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# Marginal-internal adaptation and fracture resistance of CAD/CAM crown restorations

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This study evaluated the marginal adaptation and fracture resistance of CAD/CAM-fabricated zirconia crowns luted using different luting agents. Twenty crown restorations were produced using IPS ZirCAD zirconium oxide blocks (IZC), and another 20 using Lava zirconium oxide blocks (L). Ten teeth were used as control. Luting agents used were an etch-and-rinse adhesive (Variolink II) and a self-etch adhesive (Multilink Automix). Internal and marginal adaptation was evaluated using silicone replica technique. Fracture resistance was evaluated using a compression test. Marginal discrepancy was 89.26 µm for L crowns and 88.84 µm for IZC crowns, and difference was statistically insignificant. However, L crowns showed significantly larger axial and occlusal gaps than IZC crowns ($p<0.05$). Fracture resistance of IZC-Multilink was higher than the other groups, although the difference was not significant. Results showed that CAD/CAM-fabricated crowns showed acceptable *in vitro* marginal discrepancies and fracture strengths.

*Keywords*: CAD/CAM, Crown, Internal adaptation, Marginal adaptation, Fracture resistance

## INTRODUCTION

Metal-free, all-ceramic restorations have inundated the aesthetic dentistry field because of their high aesthetic appeal, excellent mechanical properties, and biocompatibility[1-9]. Today, many framework structures for prosthetic restorations are fabricated using the computer aided design/computer-aided manufacturing (CAD/CAM) technology, where the construction of zirconia-based restorations uses a high-strength ceramic material for the framework to provide sufficient mechanical strength and resistance to chemical attack.

Another key factor that determines the clinical success of dental restorations is marginal adaptation[7-9]. Poor marginal adaptation of restorations exposes the luting agent to the oral environment, rendering the restorations susceptible to microleakage and plaque retention. The larger the marginal discrepancy, the faster will be the rate of cement dissolution[10]. Although the ideal marginal gap range of cemented restorations should be 25–40 µm, marginal gaps within this range are seldom achieved clinically. On the contrary, McLean and von Fraunhofer examined more than 1,000 crowns after five years of clinical service and stated that marginal discrepancies less than 120 µm were clinically acceptable[11].

It has been shown that milling of dense zirconia could yield restorations with high dimensional precision and high marginal fit[11-13]. If zirconia material is used in a semi-sintered porous state, it can be easily machined in a computer-aided manufacturing (CAM) unit. After machining, the framework has to be densely sintered to shrink to its original size[14-16]. Volume changes occur during sintering, resulting in a linear sintering shrinkage of 15–30% and a concomitant increase in density[17,18]. Other factors that cause marginal inaccuracies may arise from the CAD/CAM scanning, designing, and/or milling processes. Varied results on the marginal accuracy of different zirconia systems have been reported. For example, a mean marginal gap of 65 µm was reported for fixed partial dentures (FPDs) milled from Lava zirconia (3M ESPE, Seefeld, Germany) in a semi-sintered state[17].

Fracture toughness of all-ceramic crowns is also an important property that has a direct correlation to their clinical success, and hence a keenly investigated subject in numerous *in vitro* studies[19-21]. Regarding the effect of luting cements on the fracture resistance of all-ceramic crowns, it remains a controversial and widely debated issue. Based on several laboratory and clinical studies which investigated the fracture resistance and retentive strength of all-ceramic crowns, resin cements emerged as an optimal luting agent[22,23]. Compared to conventional luting agents, resin cements exhibited enhanced mechanical, physical, and adhesive properties.

To simplify the luting procedure, a new group of self-etch and self-adhesive resin cements was introduced. These products contain highly acidic and hydrophilic monomers which demineralize and infiltrate enamel and dentin, resulting in strong bonding. Therefore, they do not require any conditioning or priming of tooth structure prior to bonding. For the cementation of zirconia-based crowns and fixed partial dentures, composite resin, glass ionomer, or resin-modified glass ionomer cements were recommended[1].

The purpose of this study was to investigate the marginal and internal adaptation of CAD/CAM crowns fabricated using two commercial brands of partially stabilized zirconia systems, IPS ZirCAD (Ivoclar Vivadent AG, Schaan, Liechtenstein) and Lava Frame

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(3M ESPE, Seefeld, Germany). Crown restorations were luted using two different adhesive systems, etch-and-rinse (Variolink II, Ivoclar Vivadent AG, Schaan, Liechtenstein) *versus* self-etch (Multilink Automix, Ivoclar Vivadent AG). Fracture resistance was evaluated by subjecting cemented CAD/CAM crowns to compressive loading. The two hypotheses of this study were: (1) Both zirconia systems would produce marginal gaps below 120 µm; and (2) There would be no statistically significant differences in the marginal and internal adaptation and fracture resistance of both zirconia systems.

## MATERIALS AND METHODS

*Selection of teeth*

Fifty intact, non-carious, unrestored human maxillary second premolars, extracted for periodontal reasons, were selected for this study. Immediately after extraction, teeth were scaled and immersed in a germ-free 0.1% thymol solution at room temperature for 1 day. They were then stored in distilled water not longer than 3 months before use. Prior to testing, the size (<5% deviation) and quality (free of fillings, caries, and fractures) of teeth were examined under a light microscope at ×20 magnification.

*Preparation of teeth for crown restoration*

Teeth were mounted individually in an acrylic resin (Meliodent, Heraeus Kulzer, Berkshire, UK) in a PVC ring. A dental surveyor (Kavo EWL, Typ 990, Kavo Elektrotechnisches Werk GmbH, Leutkirch im Allgau, Germany) was used to ensure that the long axis of tooth was perpendicular to the top surface of acrylic resin block. Each tooth was suspended in the middle of the ring with a 0.8-mm orthodontic wire (Leowire round spring hard wire 0.8 mm, Leowire s.p.a. Firenze, Italy) which engaged the tooth at cementoenamel junction (CEJ) and which rested on the edges of the PVC ring.

Prior to preparing the teeth for crown restoration, two silicone impressions of each tooth were taken. One impression was used as an orientation aid for the wax-up of the crown, while the other was cut in a vestibulo-oral direction to assist in the removal of tooth structure.

All teeth were prepared according to a standardized protocol as follows: chamfer finish line was 1 mm above the CEJ; all sharp or internal line angles were rounded; preparation margins were not bevelled. Minimum layer thickness of each ceramic material as specified by the respective manufacturers was observed for all crown restorations. Bulk reduction was carried out using large-grit diamonds, while finishing was completed using finer diamonds. All teeth were prepared by one dental technician, and standardized crown preparation was accomplished by fixing the dental handpiece in a parallelometer.

*Fabrication of CAD/CAM zirconia crowns*

Putty-wash impressions (Virtual, Ivoclar Vivadent AG, Schaan, Liechtenstein) of crown preparations were made and used for laboratory manufacturing of crown restorations. Twenty crowns were produced using CAD/CAM technology with IPS ZirCAD zirconium oxide blocks (IZC; Ivoclar Vivadent, Schaan, Liechtenstein), and another 20 crowns with Lava Frame zirconium oxide blocks (L; 3M ESPE, Seefeld, Germany). Both IZC and L crowns had a zirconia shoulder with rounded internal line angles (Fig. 1). CAD/CAM zirconia cores of 0.5 mm thickness were milled in the pre-sintered stage and then veneered with a hand-layered porcelain (IPS e.max, Ivoclar Vivadent, Schaan, Liechtenstein) at a commercial dental laboratory (Optimal Dental Laboratory, Istanbul, Turkey).

Both CAD/CAM scanner and milling machine were calibrated at the beginning of the study, and then recalibrated as prompted by the computer software. For milling, a new set of CAD/CAM milling burs was used for each group of pre-sintered IZC and L blocks.

*Cementation of CAD/CAM zirconia crowns*

Luting space was set at 25 µm. Fit of crowns was evaluated by the same dental technician, and internal adjustments were performed using diamond finishing burs. All frameworks were returned to their respective dies and manipulated to ensure complete seating. In the event of incomplete seating, additional framework adjustment was performed using a standard protocol according to published literature and clinical practice.

To identify areas that needed correction, a lipstick was applied to the die and the framework was placed on the latter without force. Red spots inside the framework were removed using a red ring diamond ball instrument (Komet 8801.016, Brasseler, GA, USA) with a water-cooling spray. This procedure was repeated until the

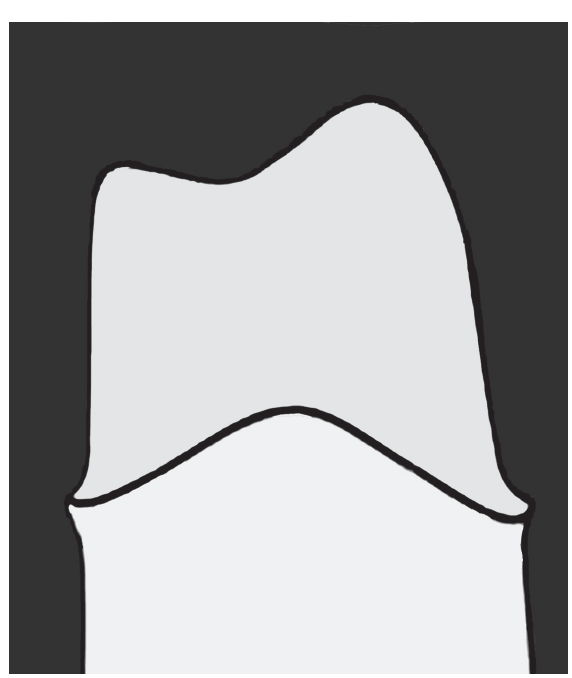

Fig. 1 Schematic presentation of framework design.

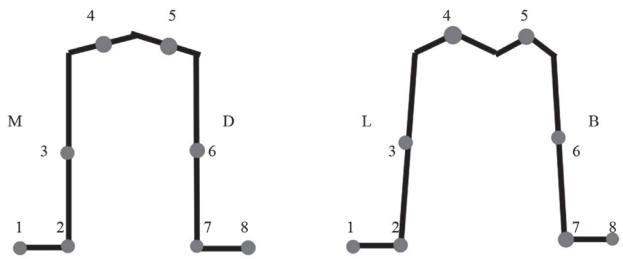


Fig. 2 Mesio-distal and bucco-lingual sections showing the locations of the measuring points.

red indicator spots disappeared, and that a uniform and even contact of the framework on the die was achieved. After each refinement, a steam cleaner was used to remove the lipstick dye from the die.

*Internal and marginal adaptation evaluation*

Internal and marginal adaptation of the crown to the prepared tooth was evaluated using silicone replica technique. Replicas of tooth specimens were sectioned buccolingually and mesiodistally, and fit on silicone replicas was examined using a light microscope (Leica Microscopes Ltd., Cambridge, UK) at ×200 magnification. Eight measurement points were assessed for each of the five sections (Fig. 2). In each specimen, 40 measurements were evaluated, amounting to a total of 1,600 measurements for both zirconia systems (40 measurements per specimen ×20 crowns per zirconia system×2 zirconia systems). By calculating the mean values of measurement points, the total mean values of occlusal, axial, internal-marginal, and marginal adaptations were obtained. Statistical analysis was performed using SPSS for Windows, version 11.0. (SPSS, Chicago, IL, USA). Results were compared using independent samples *t*-test at a significance level of 0.05.

*Fracture resistance evaluation*

Before cementation, all the prepared tooth surfaces were cleaned with pumice and rinsed with water. Ten crowns of each zirconia system were cemented using an etch-and-rinse adhesive and a high-viscosity composite resin cement (Syntac/Variolink II, Ivoclar Vivadent, Schaan, Liechtenstein); the remaining 10 crowns were cemented with a self-etch adhesive and a dual-cure universal resin cement (Multilink Automix, Ivoclar Vivadent, Schaan, Liechtenstein).

Cement was applied to the internal surface of each crown. Simulating the clinical procedure, the crown was seated on the prepared tooth with firm finger pressure. Excess cement was removed using a hand instrument. Each cemented crown was light-cured for 40 s from the occlusal, buccal, and lingual sides. After crown cementation, all specimens were stored in distilled water at room temperature for 2 days until the compression test.

To evaluate fracture resistance, each specimen was mounted in a custom-made device to ensure that loading force was applied on the occlusal surface and parallel to the long axis. Specimens were then subjected to compressive loading using a 3.5-mm-diameter steel ball in a universal testing machine (Testometric Micro 500, Testometric Co. Ltd., Lancashire, UK) at a crosshead speed of 0.5 mm/min until failure occurred. For each specimen, maximum load to fracture was measured and indicated on a digital display. Results were analyzed by analysis of variance and Tukey's test using a software package (SPSS 13.0 for Windows, SPSS Inc., IL, USA).

Fractured crowns were recovered from the device, and fracture surfaces were visually inspected for failure pattern type.

## RESULTS

*Marginal and internal adaptation*

Table 1 shows the means and standard deviations of marginal and internal gaps in each group. Marginal discrepancy was 89.26 μm for L crowns and 88.84 μm for IZC crowns. Both marginal and marginal-internal gaps between L and IZC crowns showed statistically insignificant differences. Significantly larger axial and occlusal gaps were found for L than for IZC ($p$=0.001). Axial gaps were 106.21 μm and 77.97 μm for L and IZC respectively. Occlusal gaps were 240.3 μm and 142.54 μm for L and IZC respectively.

*Fracture resistance*

Table 2 shows the means and standard deviations of failure loads obtained from the fracture test. Mean failure load of teeth restored with IZC cemented with Multilink (2,202.19±276.97 N) was higher than that of IZC cemented with Variolink (2,074.74±347.30 N). However, failure load of L cemented with Multilink (2,166.03±357.62 N) was not significantly different ($p$>0.05) from that of L cemented with Variolink (2,112.87±529.30 N). Control unrestored teeth had a mean failure of load of 1,395.68±485.27 N, which was significantly lower than the restored teeth ($p$<0.05).

Comparison of the resin cements showed that crowns (both IZC and L; $n$=20) cemented with Multilink (2,184.11±311.87 N) had a higher mean failure load than cementation with Variolink (2,093.80±436.15 N). However, the difference was not statistically significant.

*Failure patterns*

Table 3 shows the three categories of failure patterns as follows: Porcelain (P), Porcelain+Core (P+C), and Porcelain+Core+Teeth (P+C+T). Twenty-two specimens exhibited porcelain fracture, 10 exhibited porcelain+core fracture, and eight exhibited porcelain+core+teeth fracture.

For 'P' failure pattern, the fractured surfaces of both L and IZC crowns were clean and smooth. No irregularities were detected upon visual inspection without magnification. The porcelain veneer delaminated

Table 1 Mean and standard deviation values of marginal, internal-marginal, axial, and occlusal discrepancies for L and IZC (μm)

| | Marginal Points 1–8 | Internal-marginal | Axial | Occlusal |
|---|---|---|---|---|
| L | 89.26 (36.06) | 86.82 (31.47) | 106.21 (26.86) | 240.3 (79.8) |
| IZC | 88.84 (28.91) | 87.31 (22.11) | 77.97 (18.16) | 142.54 (39.95) |
| Total | 89.05 (32.26) | 87.06 (26.85) | 92.09 (26.77) | 191.42 (79.57) |
| Significance | 0.968 | 0.955 | 0.001 | 0.001 |

Table 2 Mean and standard deviation values of load at fracture

| Group | Failure load (N) |
|---|---|
| L-Multilink | 2,166.03 (357.62) |
| L-Variolink | 2,112.87 (529.31) |
| IZC-Multilink | 2,202.19 (276.97) |
| IZC-Variolink | 2,074.74 (347.3) |
| Control | 1,395.68 (485.28) |
| Total | 1,990.30 (496.58) |

Table 3 Failure pattern distribution of specimens, where P: Porcelain; P+C: Porcelain+Core; P+C+T: Porcelain+Core+Teeth

| Group | P | P+C | P+C+T |
|---|---|---|---|
| L-Multilink | 4 | 4 | 2 |
| L-Variolink | 7 | 1 | 2 |
| IZC-Multilink | 4 | 4 | 2 |
| IZC-Variolink | 7 | 1 | 2 |

about 1–2 mm from the fracture margin of the core for both L and IZC crowns. The surface where the porcelain veneer detached from the core appeared smooth with no residual porcelain detected. Comparison of the resin cements showed that cementation with Multilink (both L and IZC) showed less 'P' fractures than cementation with Variolink.

## DISCUSSION

Dental CAD/CAM systems have been available for nearly 20 years. Emergence of this technology engendered a rapid development of diverse equipment and materials available for the fabrication —and proliferation— of all-ceramic prostheses[1,2,4]. Notably, the availability of CAD/CAM processing permitted the use of polycrystalline zirconia coping and framework materials for all-ceramic fixed partial dentures in the posterior region. In the present study, IPS ZirCAD (Ivoclar Vivadent) and Lava Frame (3M ESPE) were used for crown fabrication and they were milled in partially-stabilized pre-sintered state.

*Marginal and internal adaptation*

According to published literature, marginal gaps of CAD/CAM all-ceramic reportedly ranged between 53 and 108 μm, depending on cement film thickness[24,25]. As for conventional all-ceramic crowns, marginal gaps reportedly ranged between 123 and 154 μm[25]. In the present study, marginal gaps were 89.26 μm for L crowns and 88.84 μm for IZC crowns. Both CAD/CAM zirconia systems demonstrated clinically acceptable marginal discrepancies *in vitro*.

On axial and occlusal gaps, L exhibited significantly larger values ($p<0.05$) than IZC; nonetheless, they were well within the clinically acceptable range. This large contrast in internal fit between L and IZC crowns could be due to differences in material properties, sintering shrinkage, and dimensional stability between the two zirconia systems. One *in vitro* study showed that a lack of precision in internal fit could heighten the risk of veneering fractures[26].

Tuntiprawon and Wilson[27] reported that all-ceramic crowns exhibited greater fracture strength when cement thickness at the axial wall was 73.0 μm. When cement thickness was increased to 122.0 μm, lower fracture strength was obtained without any significant improvement in seating. In this study, a thicker cement layer at the axial wall in L group might have adverse impact on the clinical performance and fracture resistance of the restorations.

At the occlusal surface, the cement thicknesses of both L and IZC crowns were markedly larger than the set value of 25 μm. These large discrepancies could be due to the shrinkage of zirconia blanks subjected to post-machining sintering.

For both L and IZC crowns, their fit was less accurate in the internal regions than at the marginal area. These results agreed with findings of previous studies regarding CAD/CAM crowns[14,17]. Crown fabrication by the CAD/CAM technique involves scanning, software design, and milling processes, where each step contributes to the overall fit of the crown. At the same time, the process of grinding down a tooth in preparation for a crown also

affects the latter's internal adaptation. The narrowest possible diameter of tooth preparation is determined by the smallest diameter of the bur used for grinding the internal surface. Thus, in structures smaller than the narrowest bur diameter, more tooth substance may be removed than necessary. This may then result in larger internal gaps than mandatory for a good fit[17].

*Fracture resistance*

Highly lauded for their mechanical and optical properties, zirconia-based restorations may be an appealing alternative to metal-ceramic restorations as they have the potential to withstand physiological occlusal forces applied in the posterior region[28]. However, the failure rate of posterior all-ceramic crowns was reported to be 3–4% per year, prevalently due to cohesive failure in the porcelain veneer[29]. In a 5-year clinical study on zirconia frameworks for posterior fixed partial dentures, no framework failures were observed but chipping of the porcelain veneer accounted for 15.2% of the failures[18]. In another clinical study on 204 zirconia single crowns among 161 patients, 78% of the crowns were placed on premolars and molars[30]. At the 3rd year's follow-up, there were no zirconia core fractures but two incidences of feldspar porcelain veneer fracture.

In the present *in vitro* study, 22 specimens exhibited porcelain fracture and the surface where the porcelain veneer delaminated from the core appeared smooth with no residual porcelain detected. A wide spectrum of factors reportedly contributed to this chipping or cracking[28,29,31,32]: framework thickness, inappropriate framework support for the veneer, mechanical insufficiency of veneering porcelain, thermal misfit between veneering porcelain and zirconia framework and hence development of residual thermal stresses in porcelain veneer, presence of unfavorable shear forces between framework and porcelain veneer or occlusal stresses. For example, Reich *et al*.[33] reported that when framework thickness of single crowns was reduced from 0.5 to 0.3 mm, fracture resistance was unfavorably reduced by 35%. To avoid porcelain fractures, suggestions to improve zirconia coping design included uniform porcelain veneer layer thickness and improved support for occlusal and lateral loading as well as compressive loading[31].

For zirconia-based crowns, most fractures occurred in the veneering porcelain. Nonetheless, zirconia cores can be veneered with a heat-pressed or sintered veneering material as they did not significantly affect the fatigue and fracture properties of zirconia cores[21]. In the present study, IPS e.max Ceram material was used to veneer the zirconia-based crowns using a hand-layering technique.

*Effect of luting agents on fracture resistance*

A strong, durable resin bond provides high retention, improves marginal adaptation, prevents microleakage, and increases fracture resistance of the restored tooth and the restoration. The composition and physical properties of zirconium oxide-based ceramics differ substantially from silica-based ceramics, such that conventional acid-etching has no positive effects on the resin bond to zirconium oxide ceramics[34]. As resin bonding to high-strength ceramics is less predictable, alternative bonding techniques are required to achieve a strong, long-term, durable resin bond. Primers containing phosphoric acid monomer, such as Metal/Zirconia Primer (Ivoclar Vivadent), could establish a chemical bond to the surfaces of oxide ceramics. Hence, they are deemed as an alternative to promote adhesion to oxide ceramics such as zirconia.

In the present study, two different adhesive systems (self-etch *versus* etch-and-rinse) were investigated for their effects on the fracture resistance of two different CAD/CAM partially stabilized zirconia systems. Cementation of zirconia crowns with self-etch adhesive (Multilink) resulted in higher fracture resistance than cementation with etch-and-rinse adhesive (Variolink), but there were no significant differences. Cementation with Multilink also resulted in less porcelain veneer fractures than cementation with Variolink.

*Limitations of an in vitro study*

In the present *in vitro* study, standardized and optimized conditions were provided for every experimental procedure, from tooth preparation and crown cementation to internal fit and fracture resistance evaluations. Therefore, the results of the present study depicted the production and precision of CAD/CAM zirconia crowns under ideal conditions in a controlled and predictable environment, but not a faithful reflection of those conditions encountered in daily clinical care.

Limitations of the present study included:

1. Gap dimensions were measured using the silicone replica technique. This meant that precision of fit was measured at only 35 defined points, which might not fully represent the complete fit.
2. Fit of the CAD/CAM zirconia crowns was recorded before cementation to compare only the fabrication procedures. Besides, cross-sectioning might have caused some damage to the specimens after cementation.

## CONCLUSIONS

Based on the results of this study, the following conclusions were drawn:

1. Differences in precision of fit between the two CAD/CAM zirconia systems tested in this study depended on the region being evaluated.
2. Both L and IZC systems demonstrated acceptable *in vitro* marginal discrepancies, with no statistically significant differences ($p>0.05$).
3. The IZC system showed significantly lower axial and occlusal discrepancies.
4. Cementation with self-etch Multilink for both L and IZC systems resulted in higher fracture resistance than cementation with Variolink, but the differences were not statistically significant ($p>0.05$).
5. Unrestored control teeth exhibited significantly

lower fracture resistance than the restored teeth.

6. As per the most common technical complication encountered for CAD/CAM zirconia frameworks, porcelain veneer fracture was the predominant failure pattern in this study.

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