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RESEARCH ARTICLE

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Posterior minimally invasive full-veneers: Effect of ceramic thicknesses, bonding substrate, and preparation designs on failure-load and -mode after fatigue

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Abstract

Objective: To evaluate the effect of ceramic thicknesses, bonding surface (enamel vs. dentin), and preparation design (box vs. no box) on the fatigue survival and failure load of minimally invasive full-veneer restorations.

Materials and Methods: Human-premolars ($n = 60$) were divided into five test groups ($n = 12$). All teeth received full-veneer preparation with the following occlusal/labial thicknesses: standard: 1.5/0.8 mm; thin: 1.0/0.6 mm; ultrathin 0.5/0.4 mm. Preparations for each ceramic thickness were refined in enamel (E-1.0 and E-0.5) or dentin (D-1.5, D-1.0, and D-0.5). Control groups DB-1.5, EB-1.0, and EB-0.5 received box preparations. Monolithic lithium disilicate restorations (IPS-e.max-Press, Ivoclar Vivadent) were adhesively cemented (Syntac-Classic/Variolink-II, Ivoclar Vivadent) and subjected to cyclic mechanical loading ($F = 49$ N, 1.2 million cycles) with simultaneous thermocycling (5–55°C). All specimens were exposed to single load-to-failure. Pair-wise differences were calculated by using a linear regression model and Student–Newman–Keuls method ($p < 0.05$).

Results: All full-veneers of group D-1.5, E-1.0, E-0.5, DB-1.5, EB-1.0, and EB-0.5 survived fatigue. Two full-veneers (D-1.0 and D-0.5) revealed cracks during fatigue, resulting in an overall fatigue survival rate of 98.1%. Mean load-to-failure values (*N*) were as followed: 1005 (D-1.5); 866 (D-1.0); 816 (D-0.5); 1495 (E-1.0); 1279 (E-0.5); 1129 (DB-1.5); 1087 (EB-1.0); and 833 (EB-0.5). Irrespective of ceramic thicknesses, enamel-based full-veneers resulted in higher failure loads than dentin-based restorations. Box preparation reduced the failure loads of thin and ultrathin enamel-based restorations.

Conclusion: All tested monolithic lithium disilicate full-veneer restorations exceeded physiological masticatory forces. Minimally invasive full-veneer restorations with

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enamel as a bonding surface and a non-retentive preparation design showed superior performance.

Clinical Significance: Enamel-based non-retentive full-veneers made of monolithic lithium disilicate may serve as a reliable and esthetical minimally invasive treatment option for premolars.

KEYWORDS

ceramic thickness, ceramics, dental bonding surface, fatigue, full-veneer

1 | INTRODUCTION

Loss of dental hard tissue caused by wear and erosion increased significantly over the last years and fostered the development of defect-oriented minimally invasive restorative treatment concepts.[1–3] In the anterior dentition, ceramic laminate veneers have proven to be a reliable, functional, and esthetic treatment option.[4] Occlusal veneers and onlays aim to replace the lost occlusal tooth substance in the posterior region.[5–12] However, when defects additionally involve cervical areas, options are either to perform a full-crown preparation or to add a cervical Class V resin filling to occlusal restorations. Whereas crown preparation requires 63%–72% removal of coronal tooth structures,[13] Class V restorations reveal limited survival and impaired esthetics in the worn dentition.[14] Due to the increased tooth structure removal, full-coverage crowns are correlated with a higher risk of biological failures, such as hypersensitivity and endodontic complications.[15]

As maxillary premolars are visible at an extent of 92%–97% during smiling the restoration of these teeth need to fulfill the highest esthetic requirements.[16,17]

To achieve minimally invasive restorative treatment and excellent esthetics the preservation of the remaining tooth structure is of upmost importance.[18–22] The direct correlation of strength degradation with increased tooth structure removal is well described in the dental literature.[23,24] Hence, complete veneers that cover occlusal, labial, and if necessary proximal areas, so-called full-veneer restorations, evolved as a defect-oriented and minimally invasive alternative to full-coverage crowns.[25–27]

Lithium disilicate (LDS) glass–ceramic manufactured by Press- or Computer-Aided Design (CAD)/Computer-Aided Manufacturing (CAM) technique complies with beneficial esthetic and mechanical properties for single-tooth restorations.[28–31] Moreover, favorable clinical long-term survival and success rates for anterior veneers, posterior inlays, onlays, and crown restorations are reported.[5,32–36] Based on these positive clinical outcomes the manufacturer reduced the recommendation for adhesively cemented LDS crown restorations to 1 mm.[37] More recently, occlusal veneers or table tops were introduced in the molar region as thin onlays with a non-retentive design representing a conservative alternative for conventional full-coverage crowns.[5,38,39]

However, for posterior defect-oriented preparation forms, such as full-veneer restorations with reduced restoration thickness, limited clinical and in vitro data is currently available.[25,26,40]

Preparation geometries for all-ceramic restorations are often derived from the traditional metal-cast—gold preparation guidelines and include retentive elements such as an occlusal box preparation.[41,42] The recommendations for ceramic thicknesses provided by the manufacturer range between 1.0 and 2.0 mm for the occlusal surface and 0.3 and 1.0 mm for the buccal aspect depending on the all-ceramic system.[37,43] Preparation guidelines for defect-oriented posterior full-veneer restorations for premolars still remain sparse.

Up to now, no definitive information on the minimum ceramic thicknesses for premolar full-veneer restorations and their impact on fatigue failure behavior are available.

The dental literature on all-ceramic veneers clearly reports that the risk of failure is significantly increased when preparations expose dentin or when the enamel in the cervical area is lacking.[44–46] Hence, a systematic analysis of the bonding substrate enamel versus dentin appeared as an important factor for the present in vitro study.

Therefore, the aim of this in vitro study was to evaluate the fatigue survival and failure load of standard, thin, and ultrathin full-veneers bonded to enamel or dentin after thermomechanical loading. The hypotheses of the study were that (I) the ceramic thickness (II) the bonding substrate and (III) the preparation of an occlusal/proximal box would not affect the failure load of LDS full-veneer restorations.

2 | MATERIALS AND METHODS

2.1 | Specimen preparation

A total of 60 human maxillary premolars, extracted for therapeutic reasons and free of caries, cracks, or restorations, were stored in 0.1% thymol solution at room temperature. The teeth were randomly divided into five test groups ($n = 12$). The control groups[25] were tested in the identical test set-up (Table 1). All teeth were embedded in a self-curing resin (Technovit 4000; Heraeus Kulzer, Wernheim, Germany). Two silicone impressions (Twinduo; Picodent GmbH, Wipperfürth, Germany) of each tooth were made before preparation. One was sectioned in a buccolingual direction to control tooth substance removal. The other silicone index was used as a mold for the fabrication of the all-ceramic restoration.

Groups differed in restoration thickness (standard: 1.5/0.8 mm; thin: 1.0/0.6 mm; ultrathin 0.5/0.4 mm), bonding substrate (E = enamel; D = dentin), and box preparation (B = Box). Due to the lack of clinical relevance, no group with standard thickness and enamel as a substrate was investigated.

A single experienced prosthodontist carried out all the operative phases for sample preparation. Preparation was performed with diamond burs (no. 878.314.012, 368.314.023; Brasseler, Lemgo, Germany) operating at high speed under the air-water spray and using 4.5-fold optical enlargement. The full-veneer preparation design of the test groups was non-retentive (no occlusal/proximal box preparation) and involved occlusal, labial, and proximal areas in the respective thicknesses (Table 1 and Figure 1A–C). The labial surface received a chamfer finish line in the respective thickness. All teeth of the control groups additionally revealed a mesio-occlusal-distal inlay/occlusal box preparation (Figure 1D–F). The finish line of the mesial and distal box was 1 mm above the cementoenamel junction. All internal cavity margins and preparation angles were rounded (20.000 rpm; no. 8878.314.012, 8368.314.023; Brasseler, Lemgo, Germany). The depth of the preparation was verified with silicone keys and a periodontal probe (Probe UNC# 12 hdL#6; Hu-Friedy, Tuttlingen, Germany).

2.2 | Fabrication of ceramic restorations

Impressions were taken with a silicone material (Affinis; Coltène/Whaledent AG, Altstätten, Switzerland) and type 4 dental stone plaster models (GC Fuji Rock EP; GC Europe N.V., Leuven, Belgium) were made. The monolithic restorations were manufactured from a pressable LDS glass–ceramic (IPS-e.max-Press; Ivoclar Vivadent, Schaan, Liechtenstein) following the manufacturer's instructions. To ensure the specific ceramic thickness, all restorations were checked in wax and before cementation with a caliper (Kroeplin GmbH, Schlüchtern, Germany).

2.3 | Adhesive cementation of ceramic restorations

Prior to adhesive cementation, the intaglio surfaces of the restorations were etched with 4.9% hydrofluoric acid (IPS Ceramic Etchant; Ivoclar Vivadent) for 20 s, thoroughly rinsed with air-water spray and air-dried. A silane coupling agent (Monobond S; Ivoclar Vivadent) was accurately applied for 60 s and afterwards, a bonding agent was added (Heliobond; Ivoclar Vivadent) to the ceramic surface. Phosphoric acid at 37% (Total Etch; Ivoclar Vivadent) was applied on enamel for 30 s and for 15 s on dentin, rinsed with water, and gently air-dried. Subsequently, the Syntac components (Syntac Primer, Syntac Adhesive and Heliobond; Ivoclar Vivadent) were applied according to the manufacturer's instructions. A dual-curing adhesive resin cement (Variolink-II, Ivoclar Vivadent) was subsequently applied, excess cement was removed with foam pellets and LED-light curing (Bluephase C8 with 800 mW/cm^2, Ivoclar Vivadent) was conducted under oxygen protection (Liquid Strip; Ivoclar Vivadent) for 40 s from each surface.

2.4 | Fatigue test

All specimens were subjected to cyclic mechanical loading and simultaneous thermocycling (5–55°C) in a mastication simulator (CS-4.8 professional line; SD Mechatronik GmbH, Feldkirchen-Westerham, Germany). A load of 49 N was applied at a frequency of 1.6 Hz for 1.2 million cycles, which was shown to be equivalent to 5 years of clinical exposure.[47–50] For the simulation of natural mastication, cyclic fatigue was applied by sliding a steatite indenter (Hoechst CeramTec, Wunsiedel, Germany, 6 mm diameter) 0.6 mm (toward the central

TABLE 1 Detailed information on: Group names, ceramic thicknesses, preparation design, and bonding substrates

	Thickness description	Ceramic thickness (occlusal/labial and proximal) (mm)		Box preparation depth/width (mm)		Substrate
Test group name						
D-1.5	Standard	1.5	0.8	–		Dentin
D-1.0	Thin	1.0	0.6	–		Dentin
D-0.5	Ultrathin	0.5	0.4	–		Dentin
E-1.0	Thin	1.0	0.6	–		Enamel
E-0.5	Ultrathin	0.5	0.4	–		Enamel
Control group name						
DB-1.5	Standard	1.5	0.8	3	2	Dentin
EB-1.0	Thin	1.0	0.6	3	2	Enamel
EB-0.5	Ultrathin	0.5	0.4	3	2	Enamel

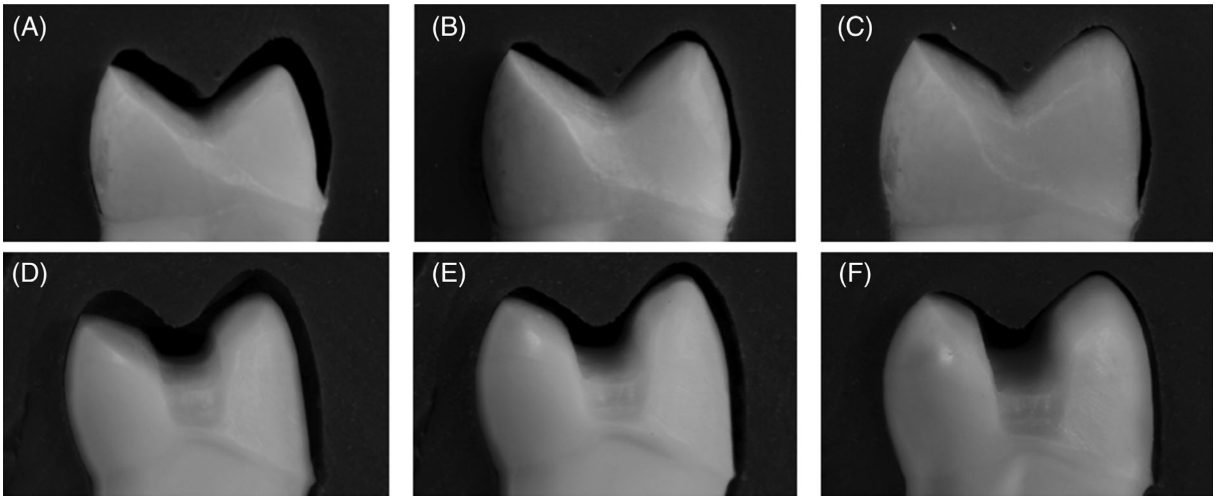

FIGURE 1 Non-retentive full-veneer preparation design with respective silicone keys. (A) Standard (B) thin (C) ultrathin thickness; full-veneer preparation with occlusal and proximal box preparation. (D) Standard (E) thin (F) ultrathin thickness

fissure) down the palatal cusp. During fatigue testing, specimens were inspected for cracks, fractures, or debonding.

2.5 | Load-to-failure

After fatigue, all specimens were subjected to single load-to-failure (SLF) in a universal testing machine (Zwick Z010/TN2S; Zwick, Ulm, Germany) with a steel ball (6 mm diameter; crosshead speed 1.5 mm/min). The indenter was aligned at the same contact point as during fatigue simulation. The specimens were axially loaded until fracture occurred and the maximum load-to-failure was recorded and evaluated with the corresponding software (TestXpert, V 7.1 Zwick).

2.6 | Failure analysis

Fractured surfaces were visually assessed under an optical microscope with a 5- and 10-fold magnification (Carl Zeiss AG, Jena, Germany) and failure modes were classified as follows: (I) Crack formation within the ceramic, (II) Cohesive fracture within the ceramic, intact tooth, (III) Fracture within ceramic and tooth structures, (IV) serious/longitudinal ceramic and tooth fracture involving the root.

2.7 | Statistical analysis

For descriptive evaluation of the data, boxplots were calculated and graphically displayed, stratified by group, thickness, bonding substrate, and preparation design. A linear regression model was used to depict correlations of ceramic thickness, bonding substrate, and preparation detail. The Student–Newman–Keuls method was applied to correct multiple testing. Pair-wise testing was performed by Student's *t*-test. Statistical significance was set at $p < 0.05$. All obtained data were statistically analyzed using the software STATA 13.1 (StataCorp LP, College Station, TX).

3 | RESULTS

3.1 | Fatigue exposure

All specimens of group D-1.5, E-1.0, E-0.5, DB-1.5, EB-1.0, and EB-0.5 survived fatigue. Two full-veneers (1 D-1.0 after 90,629 cycles; 1 D-0.5 after 111,411 cycles) revealed cracks (Figure 2) resulting in an overall fatigue survival rate of 98.1%. No debonding occurred.

3.2 | Singe load-to-failure

The results of the SLF test are presented in Table 2 and graphically displayed in Figure 3.

The ceramic thickness factor was not significant ($p > 0.05$) when full-veneer restorations with the identical bonding substrate (enamel vs. dentin) were compared in a linear regression model (D-1.0/D-1.5 $p = 0.314$; D-0.5/D-1.5 $p = 0.567$; D-0.5/D-1.0 $p = 0.996$; E-0.5/E-1.0 $p = 0.120$; *p*-values corrected by Student–Newman–Keuls method).

The effect of bonding substrate (enamel vs. dentin) was significant for the comparison at identical thicknesses (dotted line; $p < 0.05$; *t*-test) but also at different thicknesses (solid line; $p < 0.05$; linear regression model; *p*-values corrected by Student–Newman–Keuls method). Enamel-based restorations revealed significantly higher failure loads at any investigated thickness when compared to dentin-based restorations.

The preparation design (non-retentive vs. occlusal box) had no significant effect on dentin-based restorations at a standard thickness ($p = 0.3624$) but on enamel-based restorations with thin and ultrathin

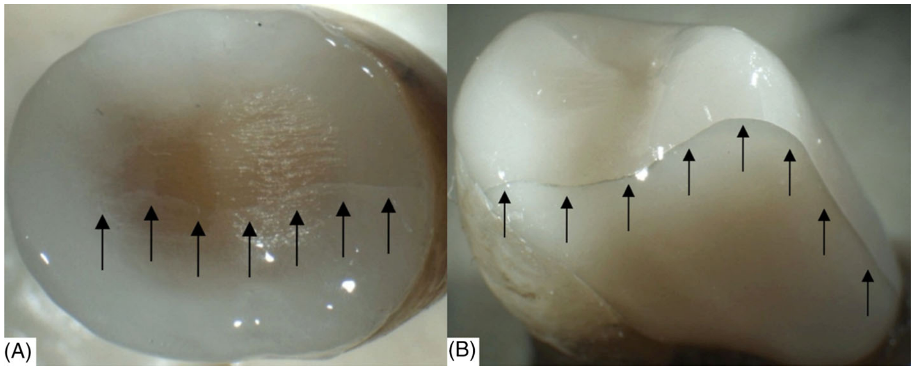

FIGURE 2 Full-veneer restorations after fatigue revealing cracks (black arrows) and wear (A) sample of group D-1.0 (B) sample of group D-0.5

TABLE 2 Failure load results of all tested groups (N = Newton)

Group name	Min	First Qu	Median	Mean	Third Qu	Max	SD
D-1.5	540	743	941	1005	1165	1660	338
D-1.0	571	656	824	866	969	1620	296
D-0.5	511	590	795	866	1105	1460	307
E-1.0	1000	1390	1460	1495	1720	1800	258
E-0.5	479	1037	1305	1279	1650	1830	443
DB-1.5	577	898	1092	1129	1319	1850	357
EB-1.0	675	898	1039	1087	1255	1510	251
EB-0.5	415	651	730	833	963	1627	311

Note: first Qu = 25% of data was below this value; median = 25% of data was below this value; third Qu = 25% of data was below this value.
Abbreviations: Max, maximum; Min, minimum; SD, standard deviation.

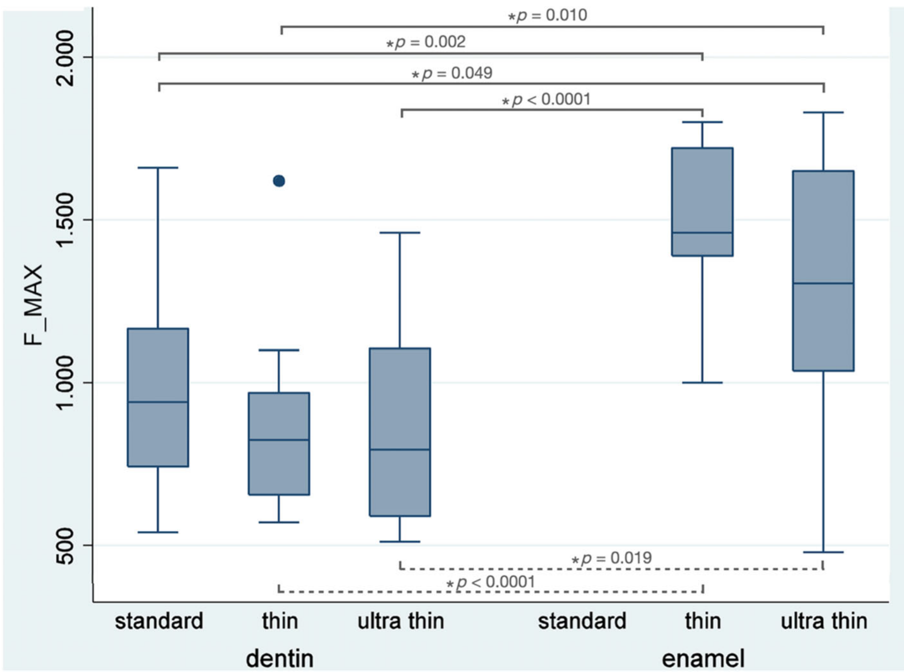

FIGURE 3 Failure load results (N) illustrated as boxplots for full-veneer restorations test groups with non-retentive preparation design. Groups were arranged according to bonding substrate (enamel vs. dentin). Comparison of failure loads with different bonding substrates at identical restoration thickness is displayed by dotted lines. Comparison of failure loads luted to enamel or dentin considering ceramic thickness are displayed by solid lines. Statistically significant differences ($p < 0.05$) are indicated by asterisks

thicknesses ($p < 0.05$) (Figure 4). Non-retentive enamel-based full-veneer restorations revealed significantly higher failure loads at thin and ultrathin thickness when compared to enamel-based restorations at identical thickness but with box preparation.

3.3 | Failure analysis after SLF

Failure mode analysis after SLF testing is given in Table 3. The dominant failure mode of non-retentive dentin and enamel-based full-

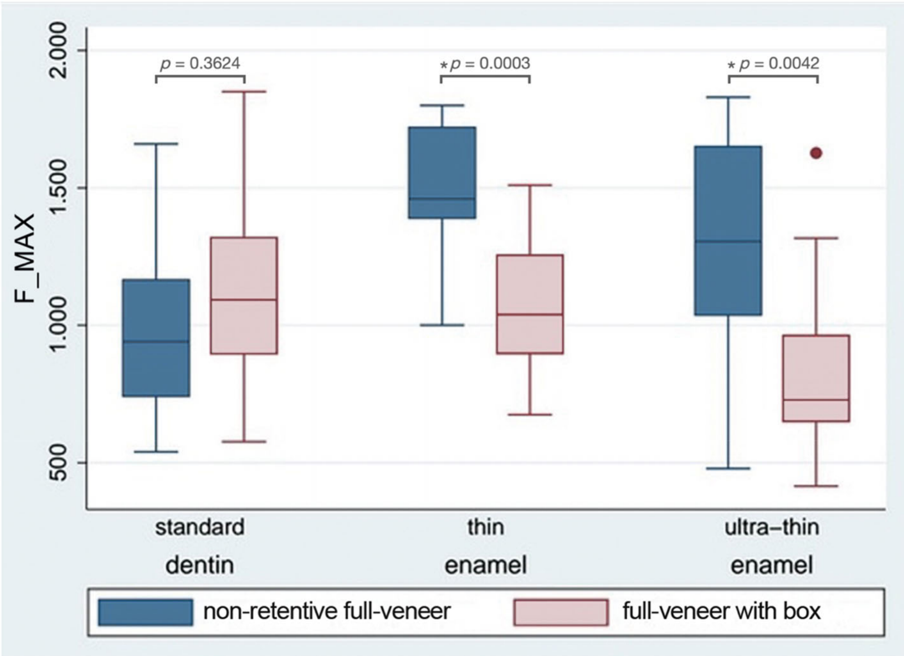

FIGURE 4 Failure load results (N) of full-veneer restorations illustrated as boxplots. Groups were arranged according to the preparation geometry (non-retentive vs. occlusal/proximal box preparation). Comparison of preparation geometries are displayed by solid lines. Statistically significant differences ($p < 0.05$) are indicated by asterisks

TABLE 3 Failure mode description after SLF

	Failure mode (%)			
Group name	I	II	III	IV
D-1.5	41.7	25.0	16.7	16.7
D-1.0	25.0	58.3	0	16.7
D-0.5	0	83.3	16.7	0
E-1.0	0	75.0	0	25.0
E-0.5	0	75.0	0	25.0
DB-1.5	0	37.5	6.25	56.25
EB-1.0	50	31.25	12.5	6.25
EB-0.5	75	12.5	0	12.5

Note: Occurrence of failure modes for each group are given as percentage rate. I: Crack formation within the ceramic, II: Cohesive fracture within the ceramic, intact tooth, III: Fracture within ceramic and tooth structures, IV: serious/longitudinal tooth fracture involving the root.
Abbreviation: SLF, single load-to-failure.

veneer restorations was cohesive fracture within the ceramic material with an intact tooth structure (Type II). The highest number of serious fractures involving the root (Type IV) were observed in dentin-based full-veneer restorations at the standard thickness with box preparation (DB-1.5).

4 | DISCUSSION

This in vitro study investigated all-ceramic full-veneer restorations with various thicknesses and preparation designs adhesively bonded to either enamel or dentin after mouth-motion fatigue. The null hypothesis was partially rejected as the bonding surface (enamel > dentin) and preparation geometry (non-retentive > box preparation) for enamel had a significant effect.

A cumulative 5-year fatigue survival rate of 98.1% was observed in the present in vitro study. A clinical long-term study that investigated occlusal LDS onlays with a thickness of 1.0 mm in the posterior region revealed a survival rate of 100% after 11 years of service.[5] Clinical trials confirmed the long-term success also for anterior veneers with various preparation designs with 97.6% survival for overlap veneers[27] and 100% survival after 7–8 years for full-veneers.[27,33]

Cracks during fatigue only occurred in groups with dentin substrate D-1.0 and D-0.5. No failures were observed in any of the full-veneer restorations with enamel support. The difference in the elastic modulus between the restorative material and the cement/tooth-supporting structure determines the critical load for radial crack initiation.[46] It is well known that enamel presents a higher modulus of elasticity than dentin.[12] Moreover, enamel as a bonding substrate resulted in significantly higher failure loads. The enamel support was also reported as an essential factor for minimally invasive restorations[18,19] with occlusal thicknesses of 0.5–1.0 mm. Moreover, a stronger adhesive bond to enamel than to dentin can be achieved,[2] especially when total-etch protocols are applied.[20,21] Adhesive cementation is reported as an essential factor to increase the mechanical stability of glass–ceramic restorations.[22] This was also confirmed in a clinical split-mouth study with significantly higher survival rates for adhesive resin cements (95.6%–87.8%) compared to self-adhesive cements (75.6%) after 18 months of service.[36] A recent in vitro study recorded also lower survival rates for LDS occlusal veneers bonded with self-etch primers[18] compared to etch-and-rinse systems.[6] In addition to the enamel support, a strong adhesive bonding system is essential for thin all-ceramic reconstructions and provides equal fatigue behavior when compared to thick restorations.[18]

Maximum bite forces of 289–738 N are reported for the natural posterior dentition.[49,50] Irrespective of ceramic thickness, bonding substrate, and preparation geometry all specimens exceeded this threshold.

Regarding LDS veneer restorations, several in vitro studies investigating occlusal veneers with different ceramic thicknesses and substrates, mainly in molars, have been published.[7–9] In one of the studies, the occlusal ceramic thickness was reduced to 0.3–0.6 mm and restorations still revealed load-bearing capacities that are comparable to healthy teeth.[7] An article reviewing preclinical studies concerning CAD/CAM occlusal veneers suggests 0.7–1.0 mm of thickness to be appropriate for LDS occlusal veneers.[23] It was additionally shown that good internal accuracy of LDS occlusal veneers increased their failure load[8] with a superior performance of pressed restorations.[29]

However, preclinical data on premolar restorations is scarce and mostly focuses on occlusal onlays not covering the labial aspect[6,10] or describe labial veneers without covering the occlusal surface.[17] One study investigated different preparation designs in premolars, including occlusal veneers and occlusal veneers with lingual and approximal surface coverage revealing higher fracture strength values compared to full-coverage crown restorations.[11] Thus, direct comparison to other studies is difficult since this non-retentive full-veneer preparation design has not been investigated previously.

Ceramic microstructure, dynamic fatigue loading, fabrication technique, preparation design, and the luting technique affect the fracture strength of all-ceramic restorations.[7,30,40] Limited information on the impact of cavity preparation with respect to stress distribution, tooth strain, fracture resistance, and fracture mode of human premolar teeth restored with all-ceramic onlays is known. An in vitro evaluation on molars showed that conventional cavity preparation with an occlusal and proximal boxes resulted in higher stress concentration in the ceramic restoration and the remaining tooth than the conservative only preparation without occlusal and proximal boxes.[41] The preservation of the remaining tooth structures might be a possible explanation leading to a more favorably stress distribution and fracture resistance.[24] These results are confirmed in the present study where non-retentive preparation design without boxes achieved higher failure loads compared to box preparations.

Failure mode analysis revealed predominantly Type II fractures (cohesive failures within the ceramic without the involvement of the underlying tooth structure) for non-retentive enamel-based and dentin-based thin and ultrathin restorations (E-1.0, E-0.5, D-1.0, and D-0.5). This is consistent with other in vitro studies, where also mainly Mode II failures were observed for thin LDS veneers.[12,17] Cohesive fractures can be explained by the concentration of tensile stresses within the brittle all-ceramic restoration itself.[31] For standard thickness dentin-based (D-1.5) and enamel-based specimens with box preparations (EB-1.0 and EB-0.5) mainly Type I failures with extensive cracks within the ceramic were recorded. Catastrophic and serious failures with involvement of the tooth (Type IV) were primarily observed in dentin-based standard thickness restorations with box preparation (DB-1.5). This can be attributed to the more extensive preparation design and removal of tooth structure with dentin exposure.[25]

As a limitation of this study, the results are applicable only to the investigated all-ceramic and luting system. Moreover, since human teeth were used, a certain lack of standardization regarding storage time, hard tissue thickness, and morphological variance among teeth remains.

To the author's best knowledge, this is the first study, which systematically investigated the non-retentive full-veneer preparation design at different thicknesses on premolars after fatigue.

Tooth wear, caused by extrinsic and intrinsic causes, such as erosion, and the associated loss of the vertical dimension (VDO) is increasing, especially in young adults with high esthetic demands.[3] The restoration design of the present full-veneer can be indicated, wherever the occlusal and labial/cervical tooth surfaces need to be restored in a minimally invasive way. The oral tooth surface remains unprepared. The described full-veneer restoration offers a treatment option for premolars with several single-surface lesions and forms a minimally invasive alternative to complete coverage crown restoration. However, it might need to be further investigated if a MOD composite core build-up has an influence on the fatigue behavior. First studies on occlusal LDS veneers adhesively bonded to enamel-framed composite fillings showed no negative effect on failure load, when pretreated appropriately.[39]

Therefore, minimally invasive non-retentive LDS full-veneer restorations with reduced thicknesses, especially adhesively cemented to enamel, revealed high failure loads and can be a viable treatment option for occlusal and labial/cervical defects, in particular for maxillary premolars. The results of this in vitro study should be further confirmed by clinical studies.

5 | CONCLUSIONS

All tested monolithic LDS full-veneer restorations exceeded physiological masticatory forces. Enamel as a bonding surface resulted in significantly higher failure loads regardless of restoration thickness. Minimally invasive non-retentive preparation designs without occlusal/proximal box preparation showed superior performance.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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