Marginal Adaptation, Gap Width, and Fracture Strength of Teeth Restored With Different All-Ceramic Vs Metal Ceramic Crown Systems: An in Vitro Study

Keywords

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ABSTRACT

This study evaluated marginal adaptation before and after thermomechanical (TCML) loading, gap width and fracture strength of all-ceramic single crowns, as compared to porcelain-fused-to-metal (PFM). Thirty extracted premolars were prepared with a round shoulder of 1.0 mm depth. Specimens were restored with zirconia-ceramic (Group 1), lithium disilicate (Group 2) and metal-ceramic single crowns (Group 3). The replica of each sample was observed with a scanning electron microscope (SEM) to evaluate the crown-cement (c-c) and tooth-cement interface (t-c). After TCML, perfect margins decreased to 91.3% (c-c) and 93.9% (t-c) in Group 1, 94.6% (c-c) and 96.0% (t-c) in Group 2 and 73.5% (c-c) and 53.1% (t-c) in Group 3. The mean fracture strengths were 654.8 ± 98.1 N for Group 1, 551.3 ± 127 N for Group 2 and 501.43 ± 110.1 N for Group 3. All-ceramic systems could substitute for metal-ceramic crowns, but chipping of veneering ceramics, especially in zirconia-based crowns, should be investigated.

INTRODUCTION

The need for aesthetic enhancement and the desire to use metal-free restorative materials have increased the demand for all-ceramic systems, in both the anterior and posterior areas.[1] The rapid improvement of these intrinsically brittle materials, combined with the use of CAD/CAM, has made all-ceramic systems increasingly popular over the past decade. All-ceramic materials show advantageous characteristics, such as translucency, color stability, biocompatibility, low thermal conductivity, high wear resistance, and greater effectiveness of diagnostic radiographs[2] Among ceramic materials, excellent aesthetic results have been obtained with the introduction lithium disilicate material (e.max press, e.max CAD), this is thermopressed or CAD/CAM glass ceramic in which the inclusion of fluoroapatite crystals causes the enhancement of translucency, brightness, light diffusion within the material and adhesion with the resin cements[3] Nevertheless, the flexural strength of these materials is approximately 400 MPa,[4] limiting their application to single crowns or fixed partial dentures (FPDs) in the anterior and premolar regions.[5]

CAD/CAM systems have been continuously developed and upgraded in prosthetic dentistry; zirconium oxide, is commonly used for single crowns and FPDs in both the anterior and posterior areas. Zirconia seems to satisfy both aesthetic[6] and mechanical needs[7-8] as a core material for all-ceramic restorations. In vitro studies of Y-TZP samples have shown values of 900–1200 MPa for flexural strength and values of [9–10] MPa·m½ for fracture toughness. Several in vivo studies were conducted with zirconia FPDs demonstrating good clinical performance, but the most commonly reported clinical complication was chipping fracture of the veneering porcelain [9-11] The causes of this phenomenon are supposedly insufficient support of the veneering material by the framework design, changes in the ceramic composition versus conventional feldspathic ceramics, mismatch of the coefficient of thermal expansion (CTE), unfavorable surface and heat treatments, and thermal conductivity of the Y-TZP.[12-14]

Based on in vivo studies, the choice of material for rehabilitation in the posterior area was difficult because only limited clinical information is available for zirconia–ceramic[15] or lithium disilicate single crowns[16]

A recent systematic review[17] of the survival and complication rates of metal–ceramic and all-ceramic single crowns after an observation period of 5 years reported an estimated survival rate of 94.7% (95% CI: 94.1-96.9%) for metal-ceramic restorations, 96.6% (95% CI: 94.9-96.7%), for leucite or lithium-disilicate reinforced glass ceramic and 92.1% (95% CI: 82.8-95.6%) zirconia single crowns. However, the 5-year survival rates of feldspathic/silica-based ceramic crowns were lower. When the clinical results in anterior and posterior regions were compared feldspathic/silica-based ceramic and zirconia crowns exhibited significantly lower survival rates in the posterior region. Zirconia retorations were more frequently replace due to veneering ceramic fractures than metal-ceramic single crowns. In addition higher 5 year rates of framework fracture were reported for the all-ceramic than for metal-ceramic single crowns.

After aesthetic and mechanical properties, marginal adaptation is considered to be one of the most important criteria in clinical success. A high marginal discrepancy leads to cement dissolution and microleakage, which can lead to plaque retention, recurrent caries and periodontal disease[18]

For monolithic lithium disilicate glass, leucite glass, and feldspathic restorations, the adhesive technique is key for successful bonding and reduced marginal discrepancies. Adhesive cementation has been shown to increase fracture loading and to improve clinical performance. The strength of an all-ceramic restoration depends on the characteristics of the material used, thickness of the crown, design of the restoration, core-veneer bond strength and cementation.[19] However, no significant difference exists between conventional and adhesive luting with zirconia restorations in terms of retention[20]

The aim of this *in vitro* study was to evaluate marginal adaptation before and after thermomechanical loading, gap width, chipping fracture during loading and the load-to-fracture of all-ceramic single crowns made with lithium disilicate and with zirconia substructure compared to metal–ceramic crowns.

MATERIALS AND METHODS

In total, 30 caries-free extracted premolars for orthodontic reason with completed root growth and nearly identical size were selected for the study. The size was measured at the cement–enamel junction (CEJ) using a digital caliper (Tresna). First, for all teeth, the points of the maximum equator on the vestibular and buccal sides were signed. Then, the equidistant point from the previous markers in the mesial and distal sides was individuated. The measurements of the mesio–distal and vestibular–buccal sides were performed using these four points. The inclusion criterion was that the difference of width measured as mesio–distal and vestibular–buccal distance was in the range of 1 mm. The teeth were stored in 0.02% thymol solution for at least 3 months at 4°C before the start of the experiment. As the total coverage restorations were clinically used in endodontically treated teeth, the root canal preparation of the all extracted premolars were performed using NiTi rotary instruments (Protaper), in a low-speed handpiece (Tecnika), under intermittent rinsing with 5% NaOCl (Niclor 5). The instruments were changed every five samples. The diameter of the final apical size was related to the diameter of each root canal using the instrument from F1 to F4. An epoxy sealer (Pulp Canal Sealer) and warm gutta percha associated with a vertical condensation technique (System B) were used as the three-dimensional canal filling system. The decision to devitalize the samples cut off at the coronal portion at 2 mm to obtain the ferrule effect and reconstruct them with post and resin composite was clinically driven. Based on a minimal intervention approach, all vital teeth are commonly treated with adhesive partial restorations, not complete crowns. Provisional restorations of the pulp chamber were made with (Cavit) before cavity preparations. Before the endodontic procedures, an impression of each tooth with a transparent, medium viscosity, two-component addition silicone (Transil) was taken in order to reproduce the same anatomic form with the restoration procedures. Then the crowns of the endodontically treated teeth were cut off 2 mm coronal to the CEJ. All teeth were restored with fiber posts (FRC Postec, Ivoclar Vivadent), luted using a dual curing composite resin cement (Multilink Automix). A composite build-up was conducted using a bonding system (Adhese), and a dual curing composite (MultiCore HB). The teeth were restored using the silicone mould of the original shape and then were prepared in a standardized manner: 2 mm of occlusal reduction, 1.5 mm of axial reduction and a round shoulder of 1.0 mm depth with ~8° convergence, placed coronal to the cement–enamel junction. Teeth preparations and finishing were made using diamond burs (881, 8881, 881EF, 8379), Dura White stones (CN1 4° convergence) and silicon points under profuse water-spray cooling. Impressions were made with polyester material (Permadyne Penta H + Permadyne Garant) with a simultaneous mixing technique, according the manufacturer's instructions. The teeth were randomly divided into three equal groups for the material and system applied for the restoration using the Random Allocation Software 1.0.

LABORATORY MANUFACTURING PROCESS

Group 1 teeth were restored with all-ceramic crowns, fabricated with a zirconia core and pressable veneering ceramic with specific CTE for zirconia (ZirCad/Zirpress) *(Table 1*). The CEREC system was used for scanning the tooth, designing the framework and milling the e.max ZirCad blocks. The thickness of the core was 0.5 mm according to the manufacturer. For Group 1 specimens, zirconium was prepared and veneered with Zirliner and placed in brass dies for the veneering process. Glass–ceramic ingots (IPS e.max ZirPress) were heat-pressed according to the manufacturer's recommended parameters (pressing temperature 910°C, pressing time 15 min, pressure 5 bar). After cooling, the crowns were cleaned under running water for 2 min and dried. Group 2 was restored with a monolithic lithium disilicate glass ceramic material (IPS e.max press). This material was processed in a dental laboratory with thermopressing equipment. A wax-up of the restoration was made before pressing the ingot of the precristallized ceramic in the refractory mound created with the final anatomy of the restorations according to the (pressing temperature 910/850°C, pressing time 15 min, pressure 5 bar). Group 3, as a control group, used a conventional metal alloy framework (IPS D.sign 91) and a pressable veneering ceramic specific for metal (IPS In Line PoM). The pressing technique of the veneering ceramic was the same as for Groups 1 and 2. The choice of pressable ceramic on metal was made to standardise the application of the veneering ceramic to the other two groups. Before the luting procedures the marginal and internal adaptation of all restorations were checked and optimized on the gypsum model by the dental technicians.

Table 1. Materials used in the study

Material	Type	description
ZirCAD	Zirconia substructure	Ittria - tetragonal zirconia polycrystal (Y-TPZ).
ZirPress	Veneering ceramic for zirconia	Fluorapatite glass-ceramic ingot.
IPS d.Sign 91	Metal substructure	Extra hard reduced gold ceramic alloy.
PoM (press on metal)	Veneering ceramic for metal	Leucite-containing ceramic.

LUTING PROCEDURE

All teeth were cleaned with a polishing brush and a fluoride-free cleaning paste (Nupro), then rinsed with a water spray and dried. Luting was effected with a self-adhesive, dual-curing composite cement (Multilink Sprint). No particle air-abrasion was performed on the inner side of the crowns. The debridements were cleaned with a gentle spray using a small steam-cleaning unit for dental laboratories (Mini Vapor ceramic). Luting was effected with a self-adhesive, dual-curing composite cement (Multilink Automix). Cement from the automix syringe was applied into the restoration and then the crown was seated in place and held with a steady pressure of 5 kilogram. Excess material was removed with a scaler and microbrush and after the setting time, the marginal area of the restoration was finished with silicone polishers (Astropol).

EVALUATION

Semi-quantitative investigation of marginal adaptation

The samples were cleaned with rotating nylon brushes and toothpaste (Signal Anti Caries) before making impressions for the replicas. Impressions of the samples were taken using polyvinylsiloxane impressions (President Plus Light-body), and replicas in epoxy resin (Epoxy VP 1031) were made before and after the artificial aging. The replicated specimens were subjected to a semi-quantitative evaluation of marginal adaptation at a standard 200× magnification with a scanning electron microscope (SEM) before and after thermal cycling and mechanical loading (TCML) with a Regensburg device. Analysis of SEM images for the complete circumference was carried out with the Optimas 6.2 system. TCML was performed to simulate a 5-year period of oral service with a Regensburg machine *(Figure 1*) [parameters: 6000 thermal cycles (5°C/55°C) 2 min each cycle, 1.2 × 106 mastication cycles at 50 N with a vertical loading] using an artificial oral environment.[21-22]

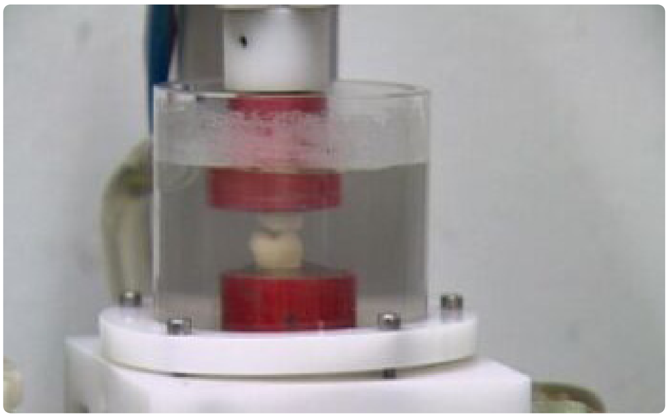


Figure 1: A sample in the Regensburg device for a thermal cycling and mechanical loading (TCML) to simulate a 5-year period of oral service.

Figure 2: Chipping of the veneering of the zirconia/ ceramic during TCML but no zirconia exposition was visible.

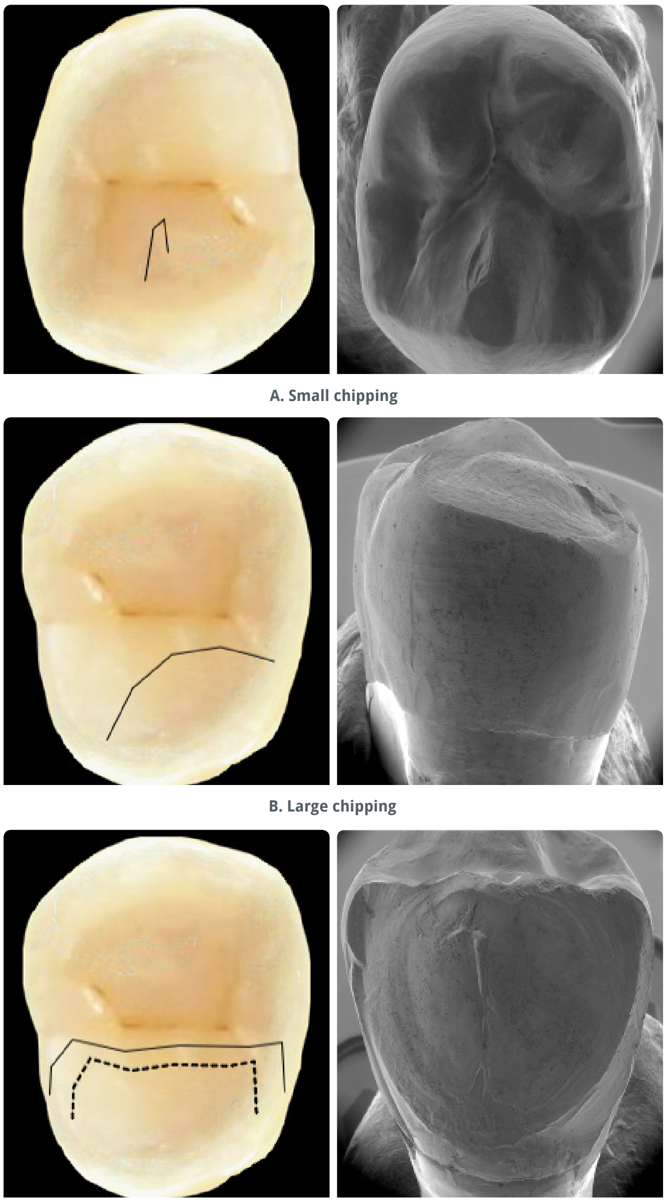
The interface between crown and cement and the interface between cement and dentine were examined. The assessment criteria were as follows:

- Perfect margin (PM): the two adjoining surfaces showed no interruption of the continuous margin and merged into each other, with no difference in level.
- Marginal gap (MG): the two adjoining surfaces showed slight imperfections with interruptions in continuity, and the formation of gaps or cracks due to loss of cohesion or adhesion.
- Non-assessable areas (NA): all adjoining areas that did not fit criteria 1 or 2. Overhangs, underfilled margins or dusty part of the sample in which is impossible see PM or MG.

The distance between tooth and restoration ('gap width') was measured only before TCML to control the thickness of the luting composite. The mean of the gap width was randomly measured every 100 micron of the perimeter for a total of approximately 200 site for each of the restoration.

Fracture resistance testing after TCML

After TCML, the restorations were loaded to evaluate the fracture resistance. Each sample was tilted at an angle of 135° with respect to the axial direction of the punch testing in a universal testing machine (v = 1 mm/min, (Zwick 1446) until fracture occurred. To distribute the force evenly and to avoid peaks, a 0.3-mm-thick tin foil was placed between the sample and the loading die. The failure procedures were evaluated using a stereomicroscope (Olympus SV8) and under SEM (JSM 5200) at ×200. Types of failure for the restorations were divided into four groups: root fracture, crown fracture, cracking of the veneering ceramic, and chipping fracture of the veneering ceramic. From all results, means, medians, and 25th/75th percentiles were calculated and statistical analyses were performed using the Mann–Whitney and Tukey–Kramer tests, at a significance level of α = 0.05.



C. Delamination

Figure 3a-c: Main fracture patterns. Dotted line: delamination of the veneering ceramic with exposed zirconia; Continous line: chipping of the veneering ceramic without exposed zirconia.

RESULTS

SEM MARGINAL ADAPTATION

The marginal adaptation for all groups is described in Table 2. Before TCML, 100.0% perfect margins were observed in Groups 1 and 2 at both interfaces, crown–cement and tooth–cement. In Group 3, the proportion of perfect margins was 81.6% at the crown–cement interface and 69.8% at the tooth–cement interface (Fig. 4 a-b).

After TCML, perfect margins in Group 1 decreased to 91.3% (crown–cement interface) and 93.9% (tooth–cement). For Group 2, values of 94.6% (crown–cement) and 96.0% (tooth–cement) were found. Group 3 revealed results of 73.5% (crown–cement) and 53.1% (tooth–cement). The percentage of non-assessable areas before and after TCML were 0%. The influence of TCML on marginal adaptation was not significant (P> 0.28). Although the results of Group 3 showed a tendency towards lower marginal adaptation, high variation in the results meant that (Man-Whitney U test comparison before and after TCML) there was no statistically significant difference among the groups before or after TCML ($P < 0.019$). The mean of the gap width among Group 1 (165 μm±21), Group 2 (97 μm±14) and Group 3 (124 μm±24) was significantly different ($P < 0.001$), while that between Groups 2 and 3 was not ($P = 0.144$). During TCML, four fractures occurred in Group 1, three of them were chipping fracture of the ceramic veneering and one was a delamination of the veneering from the zirconia, and respectively one chipping fracture each for Groups 2 and 3 (Fig. 2; 3a-c). No fractographic but only visual analysis was done after TCML and fracture test.

Table 2. Percentage of perfect margin of the marginal adaptation before and after loading at the crown-cement and tooth-cement interfaces.

Crown–cement interface	Group 1 (ZirCad/ ZirPress)	Group 2 (IPS e.max press)	Group 3 (IPS D.sign91/ PoM)
Before loading	100%	100%	81,6%
After loading	91,3%	94,6%	73,5%
Tooth–cement interface			
Before loading	100%	100%	69,8%
After loading	93,9%	96%	53,1%

Table 3. Mean and median of the load-to-fracture.

	Group 1 (ZirCad/ ZirPress)	Group 2 (IPS e.max press)	Group 3 (IPS D.sign91/ PoM)
Mean	654.8 ± 98.1 N	551.3 ± 127. N	501.4 ± 110.1 N
Median (25th/75th percentile)	643N (608 N/682 N)	556N (444 N/651 N)	496N (418 N/580 N)

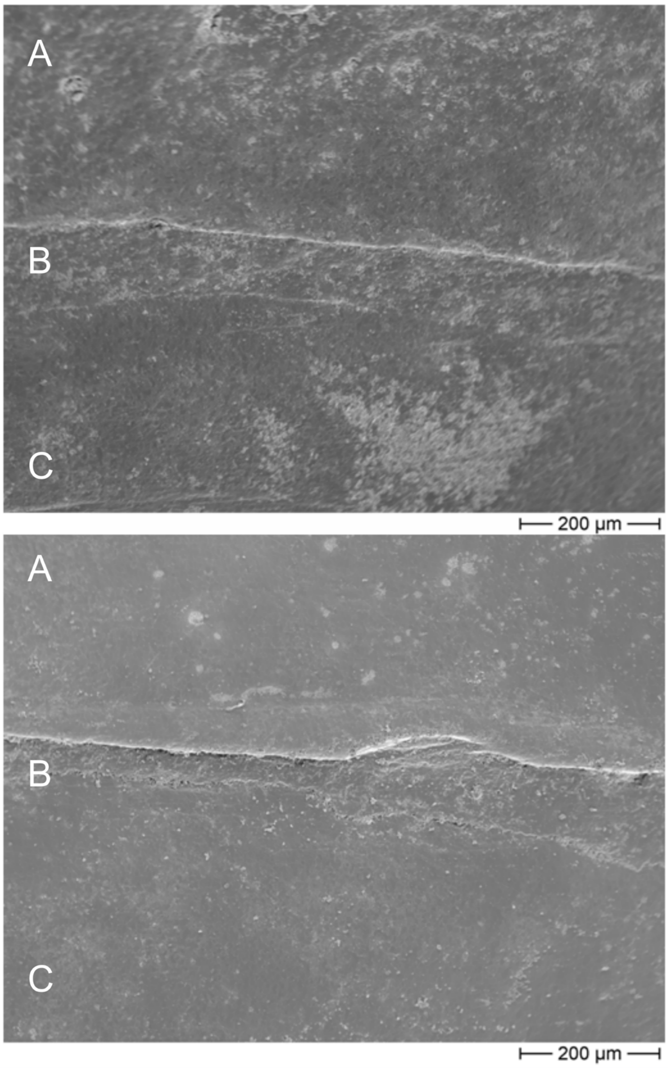


Figure 4a-b: The images show the perfect margin (PG) and the marginal gap (MG). The capital letters on the pictures indicate: A - restoration; B - luting cement; C – tooth.

FRACTURE RESULTS

The mean of load-to-fracture *(Table 3)* was 654.8 ± 98.1 N for Group 1, 551.3 ± 127. N for Group 2, and 501.4 ± 110.1 N for Group 3; The zirconia restorations showed the highest value of the load-to-fracture respect the metal-ceramic and lithium disilicate crowns. Moreover *post hoc* Tukey analysis showed no significant difference among the groups ($P < 0.05$). The median (25th/75th percentile) of load-to-fracture was 643 N (608 N/682 N) for Group 1, 556 N (444 N/651 N) for Group 2, and 496 N (418 N/580 N) for Group 3.

DISCUSSION

An *in vitro* study was conducted to examine marginal adaptation and load-to-fracture of single crowns made of different materials. Specimens restored with both ZirCad/ZirPress and e.max Press materials showed greater marginal adaptation, with a proportion of perfect margins greater than 90%, suggesting adequate clinical performance. No significant difference was seen between Groups 1 and 2 in marginal adaptation before or after the thermal cycling and mechanical loading. The highest percentage of perfect margins was at the cement–tooth interface. The results obtained for Groups 1 and 2 may be explained by the strong bonding created between the luting and the core materials. A systematic review has demonstrated the high retentive strength of all-ceramic systems with resin luting agents and an increased adhesion could be expected after physicochemical conditioning of zirconia. MDP-based resin cements showed higher results than other cements types.[23] Additionally, some treatments, such as air-abrasion with fine particles at low bars of pressure,[24] specific primers containing phosphonic acid monomers purposely prepared for zirconia,[25-26] and phosphate ester monomer[27] could increase the bond and, as a consequence, the marginal adaptation of zirconia restorations. Nevertheless, specimens from Group 3 showed a significantly lower percentage of perfect margins, after and before TCML. As expected for metal–ceramic restorations, the lowest values were found for the tooth–cement interface.[28] The results obtained were probably due to weak bonding between the luting agent and the metal alloy.

After TCML, the restorations were loaded in the axial direction until failure. The means of load-to-fracture of Groups 1 and 2 were not statistically different from that of Group 3, which suggests that all-ceramic crowns are comparable to conventional metal–ceramics restorations in terms of resistance. These results may be expected for Group 1, in which the Y-TZP substructure, with high mechanical properties, allows the production of resistant prosthetic restorations. The load-to-fracture of the monolithic lithium disilicate ceramic material showed a high load-to-fracture value, not significantly different from that of the control group. Lithium disilicate is a monolithic material, as opposed to the other groups, in which the restoration is with a combination of two materials with completely different mechanical properties. Although the mechanical properties of this material, such as the flexural strength, are lower than zirconia and metal, the results of the load-to-fracture were comparable with those of the other groups.

During TCML, four failures resulted in Group 1, one in Group 2, and another in Group 3. Visual analysis under stereomicroscope and SEM at ×200, of the failed specimens showed that the mode of fracture was the chipping fracture of the veneering ceramic. Cohesive fracture of the veneering ceramic has been reported to be the failure pattern in different in vivo studies with Y-TZP and all-ceramic FPDs. The causes of this phenomenon are supposedly due to insufficient support of the veneering material by the framework design, changes in the ceramic composition versus conventional feldspathic ceramics, mismatch of the CTE, unfavorable surface and heat treatments and thermal conductivity of the Y-TZP.[29] In our study, the high number of chipping fractures in Group 1 may have been due to insufficient support of the veneering ceramic.

Currently upgraded software for the design of the zirconia substructure could allow a framework derived from a virtual diagnostic wax-up with a digital cutback procedure. In this way, the thickness of the veneering ceramic could be equally distributed and supported.[30] However, a fractographic analysis is necessary to better evaluate causes and modes of fracture.

Various values have been reported as the maximally acceptable marginal gap width, depending on the type of restoration. McLean *et al*. that consider only marginal gap values of less than 120 μm to be within the clinically acceptable limit.[31]

Moreover, it has been demonstrated that marginal discrepancies can be affected by the type of finish line, the firing procedure of the veneering porcelain and cement, and the cementation technique. Additionally, it must be underscored that the marginal fit changes before and after luting procedures, as demonstrated by Kern *et al*.[32] In our study, although the marginal adaptation after loading and thermocycling of two all ceramic systems was greater than 90%, the gap width of zirconia-based crowns (165 μm±21) was statistically different from the other groups. This value may have been due to the CAD/CAM system used. The gap width of lithium disilicate (97 μm) and metal–ceramic crowns (124 μm) was similar to the value reported in the previous literature.

CONCLUSIONS

Within the limits of this type of *in vitro* study, no significant difference was found in terms of load-to-fracture between teeth restored with all-ceramic and metal–ceramic single crowns. Although the control group showed a tendency toward lower marginal adaption, no significant difference was detected between all-ceramic and metal–ceramic single crowns. Pressable monolithic lithium disilicate ceramic, in combination with a resin luting agent, can act as a biomimetic of enamel, optimizing the distribution of occlusal stresses at the margin and showing the same value in load-to-fracture in restorations.

MANUFACTURERS' DETAILS

- e.max press, e.max CAD: Ivoclar Vivadent, Liechtenstein.
- Transil: Ivoclar Vivadent, Liechtenstein.
- Tresna: Instruments, USA.
- Protaper: Denstply Maillefer, Switzerland.
- Tecnika: Denstply Maillefer.
- Niclor 5: Ogna, Italy.
- Pulp Canal Sealer: Kerr, USA.
- warm gutta percha: Denstply Maillefer.
- System B: Sybron Dental, USA.
- Multilink Automix: Ivoclar Vivadent.
- Adhese: Ivoclar Vivadent.
- MultiCore HB: Ivoclar Vivadent.
- 881, 8881, 881EF, 8379: Komet, USA.

- Dura White stones
- silicon points: Shofu, Japan.
- Permadyne Penta H + Permadyne Garant; 3M ESPE.
- ZirCad/Zirpress: Ivoclar Vivadent.
- IPS D.sign 91: Ivoclar Vivadent
- IPS In Line PoM: press on metal, Ivoclar Vivadent.
- Nupro: Dentsply, USA.
- Multilink Sprint: Ivoclar Vivadent.
- Mini Vapor ceramic: Brega.
- Multilink Automix: Ivoclar Vivadent.
- Astropol: Ivoclar Vivadent.
- President Plus Light-body: Colténe AG, Altstätten, Switzerland.
- Epoxy VP 1031: Ivoclar Vivadent.
- SEM; Cambridge S240 Leica, Nußloch G, Germany. Optimas Inc., USA.
- Zwick 1446, Germany.
- Stereomicroscope: Olympus SV8, Japan.
- SEM: JSM 5200, Jeol, USA.

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