Marginal discrepancy and fracture load of thermomechanically fatigued crowns fabricated with different CAD-CAM techniques

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Abstract

Purpose. To assess the effect of CAD-CAM technique (monolithic, CAD-on, or CAD-on cemented) and thermomechanical fatigue on the marginal discrepancy and fracture load of ceramic crowns.

Material and Methods. A total of 90 brass master dies were fabricated to investigate marginal adaptation and fracture load. A mandibular first molar crown's median measurements were loaded into CAD software and divided into 2 crown design groups: Monolithic (M)(IPS e.max zirCAD)(n=30) or CAD-on core (IPS e.max zirCAD) and lithium disilicate veneer (IPS e.max CAD) (n=60). The crowns and cores were milled, seated on their respective dies, and marginal discrepancy values were measured by using microcomputed tomography. After veneers were milled, the cores in veneer groups were divided into 2 groups; veneers bonded with fusion glass-ceramic (IPS e.max CAD Crystal) in CAD-on group (CO) and CAD-on cemented group (CO-C) where veneers were cemented (RelyX U200) onto cores (CO-C). The marginal discrepancy measurements were remade and the crowns were subjected to thermomechanical fatigue (TMF) by using a chewing simulator and thermocycling (5–55°C, 1,200,000 cycles). Marginal discrepancy measurements were repeated and the crowns were subjected to fracture load test by using a universal test device. Data were analyzed statistically by analysis of variance (ANOVA) and Tukey's honestly significant difference test (α=0.05).

Results. All crown groups had similar marginal discrepancy before veneering. Veneering and cementation on die increased the marginal discrepancy of crowns in cemented CAD-on group. Thermomechanical fatigue increased the marginal discrepancy of both CAD-on groups. Monolithic crown group had the lowest marginal discrepancy after thermomechanical fatigue ($P<0.001$), and the highest fracture load ($P<0.001$)

Conclusions. Fabrication technique affected the marginal fit and fracture load of CAD-CAM crowns after thermomechanical fatigue. All crowns survived the thermomechanical fatigue test without dislodgement or fracture. Monolithic crowns had the best fit and highest fracture load after fatigue testing. The CAD-on systems had similar marginal discrepancies, and static loading reproduced veneer chipping.

Keywords. Marginal fit, CAD-on, fracture load, thermomechanical fatigue, Fabrication technique

Computer-aided design and computer-aided manufacturing (CAD-CAM) technology is now commonly used for fixed prosthodontic treatment as this technology facilitates the fabrication process.[1-4] In particular, zirconia allows non-adhesive cementation and is suitable for stress-bearing areas.[5] Zirconia has been claimed to have 98% overall survival up to 10 years, making it a viable option for posterior use.[6]

The primary goal of either monolithic or layered restorations is to reintegrate form, function, and esthetics with minimal damage and maximum longevity to the remaining natural dentition. The success of zirconia restorations is related to the accuracy of the fit between the restorations and the abutment, esthetics, and fracture strength. Fabrication method affects the accuracy of the fit between the restoration and the abutment.[5-8] Small marginal discrepancy increases the longevity of the restorations and enables the maintenance of the health of the surrounding tissues.[9] Cement dissolution, secondary caries, or periodontal problems are avoided.[9]

Veneer fractures have been reported with zirconia restorations.[9-13] Fatigue resistance of dental materials is an essential factor for long-term clinical survival. Failure of the ceramic restoration may be related to flaws in the production process,[13,14] insufficient ceramic support, cementation,[15-17] coefficient of thermal expansion (CTE) mismatch, and residual stress.[12-15,19-22] A crucial goal of CAD-CAM technology is to minimize flaws.[18,19]

Digital veneering can be performed with CAD-CAM systems to produce a veneering glass-ceramic layer, which is then cemented to a zirconia core with low-viscosity ceramic or resin cement. The CAD-on (with fusion or cementing technology), is a veneering technique that has been shown to have high mechanical performance[19,23] at zirconia core or the ceramic veneer level.[24-28] CAD-on technique is advantageous compared with vonventional veneering because it offers fewer firing cycles,[29] high speed, and stability.[30] However, there have been reports of veneering porcelain fracture and chipping. Monolithic restorations have been made available to prevent the veneering porcelain from chipping.[30-32]

Clinically, veneer chipping is typically observed after aging, and veneer fractures in the short term are rare.[10] Previous studies have reported that aging by thermocycling decreased the adhesion of the resin cement to zirconia ceramic.[30,31] Furthermore, thermocycling may lead to recurrent shrinkage and expansion stresses generated by different thermal coefficients of the restorative materials.[30,32]

This study aimed to compare the marginal discrepancy and fracture load of CAD-CAM zirconia-based crowns fabricated by using different CAD-CAM designs and techniques (monolithic versus 2 CAD-on techniques) after thermomechanical fatigue. The null hypothesis was that the CAD-CAM technique would not affect the marginal discrepancy and fracture load values of zirconia-based crowns after thermomechanical fatigue.

Materials and methods

Ninety metal brass master dies of a prepared maxillary first molar were fabricated to assess marginal discrepancy, fatigue performance and fracture load of crowns. Sample size was calculated using G*Power V3.1.9.6. With 95% confidence (1-α), 95% test power (1-β), f=0.595 effect size, a total of 48 specimens, 16 in each group, were considered appropriate. Considering possible losses during fabrication and experiments, 30 specimens were included in each group.[33] All dies had 10-mm cervical diameter, 6-mm height, 6-15 degrees of axial wall taper,[34] and 1.2 mm-wide circumferential chamfer margin.[6] The dies were fabricated using a computer numerally controlled machine (Deckel Maho DMC 1035, DMG Mori) to design restorations in two forms: a complete-coverage crown or a crown core with CAD-on ceramic veneer. A scan spray was used to coat each die (Cerec Optispray, Sirona). All crowns and cores were digitally built with 30-micron cement space, 1 mm short of finish line.[35,36] The specimens were divided into three groups: 30 crowns for Group M (monolithic crowns) (IPS e.max zirCAD; Ivoclar Vivadent, Schaan, Liechtenstein) and 60 zirconia cores to be CAD-on veneered with lithium disilicate ceramic (IPS e.max CAD; Ivoclar Vivadent, Schaan, Liechtenstein) either fusing by using a glass-ceramic (IPS e.max CAD Crystall; Ivoclar Vivadent, Schaan, Liechtenstein) (CO) (n=30) or cementing (RelyX U200; 3M Espe) (CO-C) (n=30).

For Group M, the occlusal thickness was set to 1.5 mm (Fig 1a). The axial walls were 1.2 mm thick as well as the chamfer. The crowns were milled with a four-axis milling device (CEREC MC XL).

For CO and CO-C groups, 60 zirconia cores (IPS e.max ZirCAD; Ivoclar Vivadent, Schaan, Liechtenstein) with 0.7 mm thickness were selected to design the core (inLab 4.4; Sirona Dental Systems) (Fig 1b). The information was sent to the milling unit (CEREC MC XL; Sirona Dental Systems). Zirconia cores were sintered according to the manufacturer's recommendations (in fire HTC speed; Sirona Dental Systems). The zirconia cores were seated to metal dies and checked visually and by using a microscope (BM-1 stereo-microscope at 10×; Meiji Techno, Saitama, Japan) to ensure seating.

All cores were scanned with microcomputed tomography (micro-CT)[37] before veneering (CT-MINI; Procron X-Ray GmbH) by using the following scanning parameters: accelerating voltage=130 kV; current=300 mA; exposure time=5000 ms/frame; 1 mm Al filter; and image pixel size=21.43 mm. The marginal vertical distance between the outer cervical edge of each crown and finish line of the preparation completion line was measured. The margins were investigated at 4 locations on each crown; buccal, lingual, mesial, and distal. Then, the average of these 4 measurements were taken at this and the following measurement stages.

For the CO and CO-C groups, 60 lithium disilicate veneers (IPS e.max CAD; Ivoclar Vivadent, Schaan, Liechtenstein) were designed using the same software, with an axial wall thickness of 1 mm, and an occlusal thickness of 0.8 mm (Fig 1b) (inLab 4.4; Sirona Dental Systems). The information was then sent to the milling unit (CEREC MC XL; Sirona Dental Systems).

Thirty cores and veneers in Group CO were coated with 0.1 mm fusion glass-ceramic slurry (IPS e.max CAD Crystall; Ivoclar Vivadent). After the veneers were seated on the cores, the crowns were fired at 840 °C in a ceramic furnace (Programat EP 5000; Ivoclar Vivadent).

In Group CO-C, internal surfaces of the veneers (IPS e.max CAD; Ivoclar Vivadent) were etched for 20 s with 9.5% hydrofluoric acid (Porcelain Etchant Gel; Bisco), washed for 60 s, and air-dried. After the etching technique, the treated surfaces were coated with a silane coupling agent (Pre-Hydrolyzed Silane Primer; Bisco) and dried. The veneers and cores were cemented by using self-adhesive resin cement (RelyX U200; 3M ESPE,USA) and polymerized with a light-curing unit (ELIPAR S10; 3M ESPE) with an output of 1200 mW/cm^2 for 3 s.

All specimens were cemented to brass dies with a self-adhesive resin cement (RelyX U200; 3M ESPE, USA) as suggested by the manufacturer and placed under a manual dynamometer with a constant force of 50 *N* for 10 minutes.

Before thermocycling, micro computed tomography (micro-CT) scans were performed with the settings used in the first scans. All specimens were embedded in an acrylic resin substrate (Palapress Vario; Heraeus Kulzer) for fatigue testing; the modulus of elasticity of acrylic resin (12 GPa) is similar to that of human bone (18 GPa). The chewing simulator (Willytec SD; Mechatronic GmbH CS-4.4) exposed all specimens to thermomechanical fatigue (TMF) of 1,200,000 loading cycles (to represent 5 years of clinical service) with an applied force of 198 N.[38] A steel antagonist ball 6 mm in diameter was vertically placed to the central occlusal fossa of the crowns at a frequency of 1.2 Hz.[34] The simulator includes a thermocycling system by using magnetic valves in conjunction with a heating and cooling system. After TMF, a third micro-CT scan was obtained following the settings used for the first and second scans. The specimens in all study groups were allocated into three categories according to the marginal discrepancy measurements recorded at each fabrication step as follows: Z (after the fabrication zirconia framework), V/C (after veneer application and/or cementation), and T (after thermoechanical fatigue).

A universal testing machine was used to test the specimens (Model 5943; Instron). A stainless steel ball, 6 mm in diameter, was used to apply the loads to the specimens at a crosshead speed of 1 mm/min.

After the fracture test, field emission scanning electron microscopy (SEM) was used to investigate the failure mode of specimens (JSM-840A 6335 F, Jeol, LTD). Adhesive, cohesive, or mixed failure modes were identified.

The data were statistically analyzed using software (SPSS V23; IBM Corp.). The mean marginal discrepancy values and load at fracture values of the specimens after thermomechanical fatigue were analyzed with the one-way variance (ANOVA) test. Multiple comparisons were performed by using Tamhane's T2 test ($\alpha = .05$); post hoc tests were used to compare the marginal discrepancy and to analyze data of crowns of the fatigued group (survived vs. failed).

Results

The mean marginal discrepancy values and standard deviations (SD) at 3 stages (Z, V/C, and T) in 3 study groups are presented in Table 1, Figure 2 and Figures 3(a-c). Statistical analysis revealed no significant difference in the marginal discrepancy values among the groups at Z stage ($P=0.831$). The vertical marginal discrepancy of the CO and CO-C groups increased at either V or T stages ($P<0.001$). After thermomechanical fatigue, mean marginal discrepancy values of both CAD-on groups (CO (65.73 µm) and CO-C (69.73 µm)) were higher than in monolithic group (37.52 µm) ($P<0.001$).

One-way ANOVA results showed that the fracture load of CAD-CAM crown was affected by the fabrication technique, and significant differences were found in fracture load between the groups ($P< 0.05$). The greater fracture load was observed in Group M (1220 N), and there was no statistically significant difference between Group CO (1010 N) and CO-C (1005 N) ($p>0.05$). No defects were observed after the TMF test, but wear occurred at the contact points of the CO-C specimens. Mean values (N) and the number of fragments for the test groups are presented in Table 2.

Failure modes are shown in Table 2. Only adhesive and mixed failures were observed in all groups. However, adhesive failure was the most frequent failure type in all groups.

Discussion

This study tested the null hypothesis that different digital CAD-CAM techniques would not affect the marginal discrepancy and failure load of zirconia-based ceramic restorations after thermomechanical fatigue. The results revealed that the null hypothesis would be rejected, as the technique made a difference in both the marginal discrepancy and failure loads after thermomechanical aging.

The technique used, the number of measurements, and the stage in which the measurements are performed (before or after cementation, before or after firing) may alter the marginal discrepancy of restorations.[13] Various techniques have been used to measure the marginal discrepancy.[9] Micro-computed tomography was used in the present study to evaluate the marginal discrepancy because this device enables nondestructive imaging in 3 dimensions with high resolution to investigate the fit.[37]

Mean marginal discrepancy values at first stage, after fabrication were similar for all groups. The magnitude of marginal discrepancy significantly increased after veneer application and cementation (CAD-on cemented), and thermomechanical aging (CAD-on). The increase in marginal discrepancy after veneering and cementation can be due to combined effect of veneering and cementation procedures. Nevertheless, utmost effort was put to standardize the die and crown/core fabrication, cement space, and cementation procedures to focus on the effect of fabrication technique. Acceptable marginal discrepancy values have been long debated, and a maximum value of 120 μm has been reported to be clinically acceptable for traditionally fabricated restorations.[4] However, for CAD-CAM restorations, typical acceptable margin discrepancy range has been reported to be 50 to 100 μm.[32] Considering these values, the changes in mean discrepancy values from crown/core fabrication and veneering/cementation can be considered clinically small in the present study. Mean discrepancy value for all restorations at all stages was either below or within the reported range[32] and therefore, the fit of all crowns may be considered clinically acceptable.

The fit between the abutment tooth and the restoration may change depending on the distortion due to the firing phases and increase the marginal discrepancy in the cervical region, as reported previously.[8] This distortion can be due to shrinkage of veneering porcelain during firing process, which may lead to changes in the marginal gap due to ceramic elevation from the edge of the cast.[3] In the present study, the marginal discrepancy value in CO group, which was subjected to firing increased, however, this increase was not statistically significant. Nevertheless, the fact that statistical differences were not found may be due to the sample size, as slightly higher values in CO-C group was significantly different.

It has been reported that marginal discrepancy between the restoration and the abutment tooth may increase with thermal aging.[31] Similar results were presented in the current study; the marginal discrepancy values increased significantly in the CO group after TMF. This result was obtained maybe because the veneering technique is susceptible to many factors such as thermal incompatibility between the core and the porcelain veneer.[3,14] Variations in coefficient of thermal expansion (CTE) in a layered restoration leads to stress when the restoration cools down to room temperature.[8] Although thermal mismatch should be minimized, even zero thermal mismatch does not guarantee compatibility between the ceramic core and the veneering porcelain, thus, the rapid cooling process, porcelain viscoelastic behavior, and repeated sintering may result in distortion.[15] Additionally, the skill of the dental laboratory technician, differences in the composition and elastic modulus of the resin cement are of factors that may affect the final fit.[2] Even though not statistically significant, the discrepancy values also increased in CO-C group after TMF.

Fatigue did not fracture the crowns veneered with milled lithium disilicate veneers, resulting in 100% survival rate. For static loading, the highest fracture load values were measured in Group M (1220 N). Although monolithic fabrication resulted in a stronger crown, the fracture load of all groups of this investigation demonstrated a load-bearing capacity that can be considered higher than reported human maximum mastication force (850 N).[18,27] However, both CAD-on veneered crown groups displayed chipping after static loading. Both CAD-on technique veneers may still show a weak interfacial adhesion between structures,[23] and to minimize the veneer failures, a monolithic crown may be considered.[14]

Some studies have assessed the impact of different CAD-CAM techniques on bond strength.[18,26,27] The outcomes of these studies revealed that the CAD-on method, bonded using a fusion glass-ceramic between core and the veneering ceramic, showed higher strength values.[19,26,29] Due to its thixotropic characteristics, a low fusing ceramic (IPS e.max CAD Crystall) was employed to form a homogeneous bond between the core and veneers.[23,39] It was also shown that monolithic CAD-CAM crowns had higher strength because they are fabricated by using specific procedures that human error is not significantly involved. [3]

According to previous studies, veneers cemented on zirconia by using CAD-CAM technology had lower fracture strength than conventional veneering applied on zirconia.[11,18,27] Another study reported a lower adhesion rate obtained with the CAD-CAM veneers cemented to zirconia samples compared with porcelain fused CAD-CAM veneers.[25] The differences between the elastic modulus and interfacial physical properties of the materials may affect the layered structure's crack propagation and mechanical behavior.[27] Lower elastic modulus of the resin cement might have decreased hard zirconia's supportive effect on the more fragile veneering ceramic.[2] Resin cement may affect the bond strength of materials.[3] Because there is currently no universal resin cement available for all restorative dentistry procedures, clinicians should be knowledgeable about the resin cement's qualities, such as water absorption, polymerization shrinkage, adhesion and application processes. Earlier studies[2,16,17] investigated these properties and reported that the cement may alter the fracture resistance of veneering ceramic applied on zirconia core. Different fracture load results may be achieved when different cements are used to cement CAD-on veneer. The metal brass master dies used do not mimic the clinical situation because of their young modulus and adhesion properties, however, the fact that crown thicknesses tested were high enables the issues with die material potentially become less dramatic. Different results may be onbtained with dies in varying materials.

Conclusions

Within the limitations of this in vitro study, a few conclusions can be drawn. Monolithic technique resulted in improved marginal fit than the CAD-on and CAD-on cemented techniques after thermomechanical fatigue. Marginal discrepancy values increased after veneer application and cementation (CAD-on cemented), and thermomechanical fatigue (CAD-on and CAD-on cemented), but mean values in all groups were clinically small (<70 microns). All crowns survived thermomechanical fatigue test. Monolithic crowns fractured at higher loads than both CAD-on techniques.

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Figure Caption

Table 1. Mean vertical marginal discrepancy values and standard deviations (SD)(μm).

Groups	**n**	**Mean± SD (Z)**	**Mean± SD (V/C)**	**Mean± SD (T)**
M	30	34.50 ±3.90[a]	34.50 ±1.89[a]	37.52± 3.49[a]
CO	30	36.45 ± 2.80[a]	47.73 ±3.90[a]	65.73 ±2.80[b]
CO-C	30	36.86 ± 3.95[a]	49.73 ±3.90[b]	69.73 ±4.20[b]
P		0.831	<0.001	<0.001

Same superscript letters are not significantly different per t-test (P >0.05)

Table 2. Mean fracture load values (N) and standard deviations (SD)

Groups	**n**	**Mean± SD**	**Failure mode (Adhesive/Mixed)**	***P***
M	30	1220 ± 100[a]	8/2	<0.001
CO	30	1010 ± 198[b]	6/4	0.103
CO-C	30	1005 ± 183[b]	7/3	<0.123

The same superscript letters are not significantly different according to t-test (P >0.05

FIGURE LEGENDS

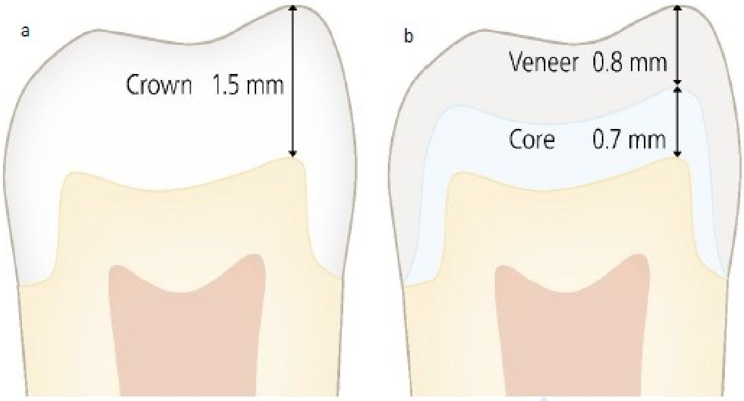

Figure 1. Schematic drawing of different crown designs: (a). monolithic, (b). veneered core

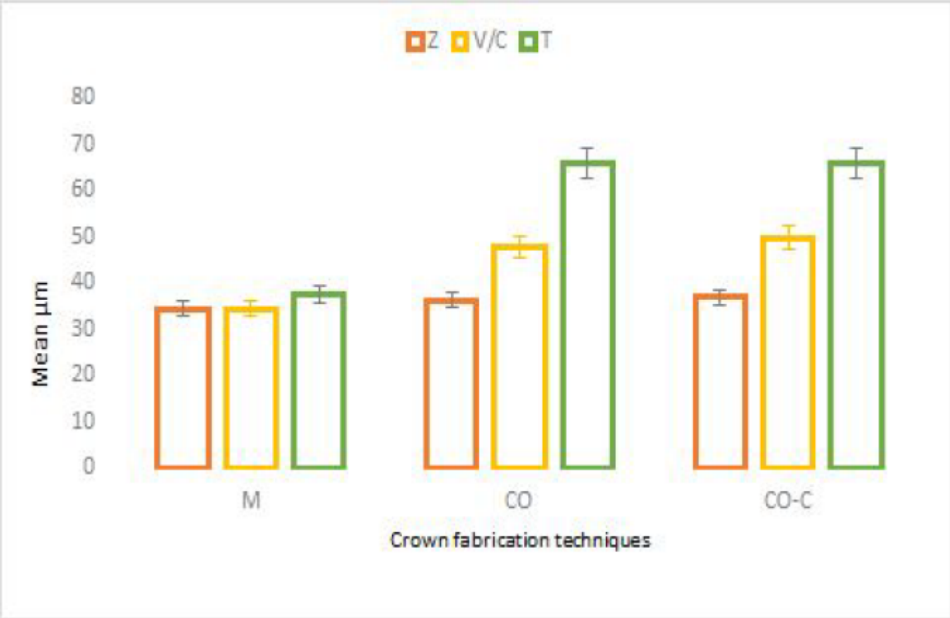

Figure 2: Marginal discrepancy values (µm) for monolithic(M), CAD-on technique (CO); CAD-on cemented technique (CO-C) at zirconia stage (Z); after porcelain veneering and cementation (V/C) and after thermomechanical fatigue (T)

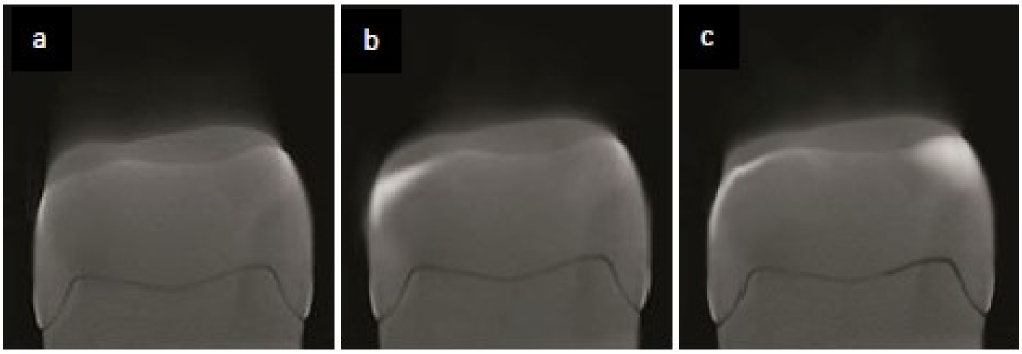

Figure 3. Micro-CT scan images for specimens for marginal discrepancy measurements: (a) Monolithic group (M), (b) CAD-on group (CO), (c) CAD-on cemented group (CO-C)