

Effect of total occlusal convergence on fit and fracture resistance of zirconia-reinforced lithium silicate crowns

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Introduction: Computer-aided design (CAD) and computer-aided manufacturing (CAM) monolithic crowns are gaining momentum. Limited evidence exists about the effect of tooth preparation total occlusal convergence (TOC) on marginal and internal gap distances in addition to load to fracture values.

Aim: The aim of this study was to evaluate, by microcomputed tomography (μ CT), the influence of 12° and 20° TOC on marginal and internal adaptation of zirconia-reinforced lithium silicate (ZLS) crowns. Moreover, values of load to fracture with and without initial cyclic loading (CL) were compared.

Material and methods: Forty ZLS crowns were fabricated on dies with TOC of 12° and 20°, 20 crowns for each group. μ CT was used to compare marginal and internal adaptation. Each specimen was measured at 140 points distributed on all tooth preparation surfaces for 2D gap distance assessment. 3D gap volume was also evaluated. Crowns were then cemented and divided into two subgroups; the first was stored in distilled water (no cyclic loading [NCL] subgroup), the second was subjected to CL (CL subgroup).

Results: Factorial repeated measures ANOVA followed by Bonferroni post hoc in addition to independent and dependent *t*-tests were used for statistical analysis. Marginal gap, absolute marginal discrepancy, and occlusal gap measurements showed significant differences between the measurement sites. Static load to fracture values showed significant differences between TOC groups for both NCL ($P=0.011$) and CL ($P=0.025$) subgroups.

Conclusion: An increase of TOC from 12° to 20° did not affect marginal and internal adaptation but resulted in higher values of load to fracture of ZLS crowns. CL simulating 1 year of service did not result in fatigue failure.

Keywords: CAD, CAM, monolithic crowns, total occlusal convergence, μ CT, marginal gap

Introduction

The convenience of computer-aided design (CAD) and computer-aided manufacturing (CAM) has resulted in increased demand for monolithic restoration materials.¹ CAD/CAM fabricated monolithic ceramic crowns in contrast to traditional slip casting and hot pressing have a more homogenous structure. Crowns are milled from standardized fabricated blocks with minimal imperfections.²

Ceramic crowns are characterized by natural appearance and biocompatibility.³ The success of ceramic crowns is greatly determined by marginal and internal adaptation, resistance to fracture, and esthetic value.^{4,5} Inadequate fit and marginal discrepancies lead to the accumulation of dental biofilm,⁶ alteration of microflora distribution,⁶ increased caries risk,⁷ microleakage,⁸ periodontal diseases especially with subgingival margins,⁵ and excessive exposure of the cement to oral environment.⁹ Values of

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marginal gap (MG) reported in the dental literature range from 3.7 μm to 200 μm .^{4,10–14} The maximum acceptable MG is considered to be 120 μm .¹²

Techniques such as direct microscopy,¹⁵ impression replica technique,¹⁶ profilometry,¹⁷ and microcomputed tomography (μCT)^{18,19} have been implemented to assess marginal and internal adaptation. μCT in comparison to the other techniques has the advantage of being non-destructive, delivers 2D and 3D reconstructions, and provides close sections with a great number of measurement points.^{17–19} Such features are not possible with the other techniques.

When lithium disilicate is used for crowns, there is no need for any metal or zirconia framework,² therefore, chipping problems could be reduced. Lithium disilicate ceramic can be pressed or milled in CAD/CAM systems and has been successfully tested in clinical trials.² Its flexural strength and fracture toughness are higher than that of conventional silicate ceramics.^{20–22} In an attempt to further improve durability, zirconia-reinforced lithium silicate (ZLS) glass ceramics has been introduced.²³ ZLS ceramic contains lithium silicate crystals with an average size of 0.5 μm with a synthetic glassy matrix and 8%–12% highly dispersed zirconia crystals.^{23,24} Zirconia is characterized by the phase transformation of its tetragonal to monoclinic phase. This transformation results in volume increase that inhibits crack propagation and increases the fracture strength.^{25,26} The excellent optical properties are still retained.²¹

One of the critical parameters for success of ceramic crowns is the tooth preparation. Total occlusal convergence (TOC), which is the convergence angle between two opposing axial surfaces, was one of the first aspects to receive numeric recommendations, and the stability of the restoration is determined by the relationship of TOC, abutment height, and abutment diameter.^{13,27–33} Low values of TOC, which range from 2° to 5°, are unrealistic and difficult to clinically achieve, and could also result in an increase in cement hydraulic pressure that negatively impacts the discharge of the excess cement.^{34–37} A number of studies assessed the effect of TOC on MG.^{35,38–42} In some of these studies, TOC had no impact on MG.^{39–42}

Fracture resistance and resistance to fatigue failure under intraoral forces are important prerequisites for a successful restoration.^{46–50} Tooth preparation TOC also influences the amount of ceramic material used to achieve acceptable contours. The amount of ceramic has an impact on the mechanical properties including the fracture resistance of the restoration.^{32,47–49}

The aim of this study was to investigate the influence of tooth preparation TOC for ZLS crowns fabricated with a CAD/CAM system on: 1) the marginal and internal adaptation; 2) cyclic fatigue; and 3) fracture load.

The null hypotheses were thus that the two different tooth preparation TOCs of 12° and 10° for ZLS crowns fabricated with a CAD/CAM system will not influence: first, the marginal and internal adaptation; second, the cyclic fatigue strength; and third, the fracture load.

Materials and methods

Two groups of ZLS crowns were fabricated. The first group was with a TOC of 12° while the second had a TOC of 20°. Each group included 20 crowns. μCT was used to compare marginal and internal adaptation of the two groups. The crowns were then cemented to their respective dies and subjected to cyclic loading (CL) followed by load to fracture tests.

A complete coverage preparation for a ZLS crown (Vita Suprinity, Vita Zahnfabrik, Bad Säckingen, Germany) was prepared on two typodont right mandibular molars (Standard model ANA-4; Frasco Franz Sachs, Tettang, Germany) by a single operator (MRA). A milling machine (Paraskop M, Model no 26060; Bego, Bremen, Germany) was used to standardize the preparation. A medium grit, diamond rotary instrument was used to prepare a 1.2 circumferential rounded shoulder finish line. The preparation depth was 2 mm on the functional cusp and 1.5 mm on the non-functional cusp. One of the two typodont teeth was reduced axially to form a TOC of 12° and the second a TOC of 20°.

The prepared typodont teeth were digitized with a laboratory scanner (ARCTICA AutoScan; KaVo Dental GmbH, Biberach, Germany) and the reference models were converted to standard triangulated language (STL) file format. Twenty duplicate dies for each group were produced from polymethyl methacrylate resin blocks (TempPremium A1-B1 95H16; Zirkozahn) with a CAD/CAM milling unit (Everest CAD/CAM System; KaVo). Replica dies were then scanned and each served as an individual master die. Individual data sets for each specimen were generated in STL format and then used on the milling machine.

All 40 crowns were designed with MultiCAD Software (KaVo). The crown margins were marked manually on the finish line of the preparation. The vertical and horizontal gaps were set at 40 μm with a 1.2 mm marginal ramp. ZLS blocks were milled using a 5-axis milling machine. Burs were changed every 20 specimens. Crown margins were examined under the microscope ($\times 10$). No adjustments of the crown

inner surface were carried out. Crowns were then positioned in a porcelain furnace (Programat CS2, Ivoclar Vivadent, Schaan, Liechtenstein, Liechtenstein) with a firing paste (Vita; Vita Zahnfabrik) for the crystallization phase. Crown margins were then reassessed under the microscope ($\times 10$).

An index was used to stabilize and position each surface of the master dies (buccal, lingual, mesial, and distal). The obtained four silicone indices were then attached to the manual milling machine. Four standardized reference indentations were then prepared below the finish line for all the dies on the buccal, lingual, mesial, and distal surfaces. These indentations were then used to standardize μ CT image assessment.

Marginal and internal adaptations were analyzed by high-resolution μ CT images (SkyScan 1172; Bruker, Kontich, Belgium). Each crown was stabilized in the scanning tube on its respective die before scanning and being positioned perpendicular to the scanning X-ray beam. The X-ray tube operated at 100 kV, 100 mA, using Al Cu filter. The image pixel size was 10 μ m, and the scanning time was approximately 60 ± 1 minutes for each specimen.

The acquired projection images were reconstructed in cross-section slices. Data viewer program was used to analyze the scans and section the 3D models. The software (CT-analyzer; Bruker micro-CT) was then used to obtain five vertical buccolingual sections with 50 equidistant slice intervals and five vertical mesiodistal sections with 30 equidistant slice intervals.

The following measuring locations were used for 2D adaptation assessment: MG, absolute marginal discrepancy (AMD), axial gap (AG), and occlusal gap (OG)¹⁴ (Figures 1 and 2). Each specimen had a total of 140 measurements (14 points/section and a total of ten sections). Additionally, 3D qualitative evaluation and visualization were carried out.

Crowns were then cemented to their respective dies. Crowns were cleaned with ethyl alcohol in an ultrasonic bath and air dried. Five percentage hydrofluoric acid gel (Ivoclar

Vivadent AG) was applied to the inner surface of the crowns for 20 seconds, they were rinsed in water and air dried. Silane coupling agent (Monobond Plus; Ivoclar Vivadent AG) was applied for 60 seconds to the inside of the crowns. Multilink Automix Primer (Ivoclar Vivadent AG) was applied on the dies. Multilink Automix (Ivoclar Vivadent AG) was used to lute the crowns under a load of 10 N. After photopolymerization of the cement, the excess was chipped away and stored in distilled water for 24 hours at 37°C.

Dies with the cemented crowns were vertically positioned in resin blocks. Each group was then divided into two subgroups (ten crowns/subgroup). The first subgroup (no CL) was left in distilled water at 37°C, while the second subgroup (CL) was subjected to CL.

Specimens of the CL subgroup were then held with their bases in a dynamic loading machine (Instron Dynamic testing machine) in 37°C distilled water (Figure 3). The specimens were subjected to 10^6 cycles at 4 Hz and a load of 88 N of cyclic fatigue to simulate a year of oral service. The specimens were then inspected for features of surface

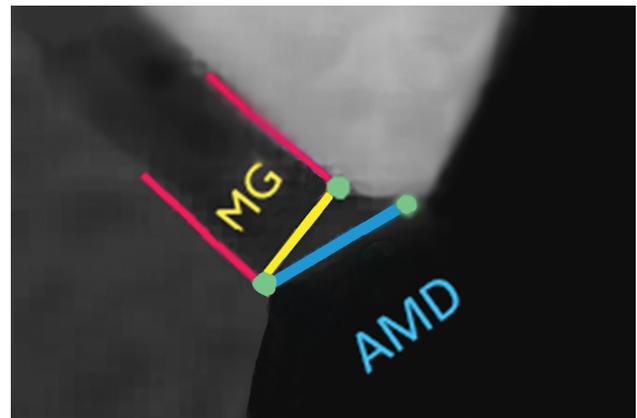


Figure 2 2D adaptation assessment: marginal gap (MG), absolute marginal discrepancy (AMD).

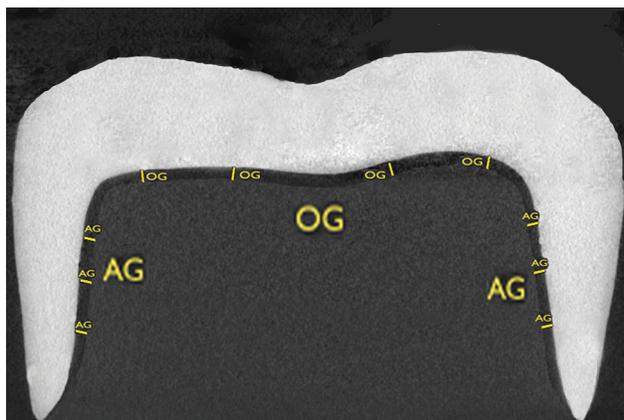


Figure 1 2D adaptation assessment: axial gap (AG) and occlusal gap (OG).



Figure 3 Specimens of the cyclic loading subgroup were held with their bases in a dynamic loading machine (Instron dynamic testing machine).

damage under the stereomicroscope. None of the specimens showed any features of damage.

All 40 specimens were then placed in a universal testing machine (Instron universal testing machine) and submitted to compressive load test (crunch the crown test) at a cross head speed of 0.5 mm/min. Load (in Newtons) to fracture was registered (Figure 4).

Power calculation software (G Power 3.1.3) was used to calculate the sample size at an estimated power of >90%. The estimated sample size for each gap distance group was 12 and 8 for each fracture strength subgroup.^{32,38} The actual sample size in this study was a total of 40 crowns divided into two groups used to compare gap distances. For fracture strength, each group was further subdivided into two subgroups of ten each. These sample sizes were thus larger than those estimated by the power calculation analysis.

Statistical analysis was carried out by using statistical software (SPSS v17.00; SPSS Inc., Chicago, IL, USA). Distribution of data for all variables was assessed by the Kolmogorov–Smirnov test. Normal distribution and homogeneity were verified. Mean values and SDs were calculated

and analyzed. Factorial repeated measures ANOVA followed by Bonferroni post hoc tests were used to compare 2D of all gap distance measurements except OG. Effects of group, site of measurement, and their interaction were analyzed. Independent *t*-test was further used for between-group comparisons for 2D, 3D, and load to fracture tests. Dependent *t*-test was used to compare the effect of CL within each group in addition to effect of site for OG points. For all statistical analyses $\alpha=0.05$.

Results

A total of 400 reconstructed images of μ CT images were evaluated for all 40 crowns. The total number of points for 2D assessment were 5,600 (MG =800, AMD =800, AG =2,400, OG =1,600).

Results of the factorial repeated measures ANOVA followed by Bonferroni post hoc test for the points MG, AMD, and AG are shown in Table 1. Results revealed insignificant effect of TOC difference (MG: $P=0.128$, AMD: $P=0.181$, AG: $P=0.205$). Buccal site gaps for MG and AMD points were significantly higher than the other sites in both groups ($P<0.001$). Differences between AG sites were insignificant (AG: $P=0.187$). There were no interactions between group and site (MG: $P=0.959$, AMD: $P=0.723$, AG: $P=0.943$). Independent *t*-tests between groups for MG, AMD, and AG at each site of measurement were statistically insignificant (Table 1).

Independent *t*-test results for OG showed an insignificant difference between TOC groups for both sites. Differences between sites analyzed by dependent *t*-test were significant (Table 2). Similarly, 3D gap space measurements showed insignificant differences between groups when compared with dependent *t*-test (Table 3).

Independent *t*-test of fracture strength revealed significant differences between TOC groups. The effect of CL in both groups assessed by dependent *t*-test was insignificant (Table 4).



Figure 4 Specimen placed in a universal testing machine (Instron universal testing machine) and submitted to compressive load test (crunch the crown test) at a cross head speed of 0.5 mm/min.

Table 1 Mean values (μ m) of MG, AMD, and AG for test groups

Variables	Mean values (μ m) of MG			Mean values (μ m) of AMD			Mean values (μ m) of AG		
	12° TOC	20° TOC	P	12° TOC	20° TOC	P	12° TOC	20° TOC	P
Mesial Mean \pm SD	52.96 \pm 18.26 ^a	50.50 \pm 16.73 ^a	0.322	86.08 \pm 30.00 ^a	86.12 \pm 28.59 ^{a,b}	0.992	66.13 \pm 27.44	65.13 \pm 30.26	0.673
Distal Mean \pm SD	50.09 \pm 16.04 ^a	49.15 \pm 16.94 ^a	0.687	82.15 \pm 31.05 ^a	80.61 \pm 27.40 ^a	0.710	63.36 \pm 25.68	62.47 \pm 25.63	0.671
Buccal Mean \pm SD	63.15 \pm 24.17 ^b	60.29 \pm 21.46 ^b	0.377	103.39 \pm 33.97 ^b	95.93 \pm 33.40 ^b	0.119	66.23 \pm 25.60	63.75 \pm 24.76	0.229
Lingual Mean \pm SD	53.54 \pm 18.67 ^a	51.75 \pm 17.88 ^a	0.490	85.39 \pm 32.91 ^a	82.47 \pm 30.14 ^a	0.514	62.49 \pm 24.77	61.40 \pm 22.97	0.575
P	<0.001	<0.001		<0.001	<0.001		0.184	0.371	

Note: Mean values followed by different letters in same column show statistical difference ($P<0.05$).

Abbreviations: MG, marginal gap; AMD, absolute marginal discrepancy; AG, axial gap; TOC, total occlusal convergence.

Table 2 Mean values (μm) of OG for test groups

Groups	Mean \pm SD mesiodistal	Mean \pm SD buccolingual	P
12° TOC	117.96 \pm 42.91	105.34 \pm 38.51	<0.001
20° TOC	114.15 \pm 40.30	102.73 \pm 36.71	<0.001
P	0.196	0.327	

Note: $P < 0.05$.

Abbreviations: OG, occlusal gap; TOC, total occlusal convergence.

Table 3 Mean values (mm^3) of cement space for test groups

Groups	Mean \pm SD
12° TOC	17.17 \pm 6.29
20° TOC	17.87 \pm 4.39
P	0.685

Note: $P < 0.05$.

Abbreviation: TOC, total occlusal convergence.

Table 4 Mean values (N) of fracture strength for test groups

Groups	Fracture strength - NCL subgroup (mean \pm SD)	Fracture strength - CL subgroup (mean \pm SD)	P
12° TOC	2004 \pm 194	2070 \pm 241	0.532
20° TOC	2247 \pm 190	2326 \pm 224	0.297
P	0.011	0.025	

Note: $P < 0.05$.

Abbreviations: N, Newton; TOC, total occlusal convergence; NCL, no cyclic loading; CL, cyclic loading.

Discussion

The first and second null hypotheses were accepted, namely that the TOC will neither affect the internal and marginal adaptation nor influence the fatigue strength of ZLS crowns. On the other hand, the third null hypothesis that the TOC will not affect the fracture strength was rejected.

Reviewing the dental literature revealed the limited number of studies assessing ZLS crowns. Increased gap distance and fracture strength are among the potential causes of failure of dental ceramics. The gap distance was assessed prior to cementation to eliminate the influence of the luting cement as a variable.³⁶ Rounded shoulder finish line was used as it seems to result in the best adaptation.⁵⁰ In some μCT cuts, the buccal MG and AMD values were greater than the other sites. This could be attributed to the finish line curvature which was relatively pronounced on the buccal surface of the first mandibular molar typodont tooth used in the study at hand.³⁸ In this in vitro study, the tooth preparation was carried out in accordance with the clinical recommendations. The finish line curvature was prepared to simulate the presence of gingival margin and the occlusal reduction to follow the occlusal anatomy. These conditions were considered to be

more realistic in comparison to studies that used metallic models with simplified margins and occlusal surfaces.⁵⁰

Studies have reported values of MG between 50 and 200 μm as acceptable.⁵¹ Boitelle et al,¹⁰ in a systematic review, reported that CAD/CAM technology can achieve an MG of less than 80 μm and that both digital and conventional impressions presented similar MG values. Papadiochou et al,¹¹ in a systematic review, concluded that the performance of CAD/CAM systems relative to MG is influenced by the restorative material. Gardner⁴ reported that the ideal marginal fit of 25–40 μm , even under ideal conditions, was very rarely achieved. McLean and von Fraunhofer¹² carried out a 5-year study and concluded that for more than 1,000 restorations, 120 μm was the maximum acceptable MG. Contrepois et al,¹³ in a systematic review, reported that 94.9% of the values of MG retrieved from their review measured less than 120 μm . The widest MG was 174 μm , and the smallest was 3.7 μm . Values of marginal and internal adaptation in the current study are comparable to those reported by Yildirim et al¹⁴ for ZLS crowns. It is worth mentioning that the MG measured in the present study did not exceed 120 μm in both groups, which is clinically acceptable.

The differences between the marginal and internal adaptations between the two preparation angulations were statistically insignificant. The term preparation angulation in the literature refers to both the taper that is the inclination of the axial wall of the preparation in relation to the long axis of the tooth and to the TOC, which refers to an imaginary angle between the opposing prepared axial walls. TOC is thus double the angle of taper.¹³ A number of studies assessed the effect of the angle of preparation on the marginal fit of CAD/CAM systems, some before and others after cementation.^{35,38–42} Most of these studies reported that angulation did not influence marginal fit.^{39–42} It is noteworthy that in one study conducted on cemented restorations, low preparation angulation hindered full seating because of increased cement hydraulic pressure.³⁵ Despite the increased retention reported with decreased TOC, there are limitations related to frictional resistance and restoration strength.³² Some authors recommended that a TOC of 4° to 10° is ideal from the point of view of retention.⁵² Parallel preparations are also difficult to perform. These values seem, however, to be unrealistic in the clinical setting.^{28,31,34} Tiu et al,³³ in a systematic review, reported that the achievable TOC ranges between 10° and 20°. Studies reported TOC values between 4.1^{o30} and 27.4^{o27} with the tendency being rather toward higher TOC even when attempting to achieve a TOC of 6°. Beuer et al^{35,41} considered 12° TOC to be ideal for CAD/CAM metal-free crowns, which

is still clinically difficult to achieve especially on the posterior teeth.²⁷ Contrepois et al,¹³ in a systematic review, reported that a TOC between 10° and 22° seems acceptable, and Goodacre²⁹ was slightly more conservative and recommended a TOC between 10° and 20°. It seems that the recommendation of Shillinburg et al³⁴ is realistic, suggesting a TOC of up to 24° mesiodistally and 20° buccolingually, thus an average of 22° for the mandibular first molars.

ZLS seems to be an attractive monolithic material with a flexural strength of 445 MPa that is higher than that of lithium disilicate (362 MPa) and of conventional silicate ceramics (134 MPa). ZLS fracture toughness is 2.31 MPa m^{-0.5} which is higher than that of lithium disilicate (2.0 MPa m^{-0.5}) and of conventional silicate ceramics (1.74 MPa m^{-0.5}).²⁰⁻²²

It was attempted to create conditions similar to the oral environment for CL. The parameters of CL were adjusted to values reported in the literature.²² Fatigue failure is the cumulative damage caused by CL that results in slow crack propagation and ends in catastrophic failure under loading below the strength of a specific material.^{26,43} None of the specimens were affected by CL. Similar results were reported by Sieper et al,²⁶ as all crowns in their study survived 1,200,000 cycles in a chewing simulator of 5 kg magnitude and with thermal cycling. In both the study at hand and that of Sieper et al,²⁶ the ceramic crowns were etched and bonded to the underlying structure. The strengthening effect of the adhesive cementation might have contributed to the favorable outcomes.⁴⁶ Preis et al⁴⁵ compared the fracture resistance of conventionally cemented, self adhesively cemented, and adhesively bonded ZLS crowns subjected to combined thermal cycling and mechanical loading. Tendency for the highest values were for adhesive bonding but with no statistical significance.

Static load to fracture test that was carried out on all specimens showed a significant increase in fracture strength with an increase in TOC. A similar finding was reported by Corazza et al,³² who compared the influence of 6°, 12°, and 20° TOC on the fracture load of yttria partially stabilized zirconia veneered with feldspathic porcelain. The 20° TOC had the best performance. The greater fracture strength with the higher TOC has been attributed to the greater material bulk.³⁸ Other studies have similarly reported that increased amount of ceramic improves the mechanical properties, including fracture resistance.⁴⁷⁻⁴⁹

It is worth mentioning that in both groups irrespective of TOC, the values of fracture strength were higher than the magnitude of intra-oral forces. Waltimo and Könönen⁴⁴ reported maximum bite force in the molar region of 847 N and 597 N for males and females respectively. In the present study, the load to fracture mean values ranged from 2,004 N

to 2,315 N, which is greater than the maximum bite forces. The values recorded in this study are comparable to those reported in the literature, which reported a fracture resistance of more than 2,200 N for 1 mm occlusal thickness.^{21,23,26,46}

The initial dynamic loading had no influence on the fracture strength of the tested specimens under static load, as there were no significant differences in load to fracture values between the subgroups that were subjected to CL in comparison to the other subgroups that were only stored in distilled water irrespective of the TOC. This finding is favorable considering the long-term service expected from ZLS crowns. Crack formation and propagation might be hindered by the transformation of the tetragonal zirconia phase that is distributed in the glass phase of lithium.^{25,26} Sieper et al²⁶ reported the presence of arrest lines that hindered failure, which supports the assumption that microcracks have a smaller effect on fracture strength in comparison to conventional lithium disilicate ceramics.

A limitation to that study was that μ CT was carried out prior to cementation. This was done to better visualize the gap distance. However, this test condition may not fully simulate the clinical situation as the cement could alter the value of the gap between the prepared abutments and the crowns.

Conclusion

The increase in TOC from 12° and 20° did not affect the marginal and internal adaptation of ZLS crowns. Increased finish line curvature on the buccal compared to the other surfaces seemed to increase gap distance. CL simulating 1 year service did not result in any fractures. A TOC of 20° resulted in higher values of load to fracture. Clinically, more realistic and applicable preparations of 20° TOC for all ceramic ZLS full coverage crowns will result in acceptable gap distance and load to fracture values.

Disclosure

The authors report no conflicts of interest in this work.

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