therefore, the aims of the present study were to evaluate the marginal adaptation and fracture resistance of 3 CAD/CAM hybrid materials, i.e., milled CE and VE and a 3D-printed VS, with 3 different occlusal thicknesses. The null hypotheses were that there were no statistically significant differences for the marginal adaptation and fracture resistance of 3 hybrid crown materials fabricated in 3 occlusal thicknesses.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Digital dentistry

Automatically dental restorations production via CAD and CAM has become growing up in dental field. Subtractive manufacturing technique obtains by milling materials from blocks or discs to be the desired shape of restorations.(19) It is widely used for crowns and bridges restorations. Homogeneous materials is the advantage of using this technique which are less likely to be affected by the operating condition.(20) The dental CAD/CAM milling uses diamond burs and tungsten carbide burs to mill the materials. The tungsten carbide bur is used to mill metals such as titanium or temporary restoration such as polymethyl methacrylate (PMMA).(21) Diamond burs are generally utilized for milling of ceramic restorations with chair side milling machines.(22) The CAD/CAM milling units are usually equipped with pairs of diamond burs, responsible for carving the CAD/CAM block into the final restoration's anatomy. These bur speeds are usually between 40,000 and 42,000 rpm and powered by two four-axis stepping motors that are capable of delivering a milling accuracy of about $\pm 25 \mu\text{m}$. Results from a study of Roperto et al.(22) in 2018 showed that both cylinder shape and step-bur diamonds sustained the milling of 32 blocks of hybrid ceramics without compromising overall quality of restoration.(23) However, significant loss of the materials milled from a block or disk is still the disadvantage of a wasteful process.(24)

An additive manufacturing technique is known as a 3D printing, building up by layer-adding materials resorting to a computer-generated design Standard Triangle Language (STL) file.(19) The generally available additive manufacturing technologies are named either indirect method including binder jetting, material extrusion and jetting, Vat polymerization, Stereolithography (SLA) and Digital Light Processing (DLP), or direct methods which include direct energy deposition and powder bed fusion.(19) This review will focus only on SLA and DLP techniques.

Firstly, the SLA is the technique that uses specific type of light, such as laser or Light Emitting Diode (LED) to build parts or one layer at a time. The light cures each layer through the surface of the liquid resin. Then, the building platform descends allowing that another layer of resin spreads over the surface and repeating the process. SLA enables a rapid fabrication and creates complex shapes with high level of accuracy and good finishing. Overall, SLA presents an excellent surface finishing, but it is still relatively expensive and lengthy post processing time for unprocessed resin removal and additional curing. (19) Secondly, DLP is containing micromirrors which act as light switches onto the projection surface. The resolution of projected image corresponds to the number of mirrors. The building platform can be vertically lowered and is immersed in a reservoir containing liquid monomer near the bottom of reservoir. Building platform is lifted to ensure that the resin flows into the gap between the platform and the reservoir in each exposure cycle. The advantage of DLP in comparison to SLA is that every layer can be cured with a single shot of laser exposure and that DLP uses smaller tray which requires smaller amount of resin. In summary, the principle of printing process with the SLA and DLP can be divided into three steps: light exposure, platform moving and resin refilling.(19, 24)

2.2 Hybrid ceramics

In the field of dental materials, ceramics have been continuously developed and improved its properties. The improvements provided ceramics with many superiorities over the metal restoration such as superb esthetic perception due to favorable optical properties (translucency and transparency). Ceramic materials are known as the combination of metallic and non-metallic parts; oxides, carbides, nitrides and silicates. Most of the ceramics used in dentistry are primarily silicon or silica based. Another type is the polycrystalline based ceramic that there is no silicon in its compositions. Recently, the “Hybrid ceramics”, a combination of resin composites and ceramics, have been introduced into a new classification system of dental ceramics.(25) The resin composite is composed of an organic matrix reinforced with inorganic fillers(26, 27) and the development of the filler technology has impressively improved its properties.(26) However, the clinical performance of indirect ceramic restorations is superior to direct resin composites restoration in aspects of color stability and durability.(26) In addition, the comparison between indirect restorations of resin composites and ceramics manufactured by CAD/CAM showed that the indirect composite restorations are still more inferior in esthetics and lower wear resistance than that of the ceramics. Thus, the new strategy for restorative materials is to combine the benefits of both resin composites and ceramics in a single material. This material seems to be alternatively good that it acquires the elastic modulus of resin composites, which is similar to the dentin, and that it provides the long-term esthetic stability of the ceramics.(27) Since the hybrid ceramics have modulus of elasticity similar to the dentin and the modulus of resilience significantly higher than felspar-based and glass-ceramics, a significantly higher stress can be absorbed to the hybrid ceramics without permanent deformation or failure.(24) The hybrid ceramic has shorter milling time using the CAM milling unit compared to other ceramic materials, as a result longer lifetime of the milling burs is another advantage. There is also no need for sintering or crystallization firing after milling. Hybrid ceramics are wear-resistant and do not abrade the opposite teeth. Moreover, these restorations can be easily repaired in the mouth.(24) The example of this hybrid material is PICN or “Vita Enamic®” (Vita Zahnfabrik, Bad Säckingen, Germany) which is commercially available. It consists of a structure with a sintered ceramic matrix (86% by weight) infiltrated with a polymer matrix (14% by weight). Indications for use of VE are minimally invasive restorations, veneers, crowns, inlays and onlays for posterior teeth and implant-supported crowns.(27) Facenda et al. in 2017 showed that VE has greater mechanical strength than feldspathic porcelains and highlighted that VE has a higher strength to degradation at low loads than most ceramics.(27) Another hybrid material is Cerasmart® (GC Corporation; Tokyo, Japan), or referred as “Flexible Nano Ceramic”.(28) It is composed of relatively tiny and uniformly distributed particles of alumina-barium-silicate embedded in a polymer matrix and it has the E-modulus of 10.0 GPa and Vickers hardness approximately 64.1 HV, which are relatively lower than VE (28.5 GPa / 189.8 HV) (27). Moreover, the marginal edge roughness of $60 \pm 16 \mu\text{m}$ is the lowest compared to the other hybrid ceramics materials.(24) Therefore, CE can be accurately milled, and resulted in sharp adaptation and resistance to chipping which ensure a long-lasting marginal seal. In addition, CE has an excellent polishing ability displaying an impressive gloss after a short polishing time.(24)

Recently, Varseosmile Crown plus® (Bego; Bremen, Germany) is a novel 3D-printable light-curing, free-flowing plastic based on methacrylic acid esters hybrid ceramic that is built up by DLP to produce permanent single crowns, inlays, onlays and veneers. The minimum thickness of the restoration recommended by the manufacturer is 1 mm. The manufacturer claims that this material has high dimensional stability, high values of flexural strength and modulus, and excellent in esthetics. (7) Thus far, there is only limited information in both mechanical and physical properties of this newly introduced hybrid materials.

2.3 Dental adhesive

In clinical situation, a permanent cementation using dental adhesive is used to retain the restorative materials onto the tooth. The classification of the dental adhesive systems have been defined according to the clinical steps used during the cementation. (29) First is the etch and rinse adhesive system, which consists of etched tooth structure and rinsed then following by the adhesive. Second is the self-etched adhesive which is the infiltration of the adhesive occurring coincident with the self-etching process. (28) Another system is self-dental adhesive and RelyX unicem® is an example of a dual luting resin cement for self-adhesive cementation of indirect ceramic, composite or metal restorations. When using self-adhesive system, bonding and conditioning of the dentin or enamel are no longer necessary. In the self-adhesive system, there is an organic matrix consists of a multifunctional phosphoric acid modified methacrylate. The phosphorylate function allows for self-conditioning of the tooth surface and thus self-adhesion without the adhesives. The inorganic filler of RelyX unicem® is approximately 72% by weight. One of the fillers has a characteristic property allowing the cement to react with the acidic functionality of monomer. (30) By mechanism, the pH value is increased in the course of setting reaction and there is also a fluoride release. The depth of cure of RelyX unicem® is 2.5 mm. (31)

2.4 Dental cement thickness

The cement space setting in CAD design will follow an International Standards for polymer-based filling restorative and luting materials mixing ratio of base and catalyst International Organization for Standardization (ISO) 4049:2019, where it sets the critical thickness of the cement at 50 µm. However, some resin cements cannot form the thickness less than 50 µm, due to different factors such as filler additions, resin consistencies and viscosities, (32) whereas the film thickness of RelyX unicem® is 16 ±2 µm recommended according to technical data information from the manufacturer (28). Moreover, the cement thickness for hybrid ceramic can virtually be set by the CAD technology. Dauti et al. in 2019 (29) evaluated the influence of two cement space setting at 50 µm and 80 µm using three luting cements: RelyX unicem®, Variolink esthetic® and Nexus 3®, on the marginal and internal adaptation of VE crowns. The study reported that both 50 µm and 80 µm virtual spacer setting by the CAD can be suggested for manufacturing of VE crowns, and RelyX unicem®, a self-adhesive resin cement, is recommended to use for cementation. (29)

2.6 Marginal adaptation

There are 6 methods that used to examine the marginal adaptation. First and the most widely used method is to evaluate by direct microscopic of the gaps along the crown margins. This method, however, has two major disadvantages where the reference points may be difficult to prove which lead to projection errors.(33) The second method is that a cemented specimen was cross-sectioned, and the marginal area was then examined under a microscope. However, only a limited number of sections could be cut on any one specimen. The third method is creating a light bodied silicone replica of the gap between crown and the die. Then the replica was sectioned and the marginal area was observed by microscope.(11) The fourth method is using laser videography involved a light-bodied silicone replica, which was digitized along with the die. In 2004, Luthardt(34) compared the accuracy between direct optical and laser digitizing and found that evaluation of 3D the internal fit using the laser videography method was proved to be suitable.(34) This method has often been used to measure internal gap, but it did not provide reliable identification of the reference points.(45) The fifth method utilizes the profilometry, which is usually used to evaluate the roughness of a surface. This method only allowed for indirect measurements of the absolute marginal discrepancy and the results were subject to false interpretation.(35) The last method is x-ray microtomography or micro computerized tomography scan (micro-CT scan). By this innovative and nondestructive technique, the marginal and internal adaptation of restoration can be simultaneously evaluated. Moreover, micro-CT provides both 2- and 3-dimensional imaging of the space between the restoration and die. This technic can provide very closed sections of the marginal area, which allows for a great number of measurement sites.(9, 35)

In 2000, Groten(33) estimated the minimum number of gap measurements on margins of single crown to produce relevant results for gap analysis. The gaps along crown margins were investigated in a scanning electron microscope on the master steel die without cementation and on replica dies after conventional cementation. They suggested 50 measurements of the marginal fit caused less than $\pm 5 \mu\text{m}$ variability for arithmetic means.(33) However, in 2004 Gassino(36) argued that the results of Groten were erroneous and suggested that only 18 points were necessary and 90 observation points for crowns manufactured from intraoral impression will produce a sample mean value within $\pm 5 \mu\text{m}$ of the true mean, with $\leq 4 \mu\text{m}$ standard error.(36)

In 2014, Yildirim(9) evaluated the marginal and internal adaptation of 3 PICN materials (VE, LU, VSU) compared with e.max.CAD using micro-CT scan with 160 measurements for each crown and 2-dimensional (2D) analysis. 16 measuring points were used for each vertical section: 2 each for marginal discrepancy (MD), absolute marginal discrepancy (AMD) and internal adaptation of shoulder area; 6 for axial space (AS) and 4 for occlusal space (OS). PICN materials were significantly better in adaption values than e.max.CAD(9) but still within a clinical acceptable range of less than $120 \mu\text{m}$ as McLean and Von Fraunhofer (1917) proposed for a clinical acceptable marginal gap and cement thickness providing successful restorations after evaluated more than 1000 crowns in 5 years.(10) A study from Azarbal in 2017 reported that VE crowns fabricated with CEREC system showed marginal adaptation superior to that of lithium disilicate (e.max.CAD®, IPS) crowns.(11)

For the *in vitro* studies, a tooth or model should be prepared in accordance with clinical conditions.(8) Thus, the use of metallic models with overly simplified shapes

or a flat occlusal surface is no relation to the actual clinical condition. According to Habib (48) in 2014, they compared the accuracy of marginal and internal adaptation of zirconia copings fabricated on anatomic, semi-anatomic and non-anatomic occlusal surfaces. The study found that anatomical occlusal preparation designs resulted in a better marginal and internal adaptation of Zr copings.(37)

2.5 Fracture resistance test

When evaluating new materials, it is important to test their mechanical properties using the basic tests specified by the ISO. Common mechanical evaluations for dental materials include flexural strength and modulus tests.(17) In three-point bending tests (ISO norm DIS 6872), various flexural strength values have been reported, indicating that CE is the strongest: CE, ranging from 181.15 ± 13.56 (38) to 216.5 ± 28 MPa;(39) VE, ranging from 148.16 ± 10.04 (40) to 155.26 ± 16.13 MPa(41); and VS, ranging from 119.85 ± 17.95 to 143.39 ± 12.88 MPa(42). The flexural modulus was found to be 25 GPa for CE,(39) 23.3 ± 6.4 GPa for VE,(39), and 4.37 ± 0.8 to 4.69 ± 0.15 GPa for VS.(42) In addition, flexural strengths reported by the manufacturers of CE, VE, and VS are 238,(15) 150–160,(43) and 116–150 MPa,(7) respectively. Goujat et al., in 2018, also found that CE (216.5 ± 28 MPa) had a significantly higher flexural strength than VE (148.7 ± 9.5 MPa).(39) However, there were no statistically significant differences in the flexural strength between the VE and VS groups ($P > 0.001$).(42) Due to the differences of loading forces applied in the laboratory setting and the actual forces in the intra oral conditions,(5) this test may not totally be suitable for evaluation of dental restorative materials. Instead, many studies investigating the fractural strength using crown shape specimens with the minimum thickness of crowns have been reported(5, 44, 45). The method tested for the fracture resistance is to use a universal testing machine with a ball steel indenter on the crown shape specimens.(46) Size of the ball steel can be estimated from the distance of a cusp that is occluded onto the fossa. The distance from the mesiobuccal cusp to the distobuccal cusp of maxillary first molar is approximately 5 mm and the distance from the mesiobuccal groove of the mandibular first molar to the occlusal embrasure between the first molar and second molar is approximately 6 mm.(46) Therefore, 5 mm diameter is the estimation size of ball steel that will be used in the universal testing machine of the present study.

The determinants of success of a dental restoration consist of three factors i.e., esthetics, resistance to fracture and marginal fit. (8) The best way to reach the esthetic treatment goal is to understand the end points that the patients need, and they are not universal depending on various factors. The best way to reach the esthetic goals is to understand the patients expectation that meet with the dental team's treatment skills. (47) The second factor is the fracture resistance especially in the minimal invasive crown preparations and ultra-thin restorations that highly effects on the strength of dental restoration. Rabeae et al. in 2020(14) studied the fracture load on lithium disilicate and VE restorations with different occlusal thicknesses at 0.3, 0.6 and 1.0 mm. The results showed no significant differences in fracture force between the 2 materials. The failure load of 0.3 mm thickness was 547-846 N, which is higher than the normal occlusal load (50-300 N) but less than the case of clenching (1200 N).(14) However, the study concluded that the thickness of 0.3 mm may not be possible to survive in oral environment. Therefore, for occlusal veneers of both materials, it was recommended to

use the thickness of 0.6 mm and 1.0 mm in the clinical situation.(14) This was confirmed by Shakour in 2020(17) that investigated the fractural strength of VE for posterior occlusal veneers with the thickness of 0.3 and 0.6 mm. They found that the thin VE occlusal veneer (0.3 mm) was strong enough in normal occlusion in the laboratory testing, but it may not survive in the natural oral condition. In case of bruxism patients, more than 0.5 mm was suggested.(17) On the other hands, Zimmermann in 2019(5) studied the fracture force of three particle-filled composite CAD/CAM materials crowns (LU, CE, BC) with 3 different occlusal thicknesses (0.5, 1.0, 1.5 mm) then compared with lithium disilicate and hybrid ceramic (e.max CAD® and VE). The study found that all particle-filled composite crowns with 0.5 mm thickness survived the fatigue testing. However, at 0.5 mm none of VE crowns and only 1 of the 9 crowns from e.max CAD group survived the fatigue testing. The conclusion was that at the same thickness, the 0.5 mm of VE and e.max CAD has less strength than that of CE.(5) However, the recommendation of minimum thicknesses from the manufacturers are 0.8 mm for VE and 1.5 mm for CE.(15) The third factor is marginal adaptation. Holmes et al.(36) in 1989 introduced marginal gap classification as the perpendicular measurement from the internal surface of the crown to the axial wall of the preparation, called the internal gap and the same measurement at the margin, called the marginal gap.(48) There are many analysis methods used for marginal adaptation, which are described in the next section.

In publications, there is the congruence that material and thickness of the crown are main factors to evaluate the fracture behavior of materials.(49) Fracture resistance is mainly determined by E-Modulus of the supporting structures.(50) All-ceramic crowns' fracture forces increase with the augmentation of supporting material's E-Modulus.(51) Using natural teeth make it is difficult to standardize because of the large variations depending on tooth anatomy, patient's age and storage time after extraction.(52) Therefore, many studies using metal, epoxy resin and acrylic resin as supporting die materials for evaluating the fracture resistance.(53) From a previous study an acrylic resin die material (inCoris SLS, infiniDent, Germany) was used and the material demonstrated characteristics of 2.5 GPa of E-Modulus, 110-130 MPa fracture resistance and 80-84 Shore D of shore hardness.(5) Supporting material with a comparable E-Modulus to natural dentin (between 7 and 13 GPa)(54) is suggested to use for fracture test that results can be directly referred to clinical conditions.(5) Rigid 10K (Formlabs Inc., USA) highly glass-filled resin (9 GPa of E-Modulus, 126 MPa fracture resistance)(55) was used in the present study.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Research question

Do types (3D printed and milled CAD/CAM) of the hybrid materials and different occlusal thicknesses of crowns (0.8 mm., 1 mm., 1.5 mm.) affect marginal adaptation and fracture of dental crown restorations?

3.2 Research objective

The aims of this study are to evaluate the marginal adaptation and fracture resistance of 3 hybrid CAD/CAM dental crown materials, a 3D-printed and 2 milled hybrid materials, with different occlusal thicknesses.

3.3 Statistic hypothesis

- There are no statistically significant differences for the marginal adaptation of CAD/CAM fabricated crowns that made from 3 different materials
- There are no statistically significant differences for the fracture resistance of CAD/CAM fabricated crowns that made from 3 different materials and 3 occlusal thicknesses.

3.4 Experimental design

The present study examined marginal adaptation before cementation and fracture resistance of adhesively seated mandibular first molar CAD/CAM fabricated crowns. 2 milled and a 3D-printed hybrid materials were investigated: milled particle-filled composite CAD/CAM materials = CE (Cerasmart®; GC Corporation, Tokyo, Japan), milled hybrid ceramic = VE (Vita Enamic®; VITA Zahnfabrik, Germany), and 3D-printed hybrid material = VS (Varseosmile®; Bego, Bremen, Germany). For each material, 3 different occlusal thicknesses were investigated (0.8 mm, 1.0 mm and 1.5 mm). A total of 90 samples, 10 samples in each group were evaluated. The crowns for CE and VE groups were milled with a milling machine (CEREC MCX milling unit, Dentsply Sirona, USA) and VS was printed with a 3D printing machine (ASIGA; Anaheim Hills, USA). All crowns were cleaned with ultrasonic baths and air-dried. The marginal gap for all specimens were measured with micro-CT scan (Skyscan 1172; Bruker) before cementation. Then, all crowns were adhesively seated to 3D-printed dies (Rigid 10K; Formlabs inc., USA) using self-adhesive resin cement (RelyX Unicem®; 3M/ESPE, USA). Then storage of specimens in distilled water were carried out at 37° in a heating cabinet (LEEC Warming Cabinets; Nottingham, United Kingdom) at least 24 hr. All specimens were evaluated for marginal gap after cementation using micro-CT scan (Skyscan 1172; Bruker) again. Then, specimens were tested for fracture resistance with a universal testing machine (Shimadzu; Kyoto, Japan). The summary is shown in Figure 1 and details are described below.

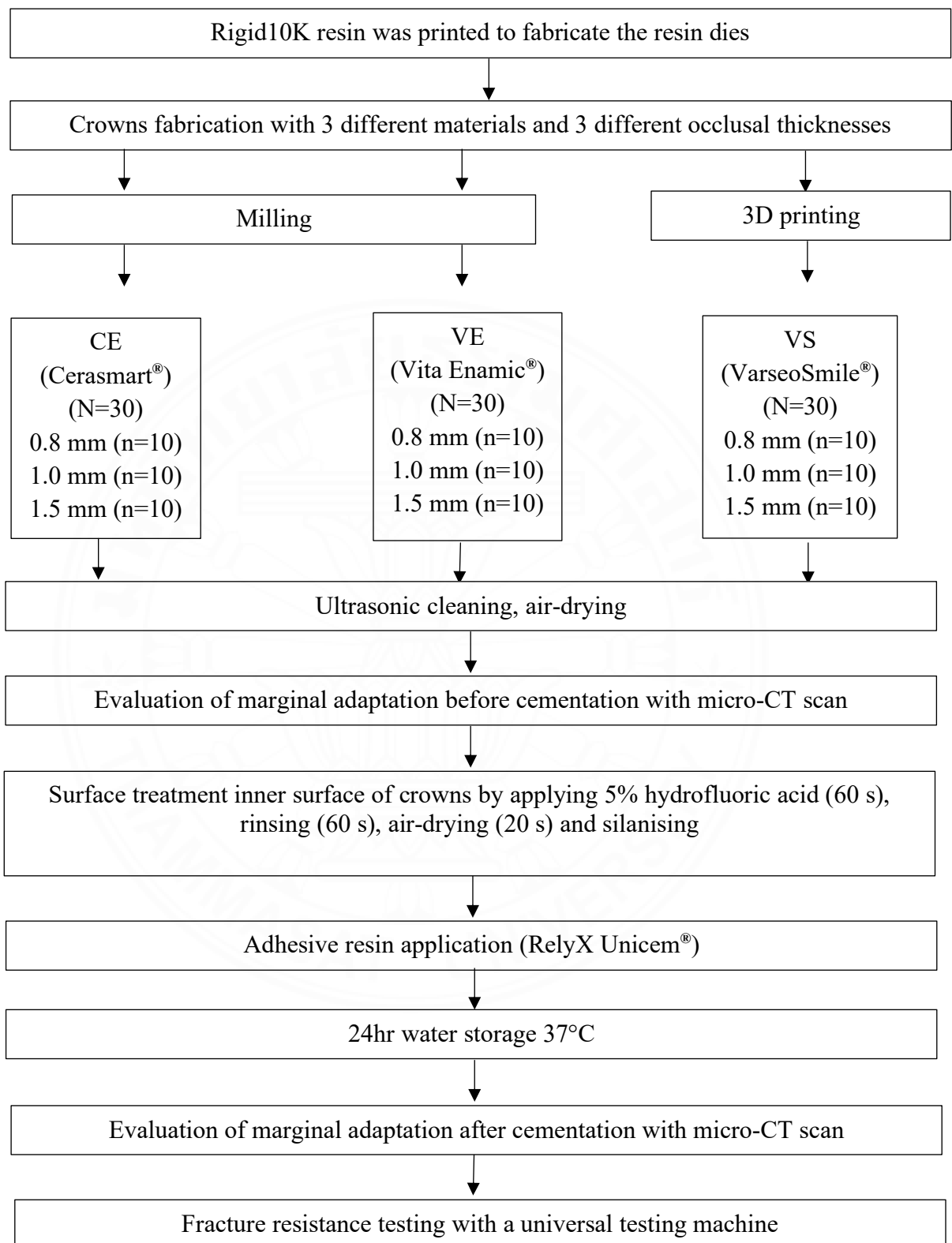


Figure 1. Experimental design

3.5 Sample size

Estimation of a total sample size with 3 different materials and 3 different occlusal thicknesses in the total of 9 groups based on $\alpha = 0.05$ significant level was performed by the means of a power analysis with G*Power v3.1 (Open Source; HHU Düsseldorf) observed power of 0.95. The effect size (Cohen's f) used in the G-Power software was calculated using the following equation.

$$\text{Cohen's } f = \sqrt{\frac{\sum_{j=1}^p (\mu_j - \mu)^2 / p}{\sigma^2}}$$

According to a previous study (5,9) where μ is a mean, σ is a common SD, and p is the number of groups which can be obtained from the results.

Table 1. Sample size's calculation for marginal adaptation test

μ	σ	p	Effect size (Cohen's f)	Numbers of group	Total sample size	Calculated sample size in each group
120.375	39.775	4	0.632	9	53	6

Table 2. Sample size's calculation for fracture resistance test

μ	σ	p	Effect size (Cohen's f)	Numbers of group	Total sample size	Calculated sample size in each group
1042.956	199.622	9	1.581	9	16	2

From the calculation, Sample size at least 6 and 2 in each group were required for marginal adaptation and fracture resistance test to have a power of 0.95 to detect statistically significant difference between groups at $\alpha = 0.05$. But there was not any study investigating about marginal adaptation and fracture resistance with different occlusal thicknesses before. Consequently, sample size of 10 in each group were set, using the two-way ANOVA, to have power more than 0.95 of detecting statistically significant difference of fracture resistance of materials between groups at $\alpha = 0.05$.

3.6 Materials and methods

Details of the materials used in the present study are described in Table 3. A mandibular 1st molar typodont tooth (Nissin; Kyoto, Japan) was scanned by an optical scanner (E3; 3shape, Denmark) and then virtually prepared to create a resin die using a CAD software (Autodesk fusion 360; CA, USA) (Figure 2) with the preparation guideline for full ceramic crowns (1.0 mm occlusal reduction, 1.2 mm proximal and axial reduction with 6 degrees of convergence profile, 0.8 mm deep chamfer crown margin and round line angles). The CAD file of prepared tooth was imported to a 3D printing machine (Form 3B; MA, USA) and a highly glass-filled resins-based methacrylate (Rigid 10K; Formlabs Inc., USA) was utilized to fabricate the resin dies (Figure 3A) and post-cured with a UV post-cured unit (Form Cure; MA, USA) for 60 min at 70 °C according to the manufacturer,(55) then stored in the same conditions in a dark storage compartment.(56)

Table 3. Lists and details of the materials

Group	Products	Manufacturer	Composition	Lot No.
Milling	Cerasmart [®] (CE)	GC Corporation; Tokyo, Japan	Silica (20 nm) and barium glass (300 nm) nanoparticles 71 wt.%, Bis-MEPP, UDMA, and DMA Polymers 29 wt.%	1807201
	Vita Enamic [®] (VE)	Vita Zahnfabrik; Bad Säckingen, Germany	Feldspar ceramic 86 wt.%, Methacrylate polymer 14 wt.%	90001
3D- Printing	Varseosmile [®] (VS)	Bego; Bremen, Germany	Total content of inorganic fillers (particle size 0.7 μ m) 30–50 wt.%, 4,4'-isopropylidiphenol, ethoxylated and 2- methylprop-2enoic acid, silanized dental glass, methyl benzoylformate, diphenyl (2,4,6-trimethylbenzoyl) phosphine oxide	600512
Resin luting cement	RelyX Unicem [®]	3M ESPE; USA	Powder: glass fillers, silica, calcium hydroxide, self-curing initiators, pigments, light-curing initiators, substituted pyrimidine, peroxy compound Liquid: methacrylated phosphoric esters, dimethacrylates, acetate, stabilizers, self- curing initiators, light- curing initiators	8713388
Silane Coupling Agent	RelyX Ceramic Primer [®]	3M ESPE; USA	Ethyl alcohol, water, 3-methacryloxypropyltrimethoxysilane	NF21800
Resin die	Rigid 10K Resin	Formlabs Inc.; USA	Highly glass-filled resins-based methacrylate (9 GPa of E-Modulus after UV-post-cured)[18]	4c- 0000001f 3f36

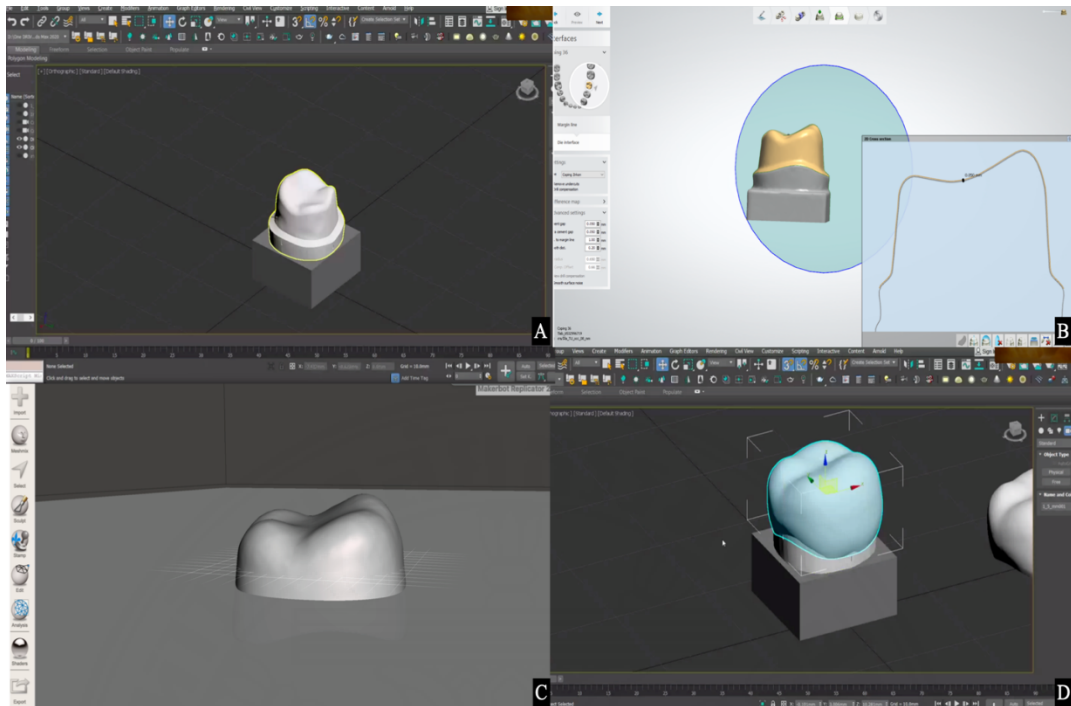


Figure 2. Virtual CAD design of resin dies and crowns with different occlusal thicknesses using Autodesk Fusion 360 program. Virtual die preparation for all-ceramic crown designed for the mandibular 1st molar (A), setting of 50 µm cement spacer parameter (B), a CAD design of single-molar crown (C), and virtual seating of the designed crown over the die (D).

A CAD design of single molar crown with occlusal thicknesses of 0.8 mm, 1 mm and 1.5 mm (Figure 4) was carried out using a CAD software (3shape dental system version 2020), and a 50 µm was set for the cement spacer whereas other parameters were set to 0 µm (Figure 2B). Milling fabrication (Figure 3B, 3C) was performed by the CEREC MCX (Dentsply Sirona; New York, USA) equipped with cylinder pointed bur 12 S and step bur 12. To prevent damaging of the samples, the milling burs were replaced after finishing of 30 crowns and at the beginning of the new material.(20) 3D-printed group was fabricated by the DLP-based 3D printer Freeform Pro 2 (ASIGA; Anaheim Hills, USA) (Figure 3D) with the imported STL data file and post-cured following the manufacturer's recommendation.



Figure 3. CAM fabrications of specimens; Rigid 10K resin dies (A), Cerasmart® milled crowns (B), Vita Enamic® milled crowns (C), Varseosmile® 3D-printed crowns (D)

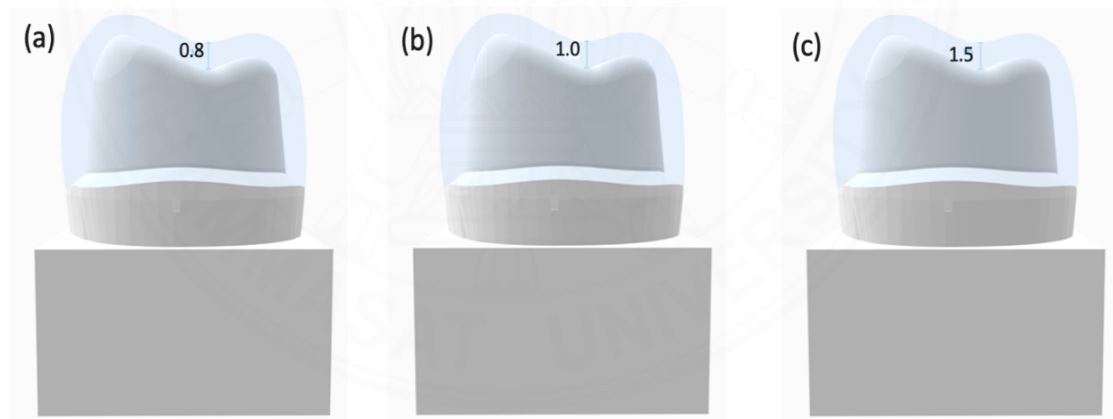


Figure 4. Resin dies designed in a CAD software. The surface of bucco-lingual view shows different occlusal crown thicknesses at 0.8 mm (a), 1.0 mm (b), 1.5 mm (c)

The marginal adaptation was investigated by using a micro-CT scan (Skyscan 1172; Bruker) before and after cementation of the crowns. All crowns were cleaned with ultrasonic baths and air-dried and then passively seated onto the 3D-printed dies directed by 4 indentation points (mesial, lingual, buccal and distal) and temporary adhesive with spots of clear glue fixation (DUO glue clear adhesive; American international industries, USA). The marginal adaptation of all specimens was measured by placing each specimen perpendicular to the x-ray beam scanning tube (9) with operation of 67 kV and 41 μ A using Al 1 mm filter and an image pixel size of 10 μ m, averaging 3

frames, 360 degrees scanning with 0.2-degree rotation step and then acquired projection images were reconstructed into cross-section slices (Figure 5A) using a software (NRecon v1.6.9; Bruker Micro-CT). Depending on the numbers of slices, 5 coronal sections (Figure 5B) were obtained with 100 equidistant slice intervals from the buccolingual direction, and 5 sagittal sections (Figure 5C) were obtained with 100 equidistant slice intervals from the mesiodistal direction. There were 4 measuring points for each slide including 2 absolute marginal discrepancy (AMD) and 2 marginal gaps (MG) (Figure 6). 40 measurements for each crown (a total of 3600 points at buccal, lingual, mesial and distal aspects) were measured by the DataViewer program (v.1.5.1.2; Bruker Micro-CT). All 2-dimensional measurements were performed by one examiner (P.S.).[13]

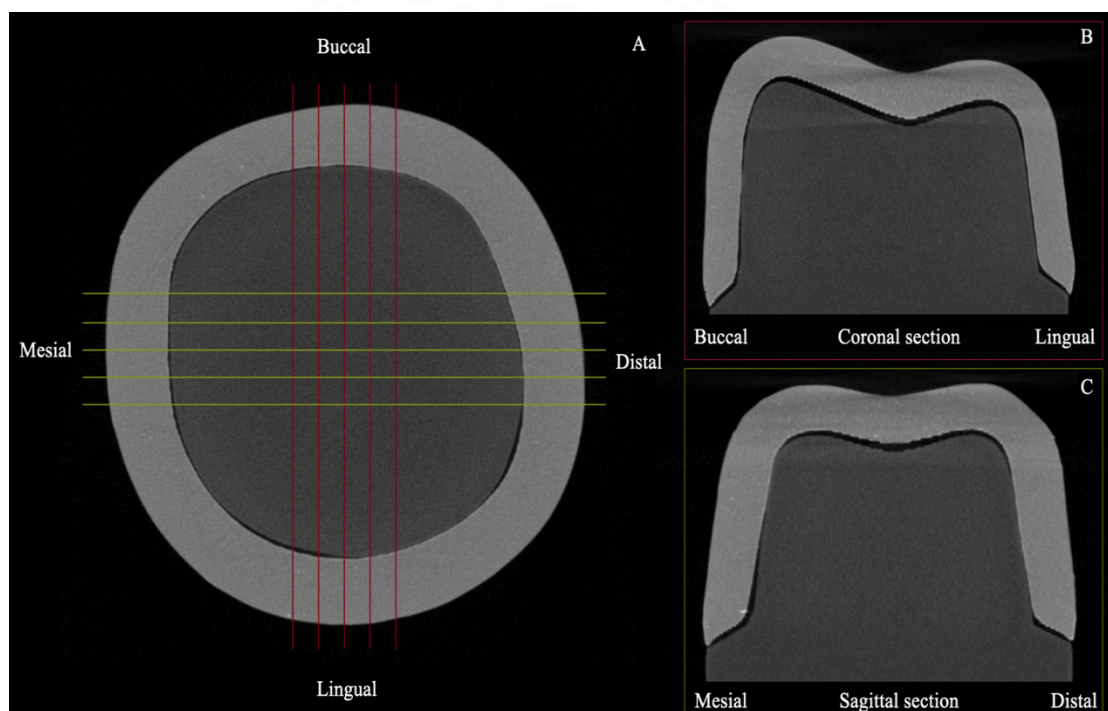


Figure 5. Micro-CT scan images. Cross-sectional slice (A) with five equidistant bucco-lingual sections (red) and five equidistant mesio-distal sections (yellow), a coronal section (B) represents the bucco-lingual measurements, and a sagittal section (C) represents the mesio-distal measurements.

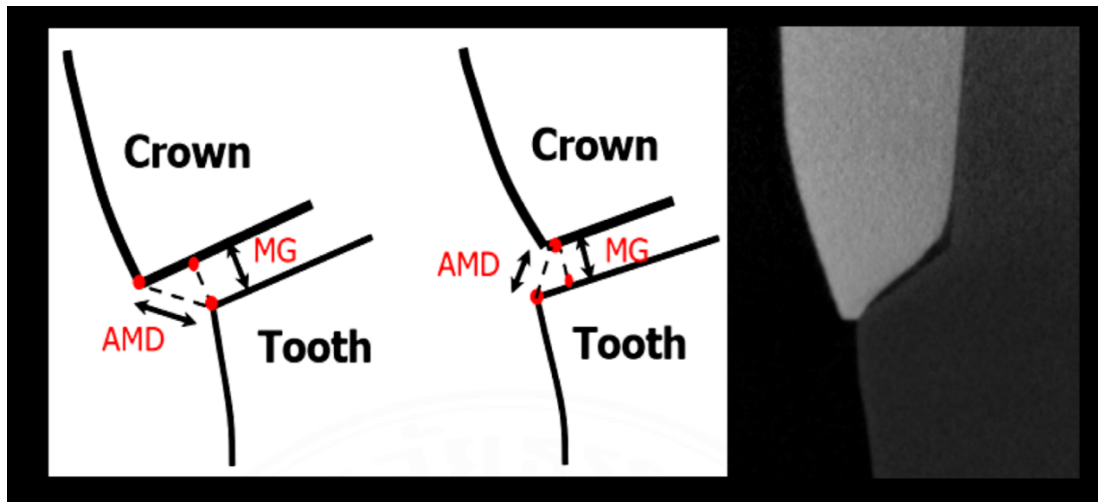


Figure 6. Measurement of marginal adaptation (perpendicular distance between crown and master die margin measured); absolute marginal discrepancy (AMD) and marginal gap (MG)

For cementation, a 5% hydrofluoric acid gel (VITA ADIVA CERA-ETCH, VITA Zahnfabrik, Germany) was applied for 60 sec in the inner surface of all crowns and 60 sec water rinsing and 20 sec air drying and then silanated (RelyX[®] Ceramic Primer, 3M/ESPE, USA).(6) A resin cement (RelyX unicem, 3M/ESPE, USA) was used for cementation according to the manufacturer's instruction and the crowns seated with a constant load of 20 N by the force gauge with a test stand,(13) residual resin cement removed and then a 20 sec light curing performed on each surface of the crown using a curing lamp of 470 nm wavelength and 1000 mW/cm² intensity (SmartLite Focus, Dentsply Sirona; USA). Then, the specimens were stored in distilled water at 37°C in a heating cabinet for 24 hr. to assure hydration and to eliminate the effect of water uptake dimensional expansion after crown cementation. All specimens were evaluated for marginal adaptation (AMD and MG) after cementation using micro-CT scan (Skyscan 1172; Bruker) again.

For single load to fracture testing, the specimens were mounted onto a universal testing machine (Shimadzu; Kyoto, Japan) and long axis of the ball steel perpendicular to horizontal plane with cross head speed 1 mm/min using 5 mm diameter ball tip stainless steel antagonist with 2000 N load cell. The load was applied at central fossa until the crown broke. Numbers of the fractured crown (*n*) and the maximum forces of fracture values (N) were recorded.

3.7 Statistical analysis

The statistical analyses were performed using an SPSS software (v26.0; IBM Corp). The Kolmogorov-Smirnov was used to verify the normality. Levene's test of equality of error variances was performed. An interaction between material types and thicknesses ($P < 0.05$). was observed when marginal adaptation was analyzed. The marginal adaptation values (AMD and MG) were analyzed using two-way ANOVA.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results

4.1.1 Marginal adaptation

4.1.1.1 Before cementation

All 3600 investigating points from 3 materials (CE, VE, and VS) with 3 occlusal thicknesses (0.8 mm, 1.0 mm, and 1.5 mm) were measured for AMD and MG. The descriptive analyses of AMD are shown in Table 4. Comparing between groups (see Appendix 1), almost all AMD values in the milled groups (CE and VE) were not significantly different ($P>0.05$). Only at buccal aspect of 1.5 mm CE ($P<0.05$), AMD values was significantly different from the other milled groups. Most of the 3D-printed VS group (8 of 12 points) had significantly lower AMD values comparing to the milled groups ($P<0.05$), except at lingual of 1.0 mm VS and distal of all VS were not significantly different ($P>0.05$). The results of MG are shown in Table 5 and Appendix 2 and a similar pattern to the AMD results was observed. Almost all MG values at lingual and distal aspects of all thicknesses of VS groups were not significant different from the milled groups ($P>0.05$), except at distal of 0.8 mm CE was significantly higher than the milled groups ($P<0.05$).

Table 4. Mean $\pm$ SD (μ m) values of AMD for test group before cementation

Types	Thickness (mm.)	N	Mean $\pm$ SD			
			Buccal (n=5)	Lingual (n=5)	Mesial (n=5)	Distal (n=5)
Cerasmart (CE)	0.8	10	85.4 $\pm$ 8.3 ^B	69.0 $\pm$ 15.8 ^{BCD}	45.6 $\pm$ 23.6 ^B	60.0 $\pm$ 14.9 ^{CDEF}
	1.0	10	58.6 $\pm$ 21.8 ^B	78.0 $\pm$ 10.9 ^{BCD}	49.6 $\pm$ 15.0 ^B	69.0 $\pm$ 8.2 ^{DEFG}
	1.5	10	32.8 $\pm$ 8.0 ^A	75.7 $\pm$ 8.8 ^{BCD}	39.6 $\pm$ 9.9 ^B	61.8 $\pm$ 9.2 ^{CDEFG}
VitaEnamic (VE)	0.8	10	74.6 $\pm$ 22.7 ^B	52.2 $\pm$ 18.8 ^{BC}	43.0 $\pm$ 6.9 ^B	51.2 $\pm$ 11.0 ^{BCDE}
	1.0	10	70.0 $\pm$ 24.6 ^B	65.4 $\pm$ 30.0 ^{BCD}	62.8 $\pm$ 21.3 ^B	70.2 $\pm$ 16.3 ^{DEFG}
	1.5	10	65.0 $\pm$ 24.3 ^B	91.4 $\pm$ 20.5 ^{CD}	54.4 $\pm$ 15.8 ^B	77.8 $\pm$ 11.7 ^{EFG}
Varseosmile (VS)	0.8	10	19.8 $\pm$ 4.8 ^A	23.4 $\pm$ 8.7 ^A	18.4 $\pm$ 5.2 ^A	28.0 $\pm$ 13.8 ^{AB}
	1.0	10	21.6 $\pm$ 7.2 ^A	31.4 $\pm$ 9.7 ^{AB}	18.0 $\pm$ 7.8 ^A	36.6 $\pm$ 10.8 ^{ABC}
	1.5	10	18.0 $\pm$ 8.7 ^A	21.4 $\pm$ 6.2 ^A	15.6 $\pm$ 7.6 ^A	27.2 $\pm$ 11.7 ^{AB}

AMD; average marginal discrepancy, N; numbers of specimens, n; numbers of image per specimen. Within the same column, the values with the same capital letter are not statistically different ($P>0.05$). Statistical analysis with two-way ANOVA and post hoc Tukey's test (significance level $\alpha = 0.05$)

Table 5. Mean $\pm$ SD (μ m) values of MG for test group before cementation

Types	Thickness (mm.)	N	Mean $\pm$ SD			
			Buccal (n=5)	Lingual (n=5)	Mesial (n=5)	Distal (n=5)
Cerasmart (CE)	0.8	10	97.2 $\pm$ 10.8 ^{DEF}	78.6 $\pm$ 13.3 ^{EF}	89.0 $\pm$ 13.1 ^{DEFG}	84.8 $\pm$ 12.6 ^H
	1.0	10	82.0 $\pm$ 10.3 ^{BCDEF}	60.8 $\pm$ 8.9 ^{BCD}	68.0 $\pm$ 16.8 ^{BCDE}	63.2 $\pm$ 11.0 ^{DEFG}
	1.5	10	72.8 $\pm$ 8.7 ^{BCD}	64.8 $\pm$ 5.5 ^{CDEF}	69.3 $\pm$ 7.4 ^{BCDEF}	58.6 $\pm$ 4.7 ^{BCDEFG}
VitaEnamic (VE)	0.8	10	78.2 $\pm$ 10.1 ^{BCDE}	80.2 $\pm$ 7.5 ^{FG}	78.0 $\pm$ 15.3 ^{BCDEFG}	65.2 $\pm$ 9.8 ^{DEFG}
	1.0	10	88.8 $\pm$ 17.4 ^{CDEF}	74.4 $\pm$ 8.6 ^{DEFG}	80.6 $\pm$ 14.0 ^{BCDEFG}	60.0 $\pm$ 10.8 ^{CDEFG}
	1.5	10	88.8 $\pm$ 8.3 ^{CDEF}	72.4 $\pm$ 9.2 ^{DEFG}	87.4 $\pm$ 9.1 ^{CDEFG}	58.0 $\pm$ 4.6 ^{ABCDEFG}
Varseosmile (VS)	0.8	10	51.0 $\pm$ 6.1 ^A	50.0 $\pm$ 3.0 ^{ABC}	44.8 $\pm$ 5.2 ^A	47.4 $\pm$ 4.0 ^{ABCDE}
	1.0	10	50.0 $\pm$ 4.4 ^A	49.4 $\pm$ 4.0 ^{AB}	46.6 $\pm$ 4.0 ^A	46.4 $\pm$ 3.1 ^{ABCD}
	1.5	10	53.8 $\pm$ 6.1 ^A	53.4 $\pm$ 4.8 ^{ABC}	48.2 $\pm$ 3.6 ^A	50.8 $\pm$ 7.1 ^{ABCDEF}

MG; marginal gap, N; numbers of specimens, n; numbers of image per specimen. Within the same column, the values with the same capital letter are not statistically different ($P > 0.05$). Statistical analysis with two-way ANOVA and post hoc Tukey's test (significance level $\alpha = 0.05$)

4.1.1.2 After cementation

All 3600 cemented investigating points from 3 materials (CE, VE, and VS) with 3 occlusal thicknesses (0.8 mm, 1.0 mm, and 1.5 mm) were measured for AMD and MG. The AMD results were in similar pattern to before cementation's results that almost all AMD values in the milled groups (CE and VE) were not significantly different ($P > 0.05$). Most of the 3D-printed VS group (7 of 12 points) had significantly lower AMD values comparing to the milled groups ($P < 0.05$). The descriptive analyses of AMD are shown in Table 6 and the comparing illustration between groups is shown in Appendix 3. In contrast, the MG results showed a different pattern from before cementation. Almost all MG values were not significantly different between the milled and 3D-printed groups ($P > 0.05$), except at buccal of 0.8 mm CE was significantly higher than 1.0 mm VS ($P < 0.05$). The descriptive analyses of MG are shown in Table 7 and the comparing illustration between groups is shown in Appendix 4.

Table 6. Mean $\pm$ SD (μ m) values of AMD for test group after cementation

Types	Thickness (mm.)	N	Mean $\pm$ SD			
			Buccal (n=5)	Lingual (n=5)	Mesial (n=5)	Distal (n=5)
Cerasmart (CE)	0.8	10	45.0 $\pm$ 19.9 ^{EF}	57.8 $\pm$ 17.0 ^{CD}	24.4 $\pm$ 11.2 ^{BCDEFG}	59.6 $\pm$ 16.2 ^{CD}
	1.0	10	29.8 $\pm$ 13.9 ^{CDEF}	64.0 $\pm$ 15.7 ^{CD}	18.6 $\pm$ 7.7 ^{ABCDEF}	57.2 $\pm$ 19.7 ^{CD}
	1.5	10	21.4 $\pm$ 7.7 ^{CDE}	67.6 $\pm$ 8.7 ^{CD}	35.4 $\pm$ 15.1 ^{DEFG}	51.2 $\pm$ 17.5 ^{CD}
VitaEnamic (VE)	0.8	10	28.6 $\pm$ 12.9 ^{CDEF}	34.4 $\pm$ 21.9 ^{BC}	17.4 $\pm$ 6.5 ^{ABCDEF}	39.8 $\pm$ 14.2 ^{CD}
	1.0	10	18.2 $\pm$ 5.3 ^{BCDE}	33.8 $\pm$ 14.1 ^{BC}	26.6 $\pm$ 11.6 ^{CDEFG}	53.4 $\pm$ 12.5 ^{CD}
	1.5	10	23.1 $\pm$ 10.7 ^{CDE}	44.8 $\pm$ 13.8 ^{BCD}	18.6 $\pm$ 9.5 ^{ABCDEF}	39.0 $\pm$ 24.2 ^{BCD}
Varseosmile (VS)	0.8	10	10.4 $\pm$ 3.9 ^{ABC}	15.2 $\pm$ 11.8 ^A	12.4 $\pm$ 4.7 ^{ABCDE}	19.6 $\pm$ 9.0 ^{ABC}
	1.0	10	9.6 $\pm$ 3.4 ^{AB}	13.4 $\pm$ 9.3 ^A	12.2 $\pm$ 4.5 ^{ABCD}	18.4 $\pm$ 15.2 ^{AB}
	1.5	10	10.4 $\pm$ 3.9 ^{ABC}	9.6 $\pm$ 3.4 ^A	12.6 $\pm$ 4.1 ^{ABCDE}	15.0 $\pm$ 6.6 ^{AB}

AMD, average marginal discrepancy, N; numbers of specimens, n; numbers of image per specimen. Within the same column, the values with the same capital letter are not statistically different ($P>0.05$). Statistical analysis with two-way ANOVA and post hoc Tukey's test (significance level $\alpha = 0.05$)

Table 7. Mean $\pm$ SD (μ m) values of MG for test group after cementation

Types	Thickness (mm.)	N	Mean $\pm$ SD			
			Buccal (n=5)	Lingual (n=5)	Mesial (n=5)	Distal (n=5)
Cerasmart (CE)	0.8	10	77.0 $\pm$ 16.0 ^{DE}	59.0 $\pm$ 18.7 ^{BCDE}	73.6 $\pm$ 26.5 ^{CDE}	68.2 $\pm$ 10.0 ^{BCD}
	1.0	10	60.0 $\pm$ 9.5 ^{BCDE}	43.4 $\pm$ 8.8 ^{ABC}	55.0 $\pm$ 5.6 ^{ABCDE}	49.0 $\pm$ 4.7 ^{AB}
	1.5	10	66.0 $\pm$ 5.9 ^{BCDE}	53.8 $\pm$ 6.1 ^{BCDE}	65.8 $\pm$ 6.1 ^{CDE}	63.0 $\pm$ 6.5 ^{BCD}
VitaEnamic (VE)	0.8	10	55.0 $\pm$ 7.8 ^{ABCD}	67.6 $\pm$ 13.4 ^{BCDE}	56.4 $\pm$ 7.8 ^{ABCDE}	64.8 $\pm$ 15.7 ^{BCD}
	1.0	10	58.0 $\pm$ 8.4 ^{BCD}	53.8 $\pm$ 6.7 ^{BCDE}	53.0 $\pm$ 6.5 ^{ABCDE}	52.8 $\pm$ 5.1 ^{ABCD}
	1.5	10	58.4 $\pm$ 11.7 ^{BCD}	71.8 $\pm$ 11.2 ^{CDE}	59.0 $\pm$ 7.7 ^{BCDE}	65.2 $\pm$ 11.0 ^{BCD}
Varseosmile (VS)	0.8	10	57.4 $\pm$ 9.6 ^{ABCD}	69.4 $\pm$ 9.9 ^{BCDE}	64.2 $\pm$ 10.8 ^{BCDE}	66.0 $\pm$ 13.5 ^{BCD}
	1.0	10	47.6 $\pm$ 3.7 ^{AB}	49.8 $\pm$ 5.5 ^{ABCDE}	48.4 $\pm$ 4.4 ^{ABC}	50.8 $\pm$ 6.1 ^{ABD}
	1.5	10	54.0 $\pm$ 4.7 ^{ABCD}	48.6 $\pm$ 3.0 ^{ABCD}	51.0 $\pm$ 3.3 ^{ABCD}	51.4 $\pm$ 6.8 ^{ABD}

MG, marginal gap, N; numbers of specimens, n; numbers of image per specimen. Within the same column, the values with the same capital letter are not statistically different ($P>0.05$). Statistical analysis with two-way ANOVA and post hoc Tukey's test (significance level $\alpha = 0.05$)

4.1.1.3 Change of marginal adaptation after cementation

The results of AMD, MG values in all groups before and after cementation (Table 8 and Table 9) showed that almost all AMD and MG values (51 of 72 comparisons) were significantly decreased after cementation ($P<0.05$). Except for AMD of both CE and VE 1.5 mm. at distal aspects and almost all VS (10 of 12 comparisons) were significantly increased after cementation ($P<0.05$). Change of MG values at distal aspect in all groups were decreased but not significantly different ($P>0.05$).

Table 8. Mean $\pm$ SD (μ m) values of AMD for test group before and after cementation

Types	Thickness (mm.)	Mean $\pm$ SD							
		Buccal		Lingual		Mesial		Distal	
		Before ^a	After ^b	Before ^a	After ^b	Before ^a	After ^b	Before ^a	After ^b
Cerasmart (CE)	0.8	97.2 $\pm$ 10.8	77.0 $\pm$ 16.0	78.6 $\pm$ 13.3	59.0 $\pm$ 18.7	89.0 $\pm$ 13.1	73.6 $\pm$ 26.5	84.8 $\pm$ 12.6	68.2 $\pm$ 10.0
	1.0	82.0 $\pm$ 10.3	60.0 $\pm$ 9.5	60.8 $\pm$ 8.9	43.4 $\pm$ 8.8	68.0 $\pm$ 16.8	55.0 $\pm$ 5.6	63.2 $\pm$ 11.0	49.0 $\pm$ 4.7
	1.5	72.8 $\pm$ 8.7	66.0 $\pm$ 5.9	64.8 $\pm$ 5.5	53.8 $\pm$ 6.1	69.3 $\pm$ 7.4	65.8 $\pm$ 6.1	58.6 $\pm$ 4.7	63.0 $\pm$ 6.5
VitaEnamic (VE)	0.8	78.2 $\pm$ 10.1	55.0 $\pm$ 7.8	80.2 $\pm$ 7.5	67.6 $\pm$ 13.4	78.0 $\pm$ 15.3	56.4 $\pm$ 7.8	65.2 $\pm$ 9.8	64.8 $\pm$ 15.7
	1.0	88.8 $\pm$ 17.4	58.0 $\pm$ 8.4	74.4 $\pm$ 8.6	53.8 $\pm$ 6.7	80.6 $\pm$ 14.0	53.0 $\pm$ 6.5	60.0 $\pm$ 10.8	52.8 $\pm$ 5.1
	1.5	88.8 $\pm$ 8.3	58.4 $\pm$ 11.7	72.4 $\pm$ 9.2	71.8 $\pm$ 11.2	87.4 $\pm$ 9.1	59.0 $\pm$ 7.7	58.0 $\pm$ 4.6	65.2 $\pm$ 11.0
Varseosmile (VS)	0.8	51.0 $\pm$ 6.1	57.4 $\pm$ 9.6	50.0 $\pm$ 3.0	69.4 $\pm$ 9.9	44.8 $\pm$ 5.2	64.2 $\pm$ 10.8	47.4 $\pm$ 4.0	66.0 $\pm$ 13.5
	1.0	50.0 $\pm$ 4.4	47.6 $\pm$ 3.7	49.4 $\pm$ 4.0	49.8 $\pm$ 5.5	46.6 $\pm$ 4.0	48.4 $\pm$ 4.4	46.4 $\pm$ 3.1	50.8 $\pm$ 6.1
	1.5	53.8 $\pm$ 6.1	54.0 $\pm$ 4.7	53.4 $\pm$ 4.8	48.6 $\pm$ 3.0	48.2 $\pm$ 3.6	51.0 $\pm$ 3.3	50.8 $\pm$ 7.1	51.4 $\pm$ 6.8

Table 9. Mean $\pm$ SD (μ m) values of MG for test group before and after cementation

Types	Thickness (mm.)	Mean $\pm$ SD							
		Buccal		Lingual		Mesial		Distal	
		Before ^a	After ^b	Before ^a	After ^b	Before ^a	After ^b	Before ^a	After ^a
Cerasmart (CE)	0.8	85.4 $\pm$ 8.3	45.0 $\pm$ 19.9	69.0 $\pm$ 15.8	57.8 $\pm$ 17.0	45.6 $\pm$ 23.6	24.4 $\pm$ 11.2	60.0 $\pm$ 14.9	59.6 $\pm$ 16.2
	1.0	58.6 $\pm$ 21.8	29.8 $\pm$ 13.9	78.0 $\pm$ 10.9	64.0 $\pm$ 15.7	49.6 $\pm$ 15.0	18.6 $\pm$ 7.7	69.0 $\pm$ 8.2	57.2 $\pm$ 19.7
	1.5	32.8 $\pm$ 8.0	21.4 $\pm$ 7.7	75.7 $\pm$ 8.8	67.6 $\pm$ 8.7	39.6 $\pm$ 9.9	35.4 $\pm$ 15.1	61.8 $\pm$ 9.2	51.2 $\pm$ 17.5
VitaEnamic (VE)	0.8	74.6 $\pm$ 22.7	28.6 $\pm$ 12.9	52.2 $\pm$ 18.8	34.4 $\pm$ 21.9	43.0 $\pm$ 6.9	17.4 $\pm$ 6.5	51.2 $\pm$ 11.0	39.8 $\pm$ 14.2
	1.0	70.0 $\pm$ 24.6	18.2 $\pm$ 5.3	65.4 $\pm$ 30.0	33.8 $\pm$ 14.1	62.8 $\pm$ 21.3	26.6 $\pm$ 11.6	70.2 $\pm$ 16.3	53.4 $\pm$ 12.5
	1.5	65.0 $\pm$ 24.3	23.1 $\pm$ 10.7	91.4 $\pm$ 20.5	44.8 $\pm$ 13.8	54.4 $\pm$ 15.8	18.6 $\pm$ 9.5	77.8 $\pm$ 11.7	39.0 $\pm$ 24.2
Varseosmile (VS)	0.8	19.8 $\pm$ 4.8	10.4 $\pm$ 3.9	23.4 $\pm$ 8.7	15.2 $\pm$ 11.8	18.4 $\pm$ 5.2	12.4 $\pm$ 4.7	28.0 $\pm$ 13.8	19.6 $\pm$ 9.0
	1.0	21.6 $\pm$ 7.2	9.6 $\pm$ 3.4	31.4 $\pm$ 9.7	13.4 $\pm$ 9.3	18.0 $\pm$ 7.8	12.2 $\pm$ 4.5	36.6 $\pm$ 10.8	18.4 $\pm$ 15.2
	1.5	18.0 $\pm$ 8.7	10.4 $\pm$ 3.9	21.4 $\pm$ 6.2	9.6 $\pm$ 3.4	15.6 $\pm$ 7.6	12.6 $\pm$ 4.1	27.2 $\pm$ 11.7	15.0 $\pm$ 6.6

Table 8., Table 9.; At the same aspect, the Before-After values with the same letter are not statistically different ($P>0.05$). Statistical analysis with paired T-test (significance level $\alpha = 0.05$)

4.1.2 Fracture resistance

Following crown cementation, the fracture resistances were evaluated. Fractured crowns were observed in 4 groups (0.8 mm VE and all thicknesses of VS) out of 9 (Figure 7). 5 out of 6 milled crowns were not fractured even with the maximum force of 2000 N (Table 10). All 3D-printed crowns were fractured at a certain compressive force (Table 10). No fracture of the supporting dies was noted. Fracture resistant forces of each group were compared in Table 11. Notably, both CE and VE (except 0.8 mm) specimens that were not broken demonstrated the plasticity phenomenon of material where loading force values were within linearity limit, observed from stress-strain plots for each tested crown under the loading forces. For VS crowns, 0.8 mm occlusal thickness was fractured at the lowest loading force (1480.3 ± 226.1 N). Fracture resistance values increased with occlusal thickness of crowns. (Table 11)

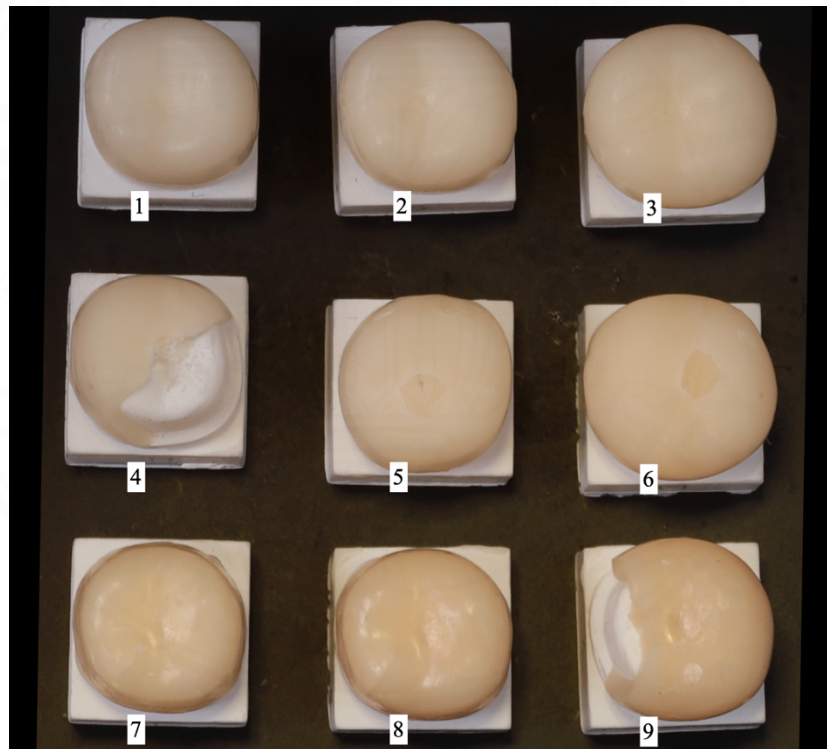


Figure 7. Exemplary pictures after loading to fracture; occlusal thicknesses of 0.8, 1, and 1.5 mm for Cerasmart; CE (1, 2, 3), occlusal thicknesses of 0.8, 1, and 1.5 mm for Vita Enamic; VE (4,5,6), occlusal thicknesses of 0.8, 1, and 1.5 mm for Varseosmile; VS (7,8,9).

Table 10. Overview results maximum loading force in Newton (N); *n* number of specimens, *n** number of fractured specimens

Types	Thickness (mm.)	<i>n</i>	<i>n</i> *	Mean	SD	Min	Max	95% CI	
								lower	upper
Cerasmart (CE)	0.8	10	0	>2000	-	-	-	-	-
	1.0	10	0	>2000	-	-	-	-	-
	1.5	10	0	>2000	-	-	-	-	-
VitaEnamic (VE)	0.8	10	10	1812.3	161.4	1404.9	1991.1	1696.9	1927.8
	1.0	10	0	>2000	-	-	-	-	-
	1.5	10	0	>2000	-	-	-	-	-
Varseosmile (VS)	0.8	10	10	1480.3	226.1	1191.1	1815.7	1318.6	1642.0
	1.0	10	10	1629.4	118.5	1479.8	1834.8	1544.6	1714.2
	1.5	10	10	1747.2	108.7	1584.3	1954.9	1669.4	1824.9

Table 11. Mean $\pm$ SD values of fracture resistance force in Newton (N)

Thicknesses (mm)	Types		
	CE	VE	VS
0.8	> 2000*	1812.3 $\pm$ 161.4	1480.3 $\pm$ 226.1 ^A
1.0	> 2000*	>2000*	1629.4 $\pm$ 118.5 ^A
1.5	> 2000*	>2000*	1747.2 $\pm$ 108.7 ^B

* In the table, the values >2000 represent specimens that are not fractured when a loading force of 2000 N is applied; therefore, the statistical analyses for the CE and VE groups are not performed. For VS group only, one-way ANOVA and post-hoc Tukey's test (significance level $\alpha = 0.05$) are used; the values are presented as mean $\pm$ SD; within the same column, the values with the same capital letters are not statistically different ($P > 0.05$).

4.2 Discussion

The null hypothesis was rejected as statistically significant differences were observed in the obtained results. Owing to the novelty of this 3D-printed hybrid crown material, no study has investigated the marginal fit and fracture load of this material made from different occlusal thicknesses or compared them with milled hybrid materials. Marginal adaptation is a major predictor of the clinical success of fixed prosthetic restorations (57, 58), and many methods have been examined. The most widely used method is the direct microscopic evaluation of gaps along the crown margins. However, this method has major disadvantages because the reference points may be difficult to prove, leading to projection errors.(33) The micro-CT scan was used in the present study, and by this innovative and nondestructive technique, the marginal and internal adaptation of the restoration can be simultaneously evaluated. Moreover, micro-CT scans provide both 2D and 3D imaging of the space between the restoration and die, providing very closed sections of the marginal area, which allows a large number of measurement sites.(9, 35) In 2000, Groten et al.(33) investigated the gaps along crown margin in a scanning electron microscope on the master steel die without cementing and on replica dies after conventional cementing. They showed that fifty measurements of the marginal fit caused less than $\pm 5 \mu\text{m}$ variability for arithmetic

means.(33) However, in 2004, Gassino et al.(36) argued that only eighteen points were necessary and ninety observation points will produce a sample mean value within $\pm 5 \mu\text{m}$ of the true mean, with $\leq 4 \mu\text{m}$ of standard error.(36) In the present study, forty measurements of each crown (3600 points in total) were performed. In 2014, Yildirim et al.(10) evaluated the AMD and MG values of hybrid materials (VE and LU) and compared them with those of lithium disilicate (e.max CAD[®]) using micro-CT scanning and demonstrated that the hybrid materials showed considerably better marginal adaption than lithium disilicate[8] with a clinical acceptable range of less than $120 \mu\text{m}$ as suggested by McLean and Von Fraunhofer in 1917.(10) Conversely, a study by Azarbal et al.,(11) in 2017, reported that VE crowns fabricated using the CEREC milling system showed marginal adaptation superior to that of lithium disilicate crowns.(11) In this study, all the hybrid material crowns produced MG values within the clinically acceptable range(10) similar to previous studies.(59, 60)

The marginal adaptation of the milled dental crowns is affected by various factors, including machinability-related aspects, such as the sharpness and diameter of the milling burs, hardness of the milled materials, abutment preparation design, cement space setting, and measuring period (before or after cementing).(61) To ensure the sharpness of the milling burs, this study used a cylindrical pointed bur 12S and a step bur 12 equipped with the CEREC MCX milling unit, and the burs were replaced according to the research protocol. From our observations, after milling the CE and VE crowns, the average wear percentages of the milling burs reduced from 100% to 25%, which may imply that the hybrid materials may cause less wear to the milling burs.[26, 27, 28] It was suggested that marginal adaptation of CAD/CAM restorations is material dependent (60, 62) and the specificity of chemical and microstructural properties of each material impacts the accuracy and precision of the CAD/CAM production.(61) The MG results of this study are similar to those of the previous study,[27] where the MG range was $68.5 \pm 23.8 \mu\text{m}$ for the milled resin ceramics (CE, VE, and BC) and were not significantly different between the groups.(61)

For the preparation design from *in vitro* studies, teeth should be prepared in accordance with clinical conditions.(10) Thus, the use of metallic models with overly simplified shapes or flat occlusal surfaces is not directly related to the actual clinical circumstances. According to Habib et al., in 2014, (37) the accuracy of the marginal and internal adaptation of zirconia copings of the anatomical preparation showed better marginal and internal adaptation.(37) In the present study, an anatomical occlusal design was used; therefore, all three hybrid material crowns demonstrated good marginal adaptation. For cement space setting, the setting in CAD design usually followed an international standard for polymer-based filling restorative and luting materials mixing ratio of base and catalyst (International Organization for Standardization (ISO) 4049:2019), where $50 \mu\text{m}$ is set as the critical thickness of the cement, and in this study, it was virtually simply set to $50 \mu\text{m}$ by the CAD process. Dauti et al., in 2019,(63) evaluated the influence of 50 and $80 \mu\text{m}$ cement space settings on the marginal and internal adaptation of VE crowns and suggested that both virtual spacer settings could be used for manufacturing without any significant differences.(63) Although the cement thickness acted as a cushion between the crown and abutment, a larger luting material thickness caused higher tensile stress in the core of the crown,

leading to a higher degree of crown flexure and failure.(64) As a result, a cement layer as thin as possible was selected. Maneenakarath et al.,(65) in 2022, also found that thinner resin cement showed a higher shear bond strength of cement-zirconia than thicker cement.(65) The present study also revealed that increasing occlusal thickness did not affect marginal adaptation.

The 3D-printed hybrid material crowns (VS) demonstrated lower AMD and MG values than the milled crowns. The results of the CE and VE groups were similar to those reported by Donmez et al., in 2022,(66) which showed that implant-supported 3D-printed definitive composite crowns (Saremco Print, Crowntec) had better marginal adaptation than those fabricated using the milling technique (CE,VE, and BC).(66) In addition, Kakinuma et al., in 2022,(67) also found that 3D-printed resin-composite crowns (TNG-GPM101, GC) demonstrated higher accuracy with fewer marginal gaps than milled crowns (CE) after twenty-eight assessments of only bucco-lingually sectioned cemented crowns with a laser microscope to represent the marginal gaps.(67) By contrast, this study used micro-CT to obtain forty assessments (3600 points in total) from both the bucco-lingual and mesio-distal sites of each crown, which truly represented the marginal adaptation. Furthermore, to disregard the influence of the luting cement characteristics, this study was performed before cementing. The results of this study indicate the advantage of additive manufacturing in producing complex shapes with undercuts or locations that cannot be produced or are limited by the milling process. Nonetheless, various printing parameters affect the accuracy of prostheses, such as build orientation, layer thickness, x-y resolution, light exposure time, post-processing, and printing materials.(3) Only a few studies have varied these factors and comparatively investigated the marginal adaptation of 3D-printed crowns. Therefore, further studies on the factors associated with 3D printing techniques are required.

Previous studies found that cementation procedure played an important role in the final accuracy of the marginal adaptation for all ceramic crown restorations.(68, 69) After cementation, almost all AMD and MG values significantly decreased ($P<0.05$). Those results may be influenced by the cementation procedure including pressure or force applied to the crown. Crown seating before cementation was performed by finger compression with light force but when cementing a constant load of 20 N was controlled by the force gauge with a test stand. Even without the luting cement, it is possible that light finger pressure may not enough to create fully seating of the crowns. Moreover, the 20 N loading force may create the better seating of the crowns with better marginal adaptation. However, increased AMD values post-cementation in most of VS groups compared to CE and VE may be affected by the smaller MG values causing binding or friction resistance due to hydraulic pressure during cementation.(70) Moreover, it may possible that lowest flexural modulus of VS itself causing the marginal distortion during the fixation. Further study is suggested. However, in the present study, the marginal adaptation values were still in a clinical acceptable range after cementation. It can be noticed that adequate force against hydraulic pressure during seating of the crowns may result in reduced AMD and MG values. Further study of internal gaps should be investigated to clarify this finding.

When evaluating new materials, it is important to test their mechanical properties using the basic tests specified by the ISO. Common mechanical evaluations for dental materials include flexural strength and modulus tests.(17) In three-point bending tests (ISO norm DIS 6872), various flexural strength values have been reported, indicating that CE is the strongest: CE, ranging from 181.15 ± 13.56 (38) to 216.5 ± 28 MPa;(39) VE, ranging from 148.16 ± 10.04 (40) to 155.26 ± 16.13 MPa(41); and VS, ranging from 119.85 ± 17.95 to 143.39 ± 12.88 MPa(42). The flexural modulus was found to be 25 GPa for CE,(39) 23.3 ± 6.4 GPa for VE,(39), and 4.37 ± 0.8 to 4.69 ± 0.15 GPa for VS.(42) In addition, flexural strengths reported by the manufacturers of CE, VE, and VS are 238,(15) 150–160,(43) and 116–150 MPa,(7) respectively. Goujat et al., in 2018, also found that CE (216.5 ± 28 MPa) had a significantly higher flexural strength than VE (148.7 ± 9.5 MPa).(39) However, there were no statistically significant differences in the flexural strength between the VE and VS groups ($P > 0.001$).(42) The strengths of these materials are consistent with the results of this study; the CE and VE groups demonstrated higher fractural strength than the VS group. As a result, CE of all occlusal thicknesses and VE when >1.0 mm could endure loading forces >2000 N without any visible cracks, which may suggest that these hybrid materials exhibit high capacities to disperse energy by elastic and plastic deformation. In contrast, all VS crowns in this study were broken and sustained the lowest maximum loading force. This may be due to the low flexural modulus of VS, which reflects the differences in its structural compositions (relatively low filler contents) and manufacturing method. Despite the low filler content, this may add an advantage in liquefying the hybrid material during the 3D-printing process.(42) Notably, VS-group specimens with occlusal thickness >1.0 mm exhibit a significant increase in toughness of the restorations against the loading force ($P < 0.05$).

However, the aforementioned conventional flexural strength test may not be suitable for the evaluation of dental restorative materials because of the differences in the loading forces applied in laboratory settings and the actual forces in intraoral conditions.(5) Instead, many studies investigating fracture strength using crown-shaped specimens with minimum crown thickness have been reported.(5, 44, 45) Usually, the fracture resistance testing method uses a universal testing machine with a ball steel indenter on the crown shape specimens.(46) In a literature review, it was found that the material and thickness of the crown are the main factors for evaluating fracture behavior.(49) In addition, the fracture resistance was mainly determined by the E-Modulus of the supporting structures.(50) Fracture forces of the all-ceramic crowns increased with augmentation of the E-modulus of the supporting material.(51) Ideally, using natural teeth makes standardization difficult because of large variations in tooth anatomy, patient age, and storage time after extraction.(52) Therefore, many studies have used metals, epoxy resins, and acrylic resins as supporting dies.(53) From a previous study, an acrylic resin die material (inCoris SLS) was used with the characteristics of 2.5 GPa E-Modulus, 110–130 MPa fracture resistance, and 80–84 Shore D of shore hardness.(5) Instead, a supporting material with an E-modulus comparable to that of natural dentin (between 7 and 13 GPa)(54) was suggested for use in fracture tests. Therefore, a Rigid 10K (Formlabs) highly glass-filled resin (9 GPa of E-modulus and fracture resistance of 126 MPa)(55) was selected in this study, and the results may be comparatively close to the natural dentin conditions.(5) In this study, all

hybrid material groups could sustain normal occlusal load (50–300 N) and clenching load (1200 N)(13) even with an occlusal thickness of 0.8 mm. According to the manufacturer, a minimum occlusal thickness of 1.0 mm is recommended for VE crown; thus, 0.8 mm VE crowns were expectedly cracked at a certain loading force. Notably, a minimum of 1.5 mm CE occlusal thickness was recommended by the manufacturer, but the results from this study demonstrated that even a 0.8 mm CE sustained the loading force without any visible cracked defects, as shown in Fig. 8. As a result, CE may require minimal occlusal reduction to achieve a good clinical outcome when there is limited occlusal space and a non-ideal preparation design and thickness.(6) Similar to the report by Sorrentino et al., in 2018,(71) CE showed sufficient fracture resistance for use in molar regions with the occlusal thickness >0.5 mm.(71)

It can be speculated that these hybrid materials can be used with a minimum of 0.8 mm thickness to sustain the loading forces. Only a few studies have investigated factors affecting the mechanical properties of 3D-printed restorations.(42, 72) Grzebieluch et al., in 2021,(42) found that vertically printed VS samples to the platform exhibited the best mechanical properties owing to printed objects positioning in such a way that tensile force generated during mastication was applied along and not across the layer. This led to a more random distribution of inorganic particles in the textures.(42) In this study, the printing orientation was designed parallel to the loading force direction.

Previous studies showed that after milling, materials with high flexural strength provide better internal and marginal adaptations because of their machinability.(39, 60–62, 72) However, although a difference in the flexural strength was observed, there was no statistically significant difference in the adaptation of the hybrid materials (VE and LU).(9) Similar to our results, marginal adaptation was not significantly different ($P>0.05$) between the milling groups (CE and VE), although it has been reported that CE has significantly higher flexural strength than VE.(39) CE and VE crowns were efficiently fabricated by the milling machine, despite the differences in surface hardness and material compositions according to the brittleness index of both CE and VE ($<4.3 \mu\text{m}^{-1/2}$), which is the cut-off point for machinability(72) and milling burs were replaced in every group as mentioned above. This suggests that machinability may be a major factor in the favorable restoration of hybrid materials with a good marginal fit. Although the VS manufactured by the 3D-printing technique had the lowest flexural strength compared to the other hybrid materials in this study, it provided the best marginal adaptation values, as mentioned earlier. Notably, the manufacturing method influenced the marginal adaptation of the restoration. The flexural strength and modulus values indicated by the structural composition of the material may be key factors for fracture resistance. Although the 3D-printing technique provided superior restorations in terms of marginal fit, the total production time was longer than that of the milling technique and required post-curing processes.

4.3 Clinical significance

1. CAD/CAM hybrid materials can be an alternative minimally invasive treatment that provides good marginal adaptation and acceptable fracture resistance, which is favorable for a clinical situation with limited occlusal space such as severe tooth attrition usually present with a short clinical crown. Furthermore, resin-bonded with a thin occlusal veneer restoration of hybrid dental materials is suggested in the case of unnecessary tooth removal.

2. The 3D-printing technique provides superior marginal adaptation over the milling ones.

3. Although the advantages of 3D printing are its low cost and the generation of less waste in the fabrication process, the mechanical properties of the 3D-printing material still need improvement to be comparable with those of other hybrid materials.

4) cementation procedure affects marginal adaptation of crown restorations



CHAPTER 5

LIMITATIONS AND CONCLUSIONS

5.1 Limitations

This is a controlled *in-vitro* experimental study with some limitations. The virtually and ideally designed dies (tooth abutment) and crown preparations with predefined CAD/CAM procedures can pose challenges in real-world non-ideal clinical scenarios. For instance, a 50 μm cement space setting may impact crown fitting, resulting in an increased marginal gap. Cementation was strictly controlled by surface treatment procedures, and only one type of adhesive was used; therefore, different surface treatment protocols and types of adhesives may yield different outcomes. Moreover, natural tooth dentin has a wide range of elastic moduli.(73) However, the present study uses a Rigid 10K resin die, which represents only a constant elastic modulus of the supporting structure, which may not be generalizable in a variety of clinical situations. In addition, fracture resistance is only a static loading test, and the clinical function of dental crowns is more complex with multidirectional forces. Variations in the above-mentioned factors are suggested for further investigations, including a higher force of the loading cell, clenching or bruxism conditions, cyclic fatigue tests, and even finite element analysis. Nonetheless, hybrid materials may also have other limitations, such as color stability and wear resistance. Further evaluation of their physical properties, especially in the *in-vivo* conditions, should also be conducted.

5.2 Conclusions

Within the limitations of the present study, it can be concluded that

- 1) The type of hybrid crown material used is directly associated with marginal adaptation and fracture resistance.
- 2) The 3D printing technique of the hybrid materials provides superior marginal adaptation compared to the milling technique.
- 3) The CAD/CAM hybrid material crown demonstrates favorable marginal adaptation and fracture resistance even with only 0.8 mm of occlusal thickness.
- 4) Occlusal thickness affects the fracture resistance.

REFERENCES

1. Van Noort R. The future of dental devices is digital. *Dental Materials*. 2012;28(1):3-12.
2. Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. *British Dental Journal*. 2008;204(9):505-11.
3. Alharbi N, Wismeijer D, Osman RB. Additive manufacturing techniques in Prosthodontics: Where do we currently stand? A critical review. *International Journal of Prosthodontics*. 2017;30(5):474-84.
4. Ahlholm P, Lappalainen R, Lappalainen J, Tarvonen P-L, Sipilä K. Challenges of the direct filling technique, adoption of CAD/CAM techniques, and attitudes toward 3D printing for restorative treatments among Finnish dentists. *International Journal of Prosthodontics*. 2019;32(5):402-10.
5. Zimmermann M, Ender A, Egli G, Mehl A, Özcan M. Fracture load of CAD/CAM-fabricated and 3D-printed composite crowns as a function of material thickness. *Clinical Oral Investigations*. 2019;23(6):2777-84.
6. Awada A, Nathanson D. Mechanical properties of resin-ceramic CAD/CAM restorative materials. *Journal of Prosthetic Dentistry*. 2015(4):587.
7. Instruction for use on Varseosmile Crown Plus. Bremen, Germany: the BEGO company group; 2022.
8. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: A systematic review. *J Prosthet Dent*. 2013;110(6):447-54.
9. Yildirim G, Uzun IH, Keles A. Evaluation of marginal and internal adaptation of hybrid and nanoceramic systems with microcomputed tomography: An in vitro study. *Journal of Prosthetic Dentistry*. 2017;118(2):200-7.
10. McLean JW, Von F. The estimation of cement film thickness by an in vivo technique. *British Dental Journal*. 1971;131(3):107-11.
11. Azarbal A, Azarbal M, Engelmeier RL, Kunkel TC. Marginal fit comparison of CAD/CAM crowns milled from two different materials. *Journal of Prosthodontics*. 2018;27(5):421-8.
12. Magne P, Schlichting LH, Maia HP, Baratieri LN. In vitro fatigue resistance of CAD/CAM composite resin and ceramic posterior occlusal veneers. *the Journal of Prosthetic Dentistry*. 2010;104(3):149-57.
13. Björn AL, Björn H, Grkovic B. Marginal fit of restorations and its relation to periodontal bone level. I. Metal fillings. *Odontologisk revy*. 1969;20(3):311-21.
14. Rabeae HS, Mohsen CA, Amgad SW. Assessment of fracture force of CAD-CAM-fabricated occlusal veneer restorations with different thicknesses. *Indian Journal of Public Health Research & Development*. 2020;11(1):1125-30.
15. Instruction for use on Cerasmart. GC America Inc., USA; 2014.
16. Venturini AB, Prochnow C, Pereira GKR, Segala RD, Kleverlaan CJ, Valandro LF. Fatigue performance of adhesively cemented glass-, hybrid- and resin-ceramic materials for CAD/CAM monolithic restorations. *Dent Mater*. 2019;35(4):534-42.
17. Okada R, Asakura M, Ando A, Kumano H, Ban S, Kawai T, et al. Fracture strength testing of crowns made of CAD/CAM composite resins. *Journal of Prosthodontic Research*. 2018;62(3):287-92.

18. Abd El Shakour AS, Mohsen CA, Ramzy MI. Fracture strength of two types of posterior occlusal veneers made of hybrid ceramics with different thicknesses. *Indian Journal of Public Health Research & Development*. 2020;11(4):913-9.
19. Galante R, Figueiredo-Pina CG, Serro AP. Additive manufacturing of ceramics for dental applications: A review. *Dental Materials*. 2019;35(6):825-46.
20. Dawood A, Marti BM, Sauret-Jackson V, Darwood A. 3D printing in dentistry. 2015:521.
21. Hotta Y, Miyazaki T, Fujiwara T, Tomita S, Shinya A, Sugai Y, et al. Durability of tungsten carbide burs for the fabrication of titanium crowns using dental CAD/CAM. 2004:190.
22. Payaminia L, Moslemian N, Younespour S, Koulivand S, Alikhasi M. Evaluating the effect of repeated use of milling burs on surface roughness and adaptation of digitally fabricated ceramic veneers. *Heliyon*. 2021;7(4).
23. Roberto RC, Lopes FC, Porto TS, Teich S, Rizzante FAP, Gutmacher Z, et al. CAD/CAM diamond tool wear. *Quintessence International*. 2018;49(10):781-6.
24. Huang S, Liu P, Mokasdar A, Hou L. Additive manufacturing and its societal impact: a literature review. *International Journal of Advanced Manufacturing Technology*. 2013;67(5-8):1191-203.
25. Bajraktarova-Valjakova E, Korunoska-Stevkovska V, Kapusevska B, Gigovski N, Bajraktarova-Misevska C, Grozdanov A. Contemporary dental ceramic materials, a review: chemical composition, physical and mechanical properties, indications for use. *Journal of Medical Sciences*. 2018;6(9):1742-55.
26. Facenda JC, Borba M, Corazza PH. A literature review on the new polymer-infiltrated ceramic-network material (PICN). *Journal of Esthetic and Restorative Dentistry*. 2018;30(4):281.
27. Della Bona A, Corazza PH, Zhang Y. Characterization of a polymer-infiltrated ceramic-network material. *Dental Materials*. 2014;30(5):564-9.
28. Kurbad A, Kurbad S. A New, Hybrid Material for Minimally Invasive Restorations in Clinical Use. 2013:69.
29. Sofan E, Sofan A, Palaia G, Tenore G, Romeo U, Migliau G. Classification review of dental adhesive systems: from the IV generation to the universal type. *Annals of Stomatology / Annali di Stomatologia*. 2017;8(1):1-17.
30. Dauti R, Lilaj B, Heimel P, Moritz A, Schedle A, Cvikl B. Influence of two different cement space settings and three different cement types on the fit of polymer-infiltrated ceramic network material crowns manufactured using a complete digital workflow. *Clinical Oral Investigations*. 2020;24(6):1929.
31. Technical data sheet of RelyX unicem. 3M ESPE company, USA; 2007.
32. Somchai U, Wutipong L, Chatcharee S. Effect of cement film thickness on shear bond strengths of two resin cements [Article]2014.
33. Groten M, Axmann D, Pröbster L, Weber H. Determination of the minimum number of marginal gap measurements required for practical in vitro testing. *J Prosthet Dent*. 2000;83(1):40-9.
34. Luthardt RG, Bornemann G, Lemelson S, Walter MH, Huls A. An innovative method for evaluation of the 3-D internal fit of CAD/CAM crowns fabricated after direct optical versus indirect laser scan digitizing. 2004:680.
35. Pelekanos S. Micro-CT evaluation of the marginal fit of different In-Ceram alumina copings. *Eur J Esthet Dent*. 2009;4(3):278-92.

36. Gassino G, Monfrin SB, Scanu M, Spina G, Preti G. Marginal adaptation of fixed prosthodontics: a new in vitro 360-degree external examination procedure. *Int J Prosthodont.* 2004;17(2):218-23.
37. Habib SR, Asiri W, Hefne MJ. Effect of anatomic, semi-anatomic and non-anatomic occlusal surface tooth preparations on the adaptation of zirconia copings. *Journal of Advanced Prosthodontics.* 2014;6(6):444-50.
38. Shafter M. Effect of thermocycling on flexural strength of different CAD/CAM material. *Journal of Dentistry & Oral Disorders.* 2017;3(3).
39. Goujat A, Abouelleil H, Colon P, Jeannin C, Pradelle N, Seux D, et al. Mechanical properties and internal fit of 4 CAD-CAM block materials. *The Journal of Prosthetic Dentistry.* 2018;119(3):384-9.
40. Lucsanskzy IJR, Ruse ND, editors. Fracture toughness, flexural strength, and flexural modulus of new CAD/CAM resin composite blocks 2020 2020/01/01; United States: Wiley-Blackwell.
41. Mahshid S, Fariba E, Behnaz E, Ali B. Evaluation of the effects of different concentrations of bleaching agents on flexural strength and microhardness of Vita Enamic. *Dental Research Journal.* 2022;19(1):32-.
42. Grzebieluch W, Kowalewski P, Grygier D, Rutkowska-Gorczyca M, Kozakiewicz M, Jurczyszyn K. Printable and machinable dental restorative composites for CAD/CAM application—comparison of mechanical properties, fractographic, texture and fractal dimension analysis. *Materials.* 2021;14(17):4919.
43. Instruction for use on Vita Enamic. Vita Zahnfabrik H., Germany; 2020.
44. Jang GW, Kim HS, Choe HC, Son MK. Fracture strength and mechanism of dental ceramic crown with zirconia thickness. *Procedia Engineering.* 2011;10:1556-60.
45. Chen SE, Park AC, Knoernschild KL, Campbell S, Yang B, Wang J. Fracture resistance of various thickness e.max CAD lithium disilicate crowns cemented on different supporting substrates: an in vitro study. *Journal of Prosthodontics.* 2019;28(9):997-1004.
46. Celebi AA, Kau CH, Lee SH. Size discrepancies in molars and first key to optimal occlusion. *European Journal of Dentistry.* 2017;11(2):250-2.
47. Surlari Z, Budală DG, Luca E, Brezulianu C, Iordache C, Ciocan-Pendefunda A-A, et al. Objectives and assessments of esthetic dental treatment-A based-evidence approach. *Romanian Journal of Oral Rehabilitation.* 2019;11(3):205-9.
48. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. *The Journal of Prosthetic Dentistry.* 1989;62(4):405-8.
49. Rekow ED, Harsono M, Janal M, Thompson VP, Zhang G. Factorial analysis of variables influencing stress in all-ceramic crowns. *Dental Materials.* 2006;22(2):125-32.
50. Van PT, Dianne ER. Dental ceramics and the molar crown testing ground. *Journal of Applied Oral Science.* 2004;12(spe):26-36.
51. Scherrer SS, De Rijk WG. The fracture resistance of all-ceramic crowns on supporting structures with different elastic moduli. *International Journal of Prosthodontics.* 1993;6(5):462-7.
52. Potiket N, Chiche G, Finger IM. In vitro fracture strength of teeth restored with different all-ceramic crown systems. *The Journal of Prosthetic Dentistry.* 2004;92(5):491-5.

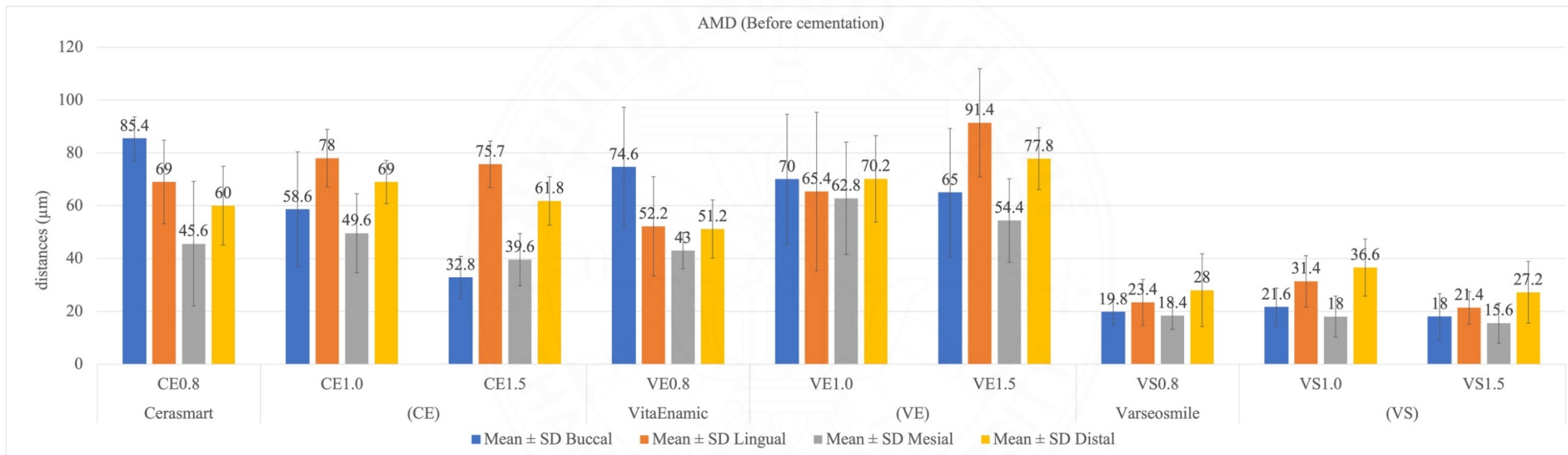
53. Sagsoz NP, Yanikoflu N, Sagsoz O. Effect of die materials on the fracture resistance of CAD/CAM monolithic crown restorations. *Oral health and dental management*. 2016;2016:165-8.
54. Kinney JH, Marshall SJ, Marshall GW. The mechanical properties of human dentin: a critical review and re-evaluation of the dental literature. *Critical Reviews in Oral Biology & Medicine*. 2003;14(1):13-29.
55. Material properties data of Rigid 10K resin. Formlabs Inc., USA; 2020.
56. Li Hsin L, Joshua G, Frank A-S, Laura D, Derek S, Khaled EA. A proposed in vitro methodology for assessing the accuracy of three-dimensionally printed dental models and the impact of storage on dimensional stability. *Applied Sciences*. 2021;11(5994):5994-.
57. Mously HA, Finkelman M, Zandparsa R, Hirayama H. Marginal and internal adaptation of ceramic crown restorations fabricated with CAD/CAM technology and the heat-press technique. *The Journal of Prosthetic Dentistry*. 2014;112(2):249-56.
58. Şeker E, Ozcelik TB, Rathi N, Yilmaz B. Evaluation of marginal fit of CAD/CAM restorations fabricated through cone beam computerized tomography and laboratory scanner data. *The Journal of Prosthetic Dentistry*. 2016;115(1):47-51.
59. Naffah N, Ounsi H, Ozcan M, Bassal H, Salameh Z. Evaluation of the adaptation and fracture resistance of three CAD-CAM resin ceramics: An in vitro study. *Journal of Contemporary Dental Practice*. 2019;20(5):571-6-6.
60. Oguz EI, Kılıçarslan MA, Özgür ME, Orhan K, Shujaat S. Comparison of marginal adaptation of different resin-ceramic CAD/CAM crowns: an in vitro study. *Journal of Advanced Oral Research*. 2021;12(1):112-8.
61. Hasanzade M, Moharrami M, Alikhasi M. How adjustment could affect internal and marginal adaptation of CAD/CAM crowns made with different materials. *Journal of Advanced Prosthodontics*. 2020;12(6):344-50-50.
62. El Ghouli WA, Özcan M, Ounsi H, Tohme H, Salameh Z. Effect of different CAD-CAM materials on the marginal and internal adaptation of endocrown restorations: An in vitro study. *The Journal of Prosthetic Dentistry*. 2020;123(1):128-34.
63. Dauti R, Lilaj B, Heimel P, Moritz A, Schedle A, Cvikl B. Influence of two different cement space settings and three different cement types on the fit of polymer-infiltrated ceramic network material crowns manufactured using a complete digital workflow. *Clinical Oral Investigations*. 2020;24(6):1929-38.
64. Liu B, Lu C, Wu Y, Zhang X, Arola D, Zhang D. The effects of adhesive type and thickness on stress distribution in molars restored with all-ceramic crowns. 2011:35-44.
65. Maneenacarath A, Rakmanee T, Klaisiri A. The influence of resin cement thicknesses on shear bond strength of the cement-zirconia. *Journal of Stomatology*. 2022;75(1):7-12-.
66. Donmez MB, Okutan Y. Marginal gap and fracture resistance of implant-supported 3D-printed definitive composite crowns: An in vitro study. *Journal of Dentistry*. 2022;124.
67. Hiroaki K, Kuniyuki I, Nobuhiro Y, Hiroshi E, Keiichi S. Comparison of the accuracy of resin-composite crowns fabricated by three-dimensional printing and milling methods. *Dental Materials Journal*. 2022;41(6):808-15.

68. Peroz I, Mitsas T, Erdelt K, Kopsahilis N. Marginal adaptation of lithium disilicate ceramic crowns cemented with three different resin cements. *Clinical Oral Investigations*. 2019;23(1):315-20.
69. Ibraheem AF, Abdullah LS. Evaluation of post cementation marginal seating of monolithic zirconia crown restorations using different preparation designs (A comparative in vitro study). *Indian Journal of Forensic Medicine and Toxicology*. 2020;14(1):787-92-92.
70. Aditya P, Madhav VN, Bhide SV, Aditya A. Marginal discrepancy as affected by selective placement of die-spacer: an in vitro study. *J Indian Prosthodont Soc*. 2012;12(3):143-8.
71. Sorrentino R, Nagasawa Y, Infelise M, Bonadeo G, Ferrari M. In vitro analysis of the fracture resistance of CAD-CAM monolithic lithium disilicate molar crowns with different occlusal thickness. *Journal of Osseointegration*. 2018;10(2):50-6-6.
72. Duangrudee C, Krongkarn S, Kanchana K, Greg H, Kimihiro Y. Machinable glass-ceramics forming as a restorative dental material. *Dental Materials Journal*. 2011;30(3):358-67.
73. Zhang Y-R, Du W, Zhou X-D, Yu H-Y. Review of research on the mechanical properties of the human tooth. *International Journal of Oral Science*. 2014;6(2):61-9.

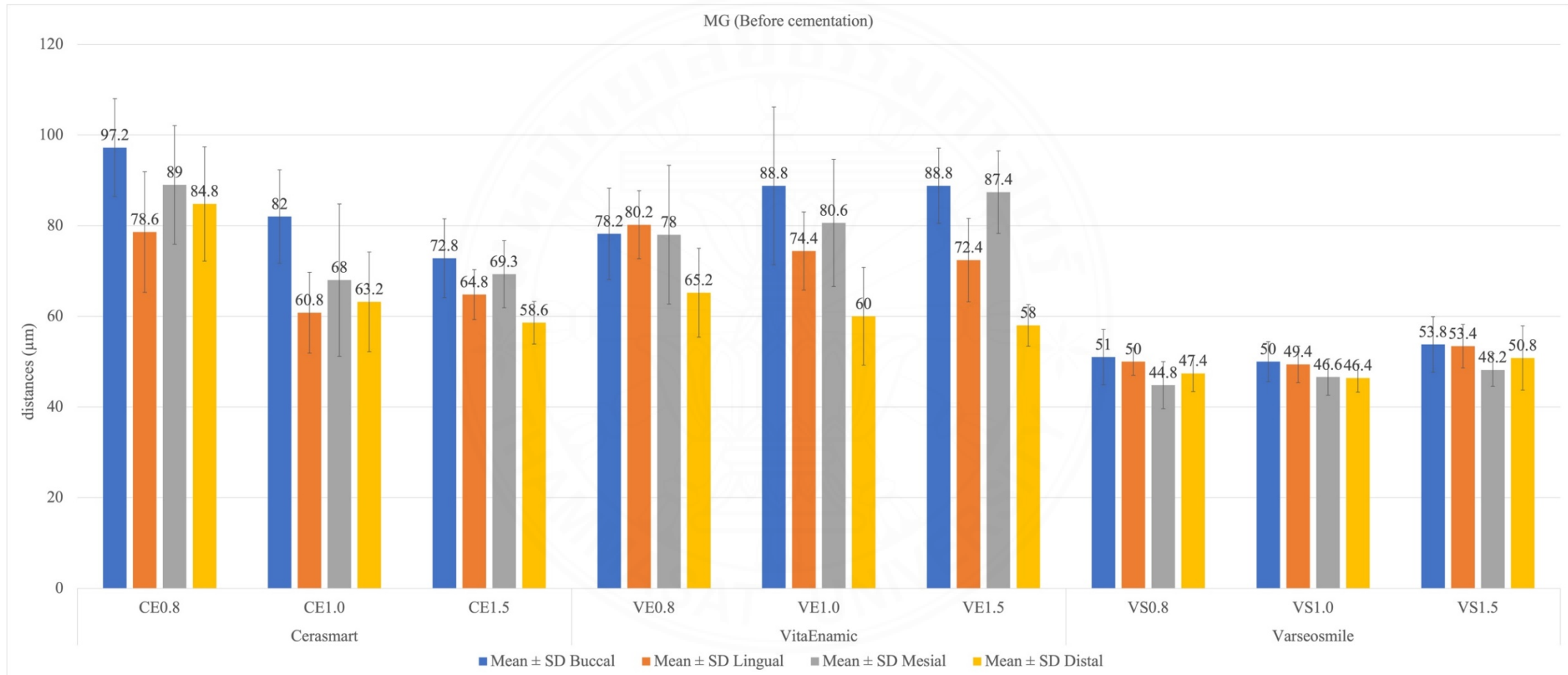
The seal of Thammasat University is a circular emblem. It features a central five-petaled lotus flower. Above the lotus is a horizontal bar with five lines, and above that is a crown-like structure. The entire emblem is surrounded by a circular border containing the university's name in Thai script at the top and 'THAMMASAT UNIVERSITY' in English at the bottom, separated by small floral motifs.

APPENDICES

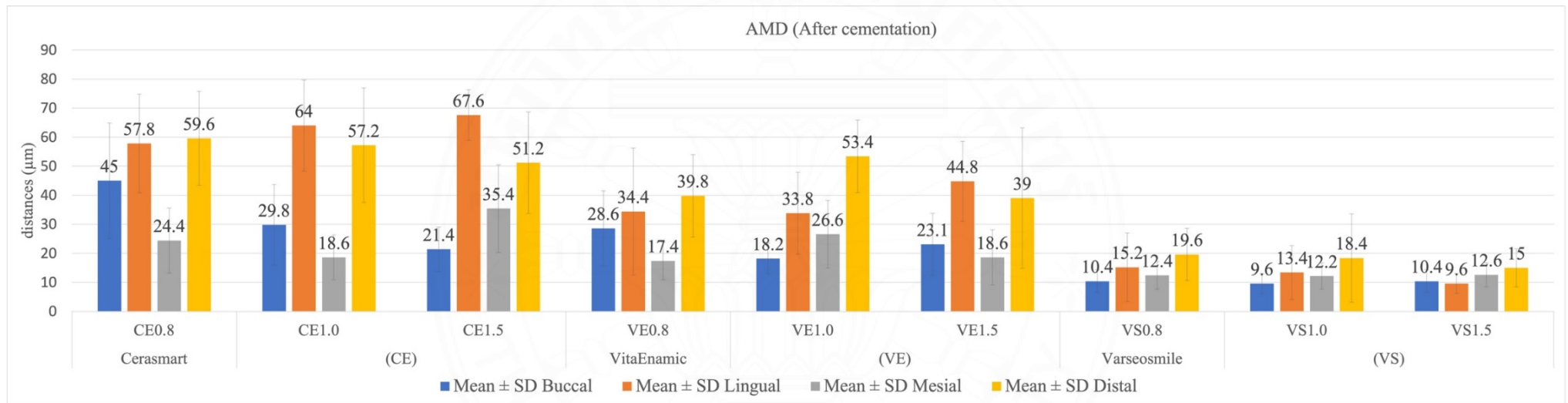
Appendix 1. The trend of different aspects absolute marginal discrepancies (AMD) of each group with different occlusal thicknesses before cementation



Appendix 2. The trend of different aspects marginal gap (MG) of each group with different occlusal thicknesses before cementation



Appendix 3. The trend of different aspects absolute marginal discrepancies (AMD) of each group with different occlusal thicknesses after cementation



Appendix 4. The trend of different aspects marginal gap (MG) of each group with different occlusal thicknesses after cementation

