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RESEARCH AND EDUCATION

Influence of thermomechanical fatigue on the fracture strength of CAD-CAM-fabricated occlusal veneers

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ABSTRACT

Statement of problem. With the development of new computer-aided design and computer-aided manufacturing (CAD-CAM) restorative dental materials, limited data regarding their survival rate and fracture strength are available when they are used as occlusal veneers. Therefore, these materials should be evaluated under conditions similar to those of the oral environment before being recommended for clinical use.

Purpose. To evaluate the influence of thermomechanical fatigue loading on the fracture strength of minimally invasive occlusal veneer restorations fabricated from different CAD-CAM materials and bonded to human maxillary premolars using self-etchnig bonding technique.

Material and methods. Sixty-four CAD-CAM occlusal veneer restorations were fabricated from group LD (lithium disilicate [e.max CAD]), LS (zirconia-reinforced lithium silicate [Vita Suprinity]), PI (polymer-infiltrated ceramic [Vita Enamic]), and PM (polymethylmethacrylate [Telio CAD]). The occlusal veneers were luted to enamel (n=16) using a self-etching primer (Multilink Primer A/B) and a luting composite resin (Multilink Automix). Half of the specimens of each group (n=8) were randomly selected and subjected to thermomechanical fatigue loading in a masticatory simulator (1.2 million cycles at 98 N with 5°C-55°C thermocycling). All specimens were quasistatically loaded until fracture. The statistical analysis was made using the Kruskal-Wallis and Mann-Whitney U tests (α=.05).

Results. According to the Kaplan-Meier analysis after the thermomechanical fatigue of the 4 groups, the cumulative survival rate was as follows: group LD, 50% group LS, 62.5% group PI, 37.5%; and group PM, 50%. Although some of the surviving specimens exhibited microcracking, their integrity or bonding to teeth was not affected. Thermomechanical fatigue significantly reduced the fracture strength of group PI (*P*=.047) and group PM (*P*=.025). Without thermomechanical fatigue, group PM showed significantly higher fracture strength than group LS (*P*=.015).

Conclusions. In general, thermomechanical fatigue decreased the survival rate and fracture strength in all test groups. (J Prosthet Dent 2019;121:644-50)

A loss of occlusal contacts between mandibular and maxillary teeth may result from pathological or functional problems such as tooth wear and caries[1] or an open posterior occlusal relationship with or without orthodontic therapy. Resulting dental problems may include a reduction of masticatory efficiency, loss of vertical dimension, hypersensitivity, and discoloration.[2,3] Under these circumstances, occlusal glass-ceramic veneers may provide a conservative prosthetic solution.[2,4] However, the space for an occlusal restoration might be limited by tooth eruption,[5] which may require removal of tooth structure[5,6] and exposure of dentin. As a result, the long-term vitality and survivability of the teeth, as well as the fracture strength of the tooth and restoration, may be adversely affected.[6-9]

Ivoclar Vivadent AG, Schaan, Liechtenstein, and VITA Zahnfabrik, Bad Säckingen, Germany, provided materials. Funded by departmental resources.
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Clinical Implications

Within the limitations of this in vitro study, the results suggest that the self-etching technique should be avoided for bonding nonretentive occlusal veneer restorations to enamel.

Fortunately, restorative dental materials with improved fracture strength have been introduced for use in minimal thicknesses.[10-12] Furthermore, improved dental adhesive systems in terms of mechanical, physical, and optical properties allow dental clinicians to use more conservative restorative approaches.[13]

High-strength glass- and oxide-ceramic materials have shown promising outcomes in terms of survival rate, integrity, wear resistance, and color stability when used as complete-coverage or partial coverage crowns, veneers, inlays, onlays, and 3-unit fixed partial dentures.[9,14-19] In addition, industrial polymerized dental polymers have been used as alternatives to glass-ceramic materials, with the assumption that they provide high-fatigue resistance.[4,20] However, polymer-based materials have limitations for use as permanent restorations, including wear, discoloration, and low fracture strength.[21-23]

Bonding techniques can be classified as etch-and-rinse (total-etch) and self-etching protocols.[24] Etch-and-rinse adhesive systems use 30% to 40% phosphoric acid to create a porous enamel surface to be penetrated by bonding resin tags.[25,26] Self-etching adhesive systems that contain monomers with grafted carboxylic or phosphate acid groups function by etching and penetrating the tooth substance simultaneously.[27] They were developed to simplify the adhesive bonding steps, save time, and reduce postoperative sensitivity.[28] Nonretentive dental restorations bonded to enamel using etch-and-rinse technique withstood the thermomechanical fatigue loading and yielded high fracture strength values.[8,9,18]

Because of the lack of sufficient data on CAD-CAM-fabricated partial coverage restorations made of ceramic, polymer, and composite resin materials, laboratory studies with different preparation designs and different bonding procedures are required to provide information on the longevity, stability, behavior, and fracture strength of such restorations. Therefore, in the present study, the fracture strength and resistance to thermomechanical fatigue of 4 different CAD-CAM occlusal veneer restorative materials with a fissure thickness of 0.5 mm and a cusp thickness of 0.8 mm and bonded to enamel using a self-etching technique were evaluated. The null hypotheses were that the CAD-CAM occlusal veneers would have similar survival rates after thermomechanical fatigue and that no differences in fracture strength would be found among the different dental CAD-CAM materials before or after thermomechanical fatigue.

MATERIAL AND METHODS

Sixty-four intact human maxillary first premolars, recently extracted for orthodontic reasons, were collected. They were cleaned of both calculus deposits and soft tissues and then stored at room temperature in 0.1% thymol solution (Caelo).

The exposed root portions of the teeth were coated 2 mm apical to the cementoenamel junction with an artificial periodontal membrane made of gum resin (Anti-Rutsch Lack; Wenko-Wenselaar). Then, the coated roots of the teeth were positioned and fixed along their long axis inside metal rings (Ø 15 mm) with autopolymerizing acrylic resin material (Technovit 4000; Kulzer GmbH).

A custom-made paralleling machine and a 120-degree angled adaptor were used to guide the handpiece during the tooth preparation. The occlusal surfaces were prepared within the enamel layer. The angle between the buccal and lingual cusp slopes (mesiobuccal and distobuccal slopes) was 120 degree, with all angles rounded.

A polyvinyl siloxane material (Virtual; Ivoclar Vivadent AG) was used in a dual-mixed technique for impression making. The impressions were poured in Type IV stone (New Fujirock; GC). A 3D scanner (D900 3D scanner; 3Shape) was used to scan the stone die and create a virtual model. The prepared teeth were randomly assigned by Excel software (Excel 2013; Microsoft Corp) into 4 groups. Occlusal veneers were designed virtually with thicknesses of 0.5 mm at the fissures and 0.8 mm at the cusps and milled from 4 different CAD-CAM materials (n=16/group); lithium disilicate ceramic (group LD; e.max CAD; Ivoclar Vivadent AG), zirconia-reinforced lithium silicate ceramic (group LS; Vita Suprinity; Vita Zahnfabrik), polymer-infiltrated ceramic (group PI; Vita Enamic; Vita Zahnfabrik), and polymethylmethacrylate (PMMA) (group PM; Telio CAD; Ivoclar Vivadent AG). The crystallization, finishing, and glazing of e.max CAD and Vita Suprinity, as well as the finishing and polishing of Vita Enamic and Telio CAD, were performed according to the manufacturers' instructions (Fig. 1).

For bonding the occlusal veneers, all teeth were treated with a self-etching primer (Multilink Primer A/B; Ivoclar Vivadent AG), which was mixed in a ratio of 1:1 for 10 seconds and applied for 30 seconds to the prepared enamel surface with a microbrush according to the manufacturer's instructions. After that, a gentle stream of air was applied to the primed surface, leaving the surface appearing glossy. The intaglio surfaces of the occlusal veneers of groups LD and LS were etched for 20 seconds

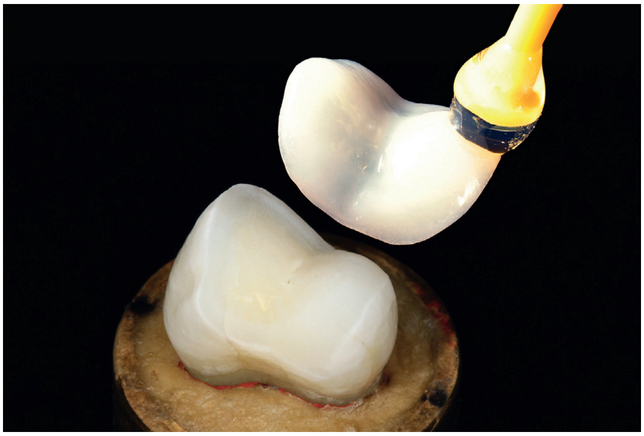

Figure 1. Occlusal veneer restoration with its respective prepared tooth.

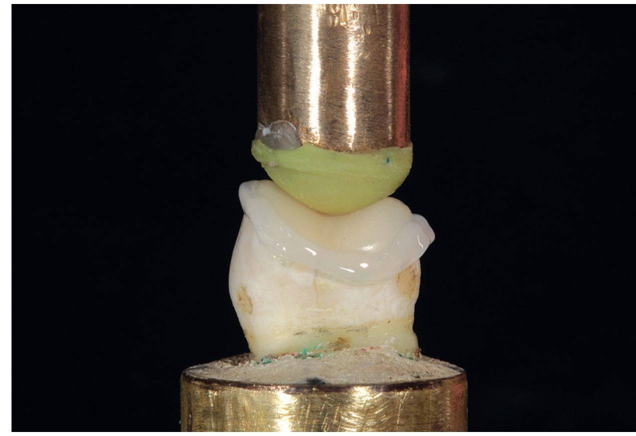

Figure 2. Cementation of occlusal veneer with standardized load of 9.8 N. Air-inhibiting gel applied along margin during polymerization process.

with a 5% hydrofluoric acid etching gel (IPS Ceramic Etching Gel; Ivoclar Vivadent AG), whereas the etching time for group PI was 60 seconds according to the manufacturer's recommendations. The etched intaglio surfaces were sprayed for 60 seconds with distilled water and then dried with oil-free compressed air. A silane-coupling agent (Monobond Plus; Ivoclar Vivadent AG) was applied immediately to the intaglio surface of each occlusal veneer, left to react for 60 seconds, and then dispersed with a stream of air.

The intaglio surfaces of group PM were airborne-particle abraded with 50-μm Al_2O_3 at a pressure of 0.05 MPa and then cleaned for 3 minutes in a 99% isopropanol ultrasonic bath. Then, a PMMA primer (Luxatemp-Glaze & Bond; DMG) was applied and exposed for 20 seconds to polymerizing light (Elipar 2500; 3M ESPE). All restorations were luted to their respective prepared teeth with dual-polymerizing composite resin cement (Multilink Automix; Ivoclar Vivadent AG). A custom-made apparatus was used to seat the restorations with a load of 9.8 N. The excess luting cement was removed from the margins, and air-inhibiting gel (Liquid Strip; Ivoclar Vivadent AG) was applied along the margin of the cemented occlusal veneers (Fig. 2). Thereafter, the restorations were light polymerized from a distance of 5 mm by using a halogen light unit (Elipar 2500; 3M ESPE) with a peak power output of 450 mW/cm^2 from the mesial, distal, buccal, lingual, and occlusal directions for 20 seconds each. After bonding, the specimens were stored in a water bath at 37°C for 3 days.

Half the specimens in each group (n=8) were cyclic loaded in a dual-axis computerized masticatory simulator (Willytec). The specimens were subjected to 1 200 000 strokes with a vertical load of 98 N and thermocycled between 5°C and 55°C in distilled water with a 30 seconds dwell time at each temperature with a total of 5500 thermocycles at a frequency of 2.4 Hz. Steatite ceramic balls with a 6-mm diameter (Hoechst Ceram Tec) were used as antagonists with a vertical movement of 6 mm and a descending speed of 30 mm/s to stroke the buccal cusps, beginning 0.5 mm below the cusp tip with a lateral sliding component of 0.3 mm toward the central fissure.[29] During the thermomechanical fatigue test, the specimens were monitored by means of surveillance cameras to record any failures in the specimens and to determine the number of cycles during which any failure occurred. For the occlusal veneers that fractured and separated from the teeth during the fatigue test, specimen failure was recorded, and the cumulative survival rate for the 4 groups was estimated according to the Kaplan-Meier analysis.

After the thermomechanical fatigue-loading test, all surviving specimens were inspected under an LED light source and optical microscope (Wild M420; Wild Heerbrugg) with ×5.8 magnification to detect any damage or microcracks in the restoration or tooth. Consequently, specimens were rated as complete successful when they did not show any macroscopic damage, as partially successful when they showed some cracks without affecting the integrity of the veneer or bonding to the teeth (Fig. 3), and as failed when a fracture or/and debonding occurred in the restoration.

All nonaged and surviving (complete and partial success) aged specimens were statically loaded until fracture in a universal testing machine (Zwick Z010/TN2A; Zwick). A layer of 0.5-mm-thick tin foil was placed and adapted on the specimens' occlusal surfaces. Then, a 6-mm-diameter stainless steel ball-ended bar was aligned and descended at the fissure along the long axis of the specimens at a cross-head speed of 1 mm/min until fracture. The required load to cause fracture for each specimen was recorded in N. Specimens failed the static fracture strength test when the stress strain curve dropped by 10%. This threshold was important especially

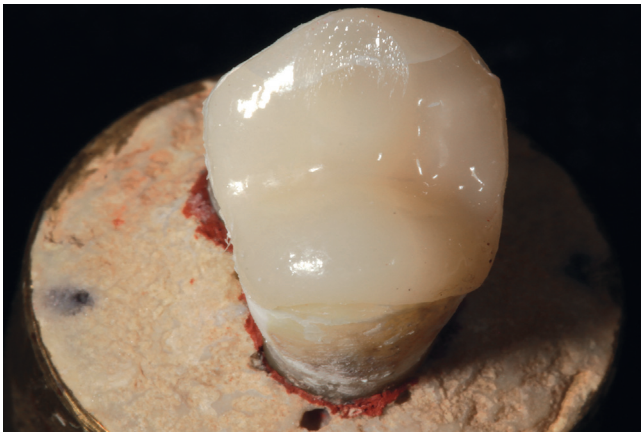

Figure 3. Specimen showing crack after thermomechanical fatigue (partial success).

for group PM because of the plastic deformation of the PMMA.

The study groups were coded according to CAD-CAM materials as shown in Table 1. To evaluate the mode of failure after the fracture strength test, all fractured specimens were inspected under an optical microscope (Wild M420; Wild Heerbrugg) with ×20 magnification. The failure mode was classified into 4 categories in accordance with Guess et al[9]: class I, extensive crack formation within the restoration; class II, cohesive fracture within the restoration; class III, adhesive fracture between the restoration and tooth structures; and class IV, longitudinal fracture of the restoration and tooth.

Normal distribution of data was explored using the Shapiro-Wilk test, which revealed that the data were not normally distributed. As a result, the Kruskal-Wallis test and Mann-Whitney U tests were used for statistical analysis. The Kruskal-Wallis test was used first to detect the overall significance, whereas the Mann-Whitney U tests were used to identify which pairs of groups demonstrated a significant difference (α=.05). Kaplan-Meier analysis was used to measure the cumulative survival rate. Statistical analysis was performed with statistical software (IBM SPSS Statistics, v20.0; IBM Corp).

RESULTS

The results regarding the cumulative survival rate according to the Kaplan-Meier analysis after the thermomechanical fatigue of the 4 groups as well as the descriptive complete and partial success for the studied groups are shown in Table 1 and Figure 4. Although the surviving specimens may have exhibited some microcracks, the integrity of the specimens or bonding to the teeth was not affected. The mean number of masticatory cycles for the failed specimens in each group during the thermomechanical fatigue loading was recorded. No statistically significant difference was found between the cumulative survival rates of the groups LD, LS, and PM (P>.05).

The fracture strength value for the failed specimens during thermomechanical fatigue loading was considered to be 98 N (the applied vertical load during the dynamic loading). Accordingly, the minimum fracture strength after thermomechanical fatigue was 98 N, whereas the maximum fracture strength was 1250.0 N in group LS. The results of the quasistatic load to fracture test of the

Table 1. Group coding, percentage of surviving specimens, and cumulative survival rate after thermomechanical fatigue

Group (Code)	Surviving Specimens, % Complete Success	Surviving Specimens, % Partial Success	Cumulative Survival Rate, %
Lithium disilicate (LD)	50	0	50
Zirconia-reinforced lithium silicate (LS)	25	37.5	62.5
Polymer-infiltrated ceramic (PI)	0	37.5	37.5
Polymethylmethacrylate (PM)	50	0	50

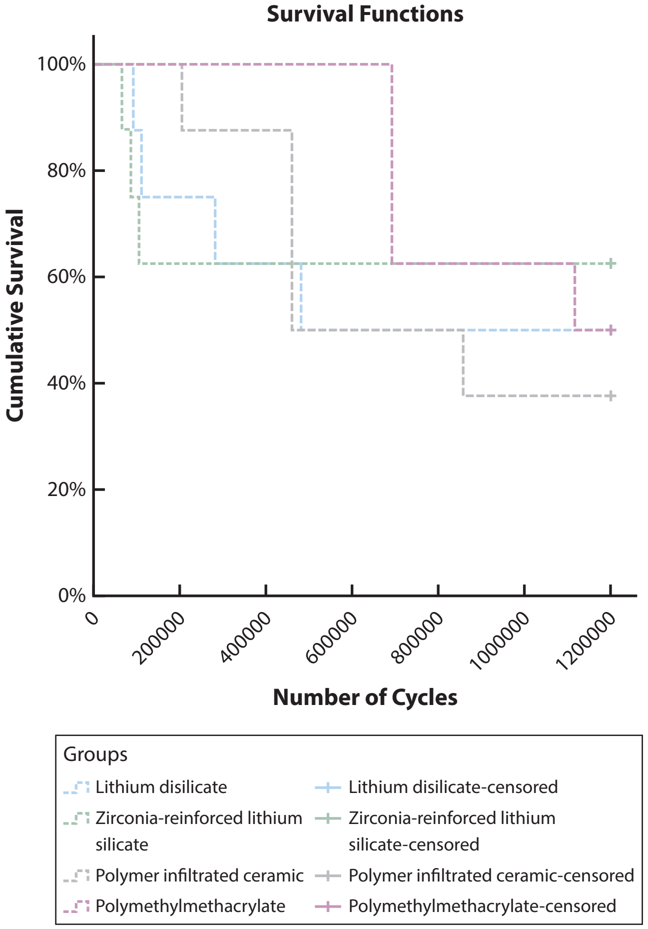

Figure 4. Kaplan-Meier curves after 1 200 000 masticatory cycles. Cumulative survival rate of specimens in 4 test groups.

Table 2. Fracture strength of groups in Newton (N), means, standard deviations (SD), medians, lower and upper quartiles, minima, and maxima (n=8)

	Without Thermomechanical Loading						After Thermomechanical Loading					
Group	Mean ±SD	Median	Q1	Q3	Min	Max	Mean ±SD	Median	Q1	Q3	Min	Max
LD	806.1 ±186.9	782.5^{ABa}	686.5	849.5	586.0	1210.0	470.8 ±428.2	328.5^{Aa}	98.0	941.3	98.0	1070.0
LS	684.0 ±90.0	668.50^{Aa}	615.0	727.8	579.0	869.0	663.8 ±482.7	881.5^{Aa}	98.0	1010.8	98.0	1250.0
PI	767.1 ±130.9	769.5^{ABa}	670.0	867.0	565.0	975.0	349.9 ±350.5	98.0^{Ab}	98.0	738.0	98.0	861.0
PM	897.5 ±164.0	909.5^{Ba}	750.3	1027.5	634.0	1120.0	462.0 ±390.8	434.0^{Ab}	98.0	839.0	98.0	888.0

LD, lithium disilicate; LS, zirconia-reinforced lithium silicate; PI, polymer-infiltrated ceramic; PM, polymethylmethacrylate. Medians with same uppercase superscript letters within same column not statistically different (P>.05). Medians with same lowercase superscript letters within same row not statistically different (P>.05).

groups are listed in Table 2. Thermomechanical fatigue significantly reduced the fracture strength of groups PI (P=.047) and PM (P=.025). Group LD did not have a significant reduction of the median fracture strength after thermomechanical fatigue.

The comparison among the 4 CAD-CAM materials tested revealed that without thermomechanical fatigue, group PM showed significantly higher fracture strength than group LS (P=.015). With thermomechanical fatigue, no statistically significant difference was found among the 4 groups. After the quasistatic failure load, the most commonly observed failure modes were class I and III for all the groups.

DISCUSSION

The fracture strength of ceramic restorations is influenced by microstructure, dynamic fatigue loading, fabrication technique, preparation design, and luting technique.[30] The parameters used in this study for masticatory simulation were adjusted to the reported physiological values.[29]

The failed specimens in the fatigue test fractured under a load of 98 N. Therefore, their fracture strength was reported as 98 N rather than 0 N, or they were excluded from the statistical analysis. The first null hypothesis that the tested CAD-CAM occlusal veneers would survive thermomechanical fatigue was partially rejected. Nearly half of the specimens in all groups failed during the thermomechanical fatigue. A laboratory study[14] reported that occlusal veneers made from lithium disilicate, bonded to enamel with the self-etching technique, had an average survival rate of 75%. However, a study[18] with the same design as the present study reported that all occlusal veneer restorations, bonded to enamel using total-etching technique, survived thermomechanical loading cycles. In the present study, the enamel was conditioned only by a self-etching primer, which clearly provided an insufficient and unstable bond between the occlusal veneer restorations and the teeth and therefore resulted in reduced survival rates.

The present study showed that the average final fracture strengths of the tested groups were lower than those reported for the natural unrestored human maxillary premolars 932 N.[16,31] Some studies recorded higher fracture strength than the present study. Yildiz et al[19] reported a higher average fracture strength of 1584 ±238 N for partial coverage crowns made from CAD-CAM lithium disilicate ceramic with an occlusal thickness of 1.5 mm. Clausen et al[8] recorded 4156 N for occlusal veneers with a fissure thickness of 1.5 mm and a cusp thickness of 2.0 mm. Sasse et al[14] reported 2355 N for occlusal veneers with a 0.5-mm fissure thickness and 0.8-mm cusp thickness when bonded to enamel with the self-etching technique. Guess et al[9] recorded fracture strengths of 997 N for occlusal onlays with a thickness of 0.5 mm and 1055 N for a thickness of 1.0 mm. Furthermore, Al-Akhali et al[18] reported not only noticeably high fracture strength for all analogous tested groups but also that thermomechanical fatigue significantly increased the fracture strengths of these groups. The higher survival rate and fracture strength in these studies might be explained by the use of etch-and-rinse technique on enamel,[8,9,18] which clearly played a major role in determining the survival ability of the tested specimens. Also, the use of molar teeth with wider preparation angles, higher ceramic thickness,[8,19] fewer masticatory cycles,[8,14] and lower vertical load[9] may be additional reasons for the high survival rates and high fracture strength reported in the previous studies.

Self-etching primers have a lower ability to etch enamel than etching with phosphoric acid; the proper morphological etch pattern and the positive adhesion effect after using etch-and-rinse technique on enamel have been observed.[25,26] Furthermore, weak and/or thin restorations are noticeably strengthened when luted with a strong adhesive bonding system. Therefore, when firmly bonded to enamel, these weak and/or thin restorations behave in a manner similar to strong and/or thick restorations.[9,13]

The second null hypothesis that no differences in fracture strength would be found between the different dental CAD-CAM materials before or after thermomechanical fatigue was partially rejected. Thermomechanical fatigue significantly influenced the fracture strength of group PI (P=.047) and group PM (P=.025). The change of temperature between 5°C and 55°C for 5500 cycles during the process of thermomechanical fatigue might lead to thermal expansion and shrinkage of the polymer contents in the composition of these 2 groups. This might have accelerated their fatigue during the thermomechanical loading procedure, resulting in a statistically significant decrease in their final fracture strength.[32] However, failed specimens during the thermomechanical fatigue test in groups PI and PM were able to survive more masticatory cycles in comparison with groups LD and LS (Fig. 4). These findings were consistent with previous laboratory studies, which showed that thin occlusal veneers made from CAD-CAM composite resin materials had a significantly higher stepwise loading fatigue resistance than those made from lithium disilicate material.[4,20] As neither study used thermocycling during the fatigue dynamic loading procedures and followed a stepwise loading fatigue from 200 N up to 1400 N at a maximum of 185 000 cycles without testing the specimens under static load, any comparison with the present study is limited.

Comparison among the different tested dental CAD-CAM materials showed that without thermomechanical fatigue, only group PM exhibited a significantly higher fracture strength than group LS. The reason for this result could be the considerable difference in the mechanical properties of the tested restorative materials,[10,12,13] although there were no statistically significant differences among the 4 tested CAD-CAM materials after thermomechanical fatigue loading. This suggests that the bond strength dominates over the differences between the materials. Furthermore, the mechanical behavior of the restored tooth complex, that is, the restorative material, adhesive system, and restored tooth, cannot be easily predicted.[33]

Limitations of the present study that may affect the clinical interpretation of the results included the difficulty in performing an equal amount of enamel layer preparation, the lack of evaluation of wear of the occlusal veneers after the thermomechanical loading, the use of different loading points during dynamic and static loading, the number of specimens tested, the use of water rather than artificial saliva during testing, and the difficulty in replicating clinical conditions.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Thermomechanical fatigue generally decreased the survival rate and final fracture strength of all tested CAD-CAM materials when bonded to enamel using self-etching technique.
2. The self-etching technique cannot be recommended for luting thin minimally invasive occlusal veneers to enamel as the long-term survivability is questionable.

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