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ORIGINAL ARTICLE

Monolithic and bi-layer CAD/CAM lithium–disilicate versus metal–ceramic fixed dental prostheses: Comparison of fracture loads and failure modes after fatigue

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Abstract
Objectives The authors analyzed the effect of fatigue on the survival rate and fracture load of monolithic and bi-layer CAD/CAM lithium–disilicate posterior three-unit fixed dental prostheses (FDPs) in comparison to the metal–ceramic gold standard.
Materials and methods The authors divided 96 human premolars and molars into three equal groups. Lithium–disilicate ceramic (IPS-e.max-CAD) was milled with the CEREC-3-system in full-anatomic FDP dimensions (monolithic: M-LiCAD) or as framework (Bi-layer: BL-LiCAD) with subsequent hand-layer veneering. Metal–ceramic FDPs (MC) served as control. Single-load-to-failure tests were performed before and after mouth-motion fatigue.
Results No fracture failures occurred during fatigue. Median fracture loads in [N], before and after fatigue were, respectively, as follows: M-LiCAD, 1,298/1,900; BL-LiCAD, 817/699; MC, 1,966/1,818. M-LiCAD and MC FPDs revealed comparable fracture loads and were both significantly higher than BL-LiCAD. M-LiCAD and BL-LiCAD both failed from core/veneer bulk fracture within the connector area. MC failures were limited to ceramic veneer fractures exposing the metal core. Fatigue had no significant effect on any group.
Conclusions Posterior monolithic CAD/CAM fabricated lithium–disilicate FPDs were shown to be fracture resistant with failure load results comparable to the metal–ceramic gold standard. Clinical investigations are needed to confirm these promising laboratory results.
Clinical relevance Monolithic CAD/CAM fabricated lithium–disilicate FDPs appeared to be a reliable treatment alternative for the posterior load-bearing area, whereas FDPs in bi-layer configuration were susceptible to low load fracture failure.

Keywords FDP · CAD/CAM · Lithium–disilicate · Metal–ceramic · Fatigue · Fracture load

Introduction

Since decades, three-unit fixed dental prostheses (FDPs) represent the treatment option of choice to restore function and aesthetics, after loss of a single tooth when implants cannot be placed due to anatomic restrictions. Long-term clinical data on metal–ceramic FPDs are available and reveal excellent survival rates even after observation periods exceeding 10 years [1].

Lately, all-ceramic materials are of growing importance in restorative dentistry, as they offer superior aesthetics due to their tooth-like color and translucency, high biocompatibility, and are of lower cost compared to precious alloys [2].

With the introduction of advanced computer-aided manufacturing/computer-aided design (CAD/CAM) technologies various high-strength ceramic materials evolved and are increasingly used for anterior and posterior FDP indication.

Owing to a transformation toughening mechanism yttria-stabilized tetragonal zirconia polycrystalline (Y-TZP) frameworks exhibit unsurpassed mechanical properties reflected by high survival rates in clinical application [3]. However, fractures within the veneering ceramic have been described

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as the most frequent mode of clinical and laboratory failure [3, 4].

Given the reported high veneer failure rates with zirconia-based FDPs, high-strength glass–ceramic systems in monolithic and bi-layer application have regained increased consideration for anterior and posterior restorations [5–8].

Lithium–disilicate ceramic (IPS Empress II, Ivoclar Vivadent, Schaan, Liechtenstein) using the lost-wax press technique was introduced in 1998 as an enhanced glass–ceramic system for single tooth and anterior three-unit FDP restorations. Although this all-ceramic system was very successful in anterior and posterior crown indication [9], heterogeneous survival rates ranging from 50 % after 2 years [10] to 70 % after 5 years [11] were reported for bi-layer FDP application.

Therefore IPS e.max Press (Ivoclar Vivadent, Schaan, Liechtenstein) was released to the market in 2001 with significantly improved mechanical and optical properties. Higher translucency and augmented shade variety enabled this lithium–disilicate glass–ceramic material in posterior indication for monolithic full-anatomic restoration fabrication with subsequent staining characterization. A promising survival rate of 87.9 % after 10 years has been reported for monolithic posterior three-unit FDP application [12].

Most recently, a CAD/CAM fabricated version of the lithium–disilicate glass–ceramic (IPS e.max CAD) was designed. Since only very limited data is available on this CAD/CAM lithium–disilicate ceramic system, a preclinical study on the in vitro performance with respect to fatigue is expected to provide valuable information on its long-term behavior in posterior FDP indication. Therefore the aim of our laboratory study was to evaluate the effect of fatigue on failure modes and fracture resistance of three-unit FDPs. A CAD/CAM lithium–disilicate ceramic system in (1) monolithic (full anatomic) and (2) bi-layer (core and veneering ceramic) configuration will be compared to the metal–ceramic gold standard.

The null hypotheses were that the investigated materials showed (1) equal failure loads but (2) different failure modes.

Materials and methods

Ninety-six extracted caries free natural human mandibular teeth (48 premolars, 48 molars), served as abutment teeth for three-unit FDPs and were randomly assigned into two test groups and one control group of 16 samples each. The Albert-Ludwig-University of Freiburg, Ethics Committee ruled that approval was not needed for use of unidentified and pooled extracted teeth for research purposes. Throughout the study all teeth were stored in 0.1 % thymol solution at room temperature. To imitate the physiological tooth mobility, roots were covered with an artificial periodontal membrane of a 0.25-mm thick layer of gum resin (Anti-Rutsch-Lack, Wenko Wenselaar, Hilden, Germany). Teeth were positioned pair-wise and embedded in a self-curing polyester resin (Technovit 4000, Hareus Kulzer, Wehrheim, Germany) with a proximal distance of 11 mm between the teeth, representing a molar gap. The preparation design included a 1.2-mm deep chamfer margin with an occlusal reduction of 2 mm and a total convergence angle of 6°. Preparation depth was verified by a silicone index. Impressions of the prepared teeth were taken with a simultaneous, dual-mix technique, using a polyvinyl-siloxane impression material (DimensionGarant L/Permadyne, 3M ESPE, Seefeld, Germany).

Fully anatomically shaped IPS e.max CAD FDPs (Testgroup M-LiCAD) and IPS e.max CAD FDP cores (Testgroup BL-LiCAD) were designed and milled with a CAD/CAM system (CEREC, 3D/InLab, Sirona, Germany) from presintered blocks (IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein). M-LiCAD FDPs revealed connector sizes of 4×6 mm. Increased vertical connector size dimensions were developed based on clinical experiences [11]. BL-LiCAD core substructures revealed an abutment thickness of 0.5 mm and connector sizes of 4×4 mm (manufacturer’s recommendation).

Final sintering of IPS e.max CAD restorations was performed after the milling procedure following the manufacturer’s instructions. Cores of the metal–ceramic control group MC were waxed-up with a minimum thickness of 0.4–0.5 mm and with connector dimensions of 3×1.5 mm (manufacturer’s recommendation). A Ni-Cr-Mo alloy (4all, Ivoclar Vivadent, Schaan, Liechtenstein) was used to cast the cores according to manufacturer’s guidelines. The cores of group BL-LiCAD and MC were veneered using the hand-layering technique (BL-LiCAD: IPS e.max Ceram, Ivoclar Vivadent, Schaan, Liechtenstein, group MC: IPS Classic, Ivoclar Vivadent, Schaan, Liechtenstein) according to the manufacturer’s guidelines. Glazing with a standard cooling procedure was applied as the final treatment for all groups. During the manufacturing process various jigs were used to standardize the dimensions of the final veneering ceramic.

The alloy surfaces of group MC were pretreated with the Rocatec system (3M Espe, Seefeld, Germany) and silanized (Espesil, 3M Espe, Seefeld, Germany) MC FDPs were conventionally cemented (Vivaglass CEM, Ivoclar Vivadent, Schaan, Liechtenstein).

The inside of the M-LiCAD and BL-LiCAD FDP restorations were etched with 5 % hydrofluoric acid (IPS ceramic etching gel, Ivoclar Vivadent, Schaan, Liechtenstein, 20 s), covered with a silane-coupling agent (Monobond S, Ivoclar Vivadent, Schaan, Liechtenstein) and were then adhesively bonded onto the abutment teeth using a dual-curing resin cement (Variolink II, Ivoclar Vivadent, Schaan, Liechtenstein). The dentin adhesive system Syntac classic (Ivoclar Vivadent, Schaan, Liechtenstein) was applied. All cementation procedures followed the manufacturer's instructions.

Eight of 16 specimens in each group were exposed to 1.2 million cycles of thermo-mechanical fatigue in a computer-controlled chewing simulator (Willytec, Munich, Germany) under clinically relevant conditions. A load of 49 N was applied in the center of the occlusal surface of the FDP pontic using a ceramic antagonist ball (r=3 mm, Steatit, Hoechst Ceram Tec, Wunsiedel, Germany) [13]. A sliding load with a vertical movement of 6 mm, a horizontal movement of 0.5 mm, and a frequency of 1.6 Hz was applied. Simultaneously, specimens were subjected to thermocycling between 5 and 55 °C for 60 s each with a dwell time of 12 s, maintained by a thermostatically controlled liquid circulator (Haake, Karlsruhe, Germany). In total 5,208 thermo-cycles were performed.

Specimens were mounted in a universal testing machine (Zwick Z010/TN2S, Ulm, Germany) and load to fracture was applied at 2 mm/min through a steel indenter (r= 3.18 mm) on the occlusal central fossa of the FDP pontic. To prevent local stress concentrations, a 1-mm thick tin foil was placed between the load indenter and the test specimen. Loading values were calculated and evaluated with a software (Zwick test Xpert V7.1, Zwick, Ulm, Germany)

Results of the load to fracture test were presented using box plots. Statistical analysis of the fracture load was performed with the Wilcoxon–Mann–Whitney test. A family-wise level of significance of 0.05 was obtained with the method of Bonferroni–Holm.

Results

Fatigue survival rate

None of the FDPs revealed failures in the form of chip or bulk fracture during fatigue, resulting in a 100 % fatigue survival rate.

Fracture load

Fracture load values of all FDPs before and after fatigue are depicted in Fig. 1. Before and after fatigue lowest fracture load values [N] occurred in the BL-LiCAD group (534/390), whereas the highest value was observed in the MC group (2,976/2,531). Statistics for group and level comparisons are presented in Table 1. Irrespective of fatigue application M-LiCAD and MC FDPs revealed comparable fracture load values, that were significantly higher than those notified for BL-LiCAD FDPs (Table 1). The applied fatigue protocol had no significant effect on any of the tested materials (Table 1).

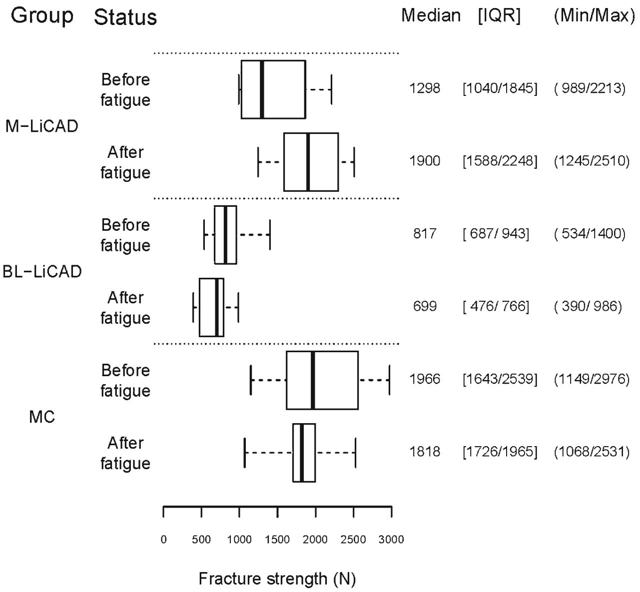

Fig. 1 Box plots of the load to failure test results in newtons [N]. *M-LiCAD* monolithic lithium–disilicate FDPs, *BL-LiCAD* bi-layer lithium–disilicate FDPs, *MC* metal–ceramic FDPs

Ceramic failure modes

M-LiCAD (Fig. 2) and BL-LiCAD (Fig. 3) both failed from ceramic bulk facture within the connector area. Chip-off fractures, only, were neither observed within the LiCAD ceramic of M-LiCAD FDPs nor within the veneering ceramic of the BL-LiCAD FDPs. In the BL-LiCAD group bulk fracture failure affected both, the veneering ceramic and the LiCAD core ceramic.

MC failures were limited to ceramic veneer chip-off fractures exposing the metal core (Fig. 4). Metal core fractures were not observed.

Discussion

Posterior restorations are subject to a demanding environment of repetitive contact load in aqueous solutions. Therefore in vitro simulations and laboratory tests were developed to investigate new dental materials, indications, and to predict lifetimes and failures [14–16]. Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. As fatigue is a significant factor limiting the lifespan of all-ceramic restorations it represents a prerequisite for valid in vitro testing [17]. Hence the main requirement for a realistic fatigue chewing simulation device is the ability to simulate human masticatory parameters. Presently, there are no internationally accepted standards of loading parameters for dynamic loading of all-ceramic restorations in chewing simulators [18]. Physiological bite forces in the human mouth show a high

Table 1 Results of fracture load comparisons

Group 1	Group 2	Level	Raw p value	Bonferroni–Holm adjusted p value
M-LiCAD	BL-LiCAD	Before fatigue	0.0047	0.0280
M-LiCAD	MC	Before fatigue	0.0650	0.3248
BL-LiCAD	MC	Before fatigue	0.0003	0.0022
M-LiCAD	BL-LiCAD	After fatigue	0.0002	0.0014
M-LiCAD	MC	After fatigue	0.9591	1.0000
BL-LiCAD	MC	After fatigue	0.0002	0.0014
Before fatigue	After fatigue	M-LiCAD	0.0830	0.3319
Before fatigue	After fatigue	BL-LiCAD	0.1605	0.4816
Before fatigue	After fatigue	MC	0.6454	1.0000

Raw p values from Wilcoxon–Mann–Whitney test, and adjusted p values according to Bonferroni–Holm. Family-wise level of significance, 0.05

variability among individuals and range between 10 and 120 N during chewing of food or swallowing [19–23]. Maximum forces are considerably higher and range from 200 to 360 N in the molar region [15,24–26]. Hence the fatigue protocol of the present study included a cyclic load of 49 N that was applied for 1.2 million cycles. These parameters are reported to correspond to a simulated clinical service time of 5 years [27]. Several in vitro studies used these test parameters for evaluating the fracture resistance of FDPs after fatigue [28,29].

The resistance of fracture of FDPs is depending on various factors such as the material type for framework and veneering as well as on connector dimensions [30]. Moreover, core veneer thickness ratios, design, processing conditions as well as elastic and mechanical properties affect the fracture resistance of multilayered restorations [31].

The presently investigated monolithic CAD/CAM lithium–disilicate FDPs (median, 1,900 N) showed fracture failure at comparable load levels to the metal–ceramic gold standard (median, 1,818 N) and therefore appeared to be as fracture resistant. Both obtained median fracture load values after fatigue exceeded posterior physiologic chewing forces by a substantial margin.

By contrast hand-layer veneered CAD/CAM lithium–disilicate FDPs revealed very limited median fracture load values after fatigue (699 N). These results are comparable to previous findings for veneered pressable lithium–disilicate FDPs, tested using identical methodologies (IPS Empress II, 928 N) [28]. As the 25th percentile of BL-LiCAD FDPs (476 N) is in the lower range of physiologic chewing forces, low load fracture failures can be expected under clinical circumstances. These laboratory results on bi-layer FDPs are in accordance with clinical findings on IPS Empress II FDPs, revealing high fracture rates of 50 % after a 2-year observation time [10].

The first null hypothesis that the investigated materials showed equal failure loads has to be rejected in parts.

The higher fracture resistance of the full-anatomic CAD/CAM lithium–disilicate FDPs can be predominately attributed to the monolithic application of the presented material [12,32]. As no veneer was applied, the thickness of the CAD/CAM lithium–disilicate FDPs was significantly higher in all dimensions as compared to bi-layer FDP restorations. Due to this design configuration, cyclic loading during fatigue was directly applied on the high-strength CAD/CAM lithium–disilicate ceramic (360 MPa). Related to the micro-structural characteristics, such as volume fraction, size, and distribution of the second-phase particles and chemical composition of the glassy matrix, all-ceramic materials reveal different behaviors in terms of susceptibility to slow crack growth. A high volume fraction of crystalline phases such as lithium–disilicate elongated crystals

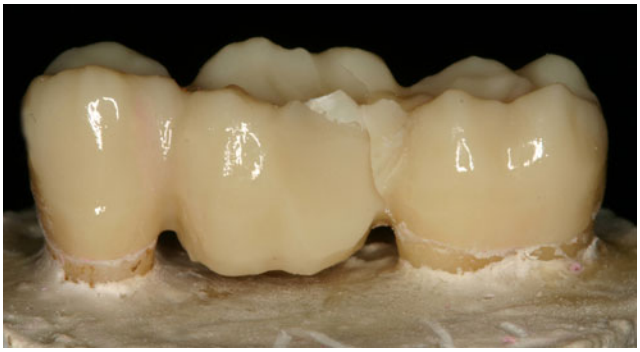

Fig. 2 Ceramic bulk fracture at the distal connector of a M-LiCAD FDP

Fig. 3 Ceramic bulk fracture at the distal connector of a BL-LiCAD FDP

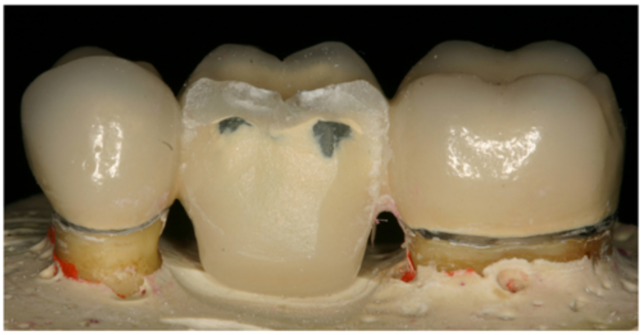

Fig. 4 Cohesive fracture within the veneering ceramic of a MC FDP exposing the metal core

dispersed in their glassy matrix can form a potent barrier to slow crack propagation, compared to low and high fusing veneering ceramics. The higher mean particle length and the higher shape factor, result in an increased crack deflection toughening mechanism [33].

In contrast to that, low-strength veneering materials (IPS e.max Ceram: 90 MPa) are prone to fail at low loads during the evolution of complex tensile fields in function. It is well known that the load to cause bulk fracture increases as the square of the thickness increases [34]. FEA studies additionally confirmed, that deleterious tensile stresses are significantly lower with full-anatomic FDP restorations (336 MPa) as compared to reduced framework designs (670 MPa) [31]. Therefore the occlusogingival connector dimensions should be extended to maximum to ensure mechanical stability. However, under clinical circumstances required connector dimensions are often limited by the available anatomical conditions, such as abutment tooth height, surrounding gingival tissue, and the opposing dentition. Moreover, a gingival embrasure must be maintained to provide access for oral hygiene and to avoid iatrogenic periodontal inflammation. Additionally, increased connector dimensions are commonly related to bulky appearance of the labial aspect and compromise aesthetics [12,35].

Due to the industrialized fabrication of the CAD/CAM lithium–disilicate blanks and its microstructure, containing fine-grain lithium–disilicate crystals embedded in a glassy matrix, this ceramic reveals a high homogeneity with minimal inherent flaws as compared to the hand-layer veneering ceramic of the bi-layer FDPs. A high Weibull modulus and increased reliability as well as augmented characteristic strength have been recently reported for this CAD/CAM lithium–disilicate ceramic system [6,36].

Fatigue loading in the artificial oral environment did not result in a significant reduction in the fracture strength values in neither of the monolithic or bi-layer CAD/CAM lithium–disilicate nor in the metal–ceramic FDPs.

The second null hypothesis that the investigated materials showed different failure modes has been accepted in parts.

Failure mode analysis of monolithic or bi-layer CAD/CAM lithium–disilicate FDPs revealed that failures occurred from crack initiating from the lower surface of the connector ultimately leading to bulk fracture. Identical connector bulk fracture failures were observed in clinical studies on veneered IPS Empress II FDPs (50 % connector bulk fracture after 2 years [10]) and with monolithic IPS e.max Press FDPs (12.1 % connector bulk fracture after 10 years [12]). Fractographic analyses on clinically fractured veneered IPS Empress II FDPs and monolithic IPS e.max Press FDPs confirmed that failure initiation was located in the lower side of the connector area [5]. Chip-off fractures were reported at a significant lower level for monolithic and bi-layer FDP (5.5 and 6.1 % after 6 and 10 years [12,37] and for crown indications (3.3 % after 9 years [38]). No clinical data on IPS e.max CAD FDPs is currently available for comparison. IPS e.max CAD is not yet recommended for FDP indication by the manufacturer.

Due to the escalating costs of high precious alloys and their thus decreasing application, a Ni-Cr-Mo alloy was chosen as framework material for the control group in the present study. Moreover, in vitro data on the effect of substructure properties on the longevity of metal–ceramic specimens showed, that veneering ceramics applied on a higher modulus core (non-precious alloy) fractured chiefly from occlusal surface damage, whereas veneering ceramics placed on low modulus (gold infiltrated) alloys were vulnerable to both occlusal surface damage and veneer lower surface radial facture [39]. Metal–ceramic restorations have an inherent stress absorbing mechanism in the metal substructure that limits crack propagation [40], which explains the superior performance of this system compared to the bi-layer all-ceramic system (BL-LiCAD). Fracture failure modes that were limited to the veneering ceramic exposing the metal core were confirmed by clinical observations [41,42]. Hence, it can be concluded that the present in vitro test set-up was able to provide clinical relevant failure modes. According to the recently described classification of veneer fracture failures, the metal–ceramic veneer fractures observed in the present study would require replacement of the affected prostheses as the fracture surface extends into a functional area and repair is not feasible [41,42].

From an economic point of view traditional veneering methods such as the powder layering technique appear to be inefficient. Due to a partial crystallization technology of the investigated CAD/CAM lithium–disilicate ceramic, restorations are processed in an intermediate phase which enables fast machining in a milling device. Hence CAD/CAM processing of fully anatomically designed FDPs can lead to a significant reduction in fabrication time.

Conclusions

- Monolithic CAD/CAM generated lithium–disilicate FDPs with the investigated connector dimensions revealed high failure loads after fatigue and can be considered for selected posterior FDP indications. Bilayer CAD/CAM generated lithium–disilicate FDPs were susceptible to low-load fracture failure and can therefore not be recommended for posterior FDP indication.
- Further laboratory and clinical investigations are needed to confirm the presented results.

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The authors declare that they have no conflict of interest.

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