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Fatigue resistance of ultrathin CAD/CAM ceramic and nanoceramic composite occlusal veneers

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ABSTRACT

Objective. The fracture resistance of different ultrathin occlusal computer-aided design/computer-aided manufacturing (CAD/CAM) veneers was investigated under cyclic mechanical loading to restore combined enamel-dentin defects.

Methods. Eighty-four molars were reduced occlusally until extensive dentin exposure occurred with a remaining enamel ring. Twenty-four molars were ground flat for examination of highly standardized specimens, of which 8 were treated with uniformly flat 0.3 mm IPS Empress CAD and 0.3 and 0.5 mm IPS e.max CAD restorations. Sixty-four molars were anatomically prepared until dentin exposure and were restored using occlusal veneers with fissure/cusp thicknesses of 0.3/0.5 mm from 3 different dental CAD/CAM materials: IPS Empress CAD, IPS e.max CAD and Lava Ultimate CAD/CAM. Teeth were etched with 37% phosphoric acid, and occlusal veneers were bonded using an adhesive luting system (Syntac Primer, Adhesive, Heliobond and Variolink II). Specimens were placed under cyclic mechanical loading in a chewing simulator (1 million cycles at 50 N) and were examined for cracks after each cyclic loading sequence. The anatomical 0.3/0.5 mm IPS e.max CAD specimens experienced an additional 1 million cycles at 100 N. Kaplan–Meier survival curves and log-rank tests were used for data analysis.

Results. All highly standardized and 0.3/0.5 mm IPS e.max CAD specimens tolerated cyclic loading. One anatomical Lava Ultimate CAD/CAM and 10 IPS Empress CAD specimens showed cracks.

Significance. Ultrathin occlusal veneers of lithium disilicate ceramic and nanoceramic composite showed remarkably high fracture strength under cyclic mechanical loading. These veneers might be a tooth substance preserving option for restoring combined dentin–enamel defects.

1. Introduction

Erosive tooth wear has been of minor importance to clinical dentistry and dental research for many years [1]. With increasing tooth survival in the 21st century, this pathological loss of the tooth structure continues to gain importance [2]. Lussi et al. found in a population of Swiss adults 29.9%

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occlusal erosion involving dentin in 26- to 30-year-old patients and 42.6% in 46- to 50-year-old patients [3]. Khan et al. determined a linear relationship between the number and size of erosive lesions and the age of the patients [4]. However, the prevalence of erosion in younger patients has also increased significantly [5]. This pervasiveness could be explained by changed lifestyles and the amount and frequency of the consumption of acidic foods and drinks [1]. In the US alone, soft drink consumption increased by almost 300% in 20 years [6] and O'Sullivan and Curzon showed that there is an association between the presence and progression of erosion and four or more acid intakes per day in the absence of other risk factors [7].

Treatment of severe erosions depends on the size and extension of the defect and should be minimally invasive where possible [8]. However, these tooth hard tissue defects often reach the dentin, resulting in vertical bite height loss, which can lead to interferences of the anterior teeth with enamel chipping of the incisal edges, cervical defects and overloading in the periodontium [9]. These issues lead to a necessary reconstruction of the larger defects with direct composite restorations, occlusal veneers or partial crowns [8]. Direct composite restorations are less expensive than labside restorations, but are much more time-consuming and strenuous, as the entire occlusion must be modelled by hand. Alternatively, composite restorations can also be made by injection moulding with a wax-up and laboratory-fabricated transfer splints [10,11]. The fabrication of occlusal veneers should also be considered, as their occlusion can be correctly pre-adjusted from the labside. In addition to ceramic materials, composites are now also available for the indirect rehabilitation of posterior occlusal surfaces [12]. In contrast to composites, ceramic occlusal veneers also have advantages in terms of abrasion resistance, wear, biocompatibility and colour stability. Demanding a minimum thickness of 1.5–2 mm for occlusal veneers by the ceramic manufacturers or even only 1 mm for IPS e.max (CAD) (Ivoclar Vivadent, Schaan, Liechtenstein) restorations, the additional tooth substance removal outlines an issue [13–16].

Due to the development of non-prep veneers in the anterior region, which require only up to 0.3 mm minimum layer thickness, a question arises as to whether modern high-performance ceramics with an ultrathin layer thickness can also be used in the posterior region to restore larger erosion defects without sacrificing further tooth substances. Due to the adhesive attachment to enamel, anterior veneers perform well despite the low ceramic thickness, and fractures rarely occur, even if the bending loads in the anterior region favour them [17]. In severe occlusal abrasion or erosion, dentin is already exposed, and a circular enamel margin borders the defect. This occurrence represents the hardest possible condition for an adhesively bonded occlusal veneer. The high modulus of elasticity of enamel contributes to the stabilization of a restoration attached adhesively to it since the deflection values of the restoration are lower than with pure dentin attachment. In addition, the adhesive bond between the restoration and enamel is more resilient than that between the restoration and dentin. The remaining enamel provides an excellent adhesive bond, and the thicker enamel portion could increase the stability of the remaining tooth, allowing the restoration to be thinner while maintaining the same load-bearing capacity [18].

The mechanical properties of the restoration materials have been improved in recent decades, as have adhesive luting materials (dentin adhesives and luting composites). The combination of the higher mechanical strength of modern materials with a minimally invasive preparation raises the question of how this affects the long-term stability of the restoration. Ceramics and composites are both materials that are available for the indication of occlusal veneers. Due to significant differences in the mechanical properties of these materials, it should also be examined as to whether these differences influence the survival probability of ultrathin occlusal veneers that are adhesively bonded to dentin and the circular enamel margin.

This study should answer the question of whether ultrathin ceramics with an adhesive attachment to dentin and a circular enamel margin can be considered a treatment option for the reconstruction of erosive defects. To investigate this question, the simulation of subcritical cyclic mechanical loads in a chewing simulator was chosen. In addition, materials with differing moduli of elasticity and viscoelastic properties were selected to consider a wide range of mechanical properties in the simulation.

2. Materials and methods

The tested materials should be usable with as little effort as possible and should differ substantially in their material science properties. For this reason, three different materials were tested. The first material selected was IPS Empress CAD (Ivoclar Vivadent, Schaan, Liechtenstein), a leucite glass ceramic that has been used successfully in our dental clinic since 1992 and was therefore used as a reference. As a second material, IPS e.max CAD (Ivoclar Vivadent, Schaan, Liechtenstein), a lithium disilicate ceramic, was chosen because it is currently the most fracture-resistant glass ceramic for the indication of partial crowns, inlays and onlays [19,20]. Lava Ultimate CAD/CAM (3M ESPE, Seefeld, Germany), a nanoceramic composite, was used as the third material since it is now available for the aforementioned indications and has advantages in terms of the wear of the antagonists as a composite.

Eighty-four extracted caries- and crack-free human molars, within the limitations of the biological variance and, as far as possible, equal in the form and dimensions of the clinical crown, were cleaned and stored in sodium azide. The Ethics Committee of the Medical Faculty of the Ludwig-Maximilians University of Munich approved the use of unidentified pooled human teeth (approval no. 003-14).

The teeth were divided into two groups. For the simulation of the fatigue behaviour with highly standardized plane specimens, 24 teeth (8 of each material) were selected. For clinically relevant simulations, 60 teeth were used (20 of each material). The roots were removed at the cementoenamel junction. To embed all specimens at the same height, silica-modified aluminium oxide (Rocatec Pre, 110 μm, 2.8 bar; 3M ESPE; Seefeld, Germany) blasted Willytec sample holders (Willytec GmbH, Gräfelfing, Germany) were placed together with the teeth in a self-constructed fixture. All specimens were embedded with an auto-polymerizing resin (Technovit 4000, Heraeus Kulzer GmbH & Co. KG, Hanau, Germany).

2.1. *Preparation of the highly standardized plane specimens*

To determine the minimum thickness of the specimens with acceptable fatigue strength, the thinnest possible ceramic discs were initially manufactured and tested. The original intention was to increase the thickness until a sufficient number of specimens survived the mechanical stress without fracture. Molars were ground flat with 180-grit silicon carbide grinding paper under permanent water cooling (wet grinding and polishing system, LECO VP100, Saint Joseph, USA). In all teeth, the dentin was extensively exposed occlusally, and enamel was only present circularly. In this way, grade 3 erosion defects were simulated, corresponding to a worst-case simulation (basic erosive wear examination >50% enamel loss, occlusal) [21].

For each of the two different ceramic types (IPS e.max CAD, IPS Empress CAD), eight platelets with a minimum possible thickness of 0.3 mm were cut with a saw microtome (Leica SP 1600; Leica Biosystems, Nussloch, Germany) from ceramic blocks. All platelets were polished with 320, 800, 1000, 2500 and 4000 grit silicon carbide grinding papers. IPS e.max CAD platelets were crystallized in a ceramic furnace. For the IPS Empress CAD ceramics, eight additional specimens with thicknesses of 0.5 mm were made. All materials used are listed in Table 1.

2.2. *Preparation of the clinically relevant specimens*

Sixty molars were anatomically reduced at the occlusal surface, imitating grade 3 erosion and abrasion defects. The preparation was conducted with an egg-shaped diamond bur (46 μm diamond grit size, 8379.314.018, Gebr. Brasseler GmbH & Co. KG, Lemgo, Germany). A 0.3–0.5 mm layer of occlusal indicator wax, equivalent in form and size to the later restoration, was placed on the preparation and scanned with CEREC Bluecam (Sirona Dental GmbH, Wals, Austria) using scan spray (scan‘dry, Dentaco GmbH & Co. KG, Essen, Germany). After removing the indicator wax, the anatomically prepared molars were scanned a second time. The restorations were designed with CEREC Software 4.1 (Sirona Dental GmbH, Wals, Austria) while setting the restoration type to “Inlay/Onlay” and the design mode to “Biogeneric Copy”. The suggested restoration was manually individualized to a 0.3–0.5 mm thickness and milled with a CEREC milling and grinding unit (Sirona Dental GmbH, Wals, Austria) from IPS e.max CAD, IPS Empress CAD and Lava Ultimate CAD/CAM blocks. This corresponds to the minimum layer thickness that can be produced; otherwise, the samples will break during production. IPS e.max CAD restorations were crystallized in a ceramic furnace. All ceramic restorations were polished under water cooling with zirconium oxide polishers (Gebr. Brasseler GmbH & Co. KG, Lemgo, Germany).

2.3. *Adhesive cementation*

The inner surfaces of the ceramic restorations and the ceramic platelets were etched with 5% hydrofluoric acid (Vita Ceramics Etch, Vita, Bad Säckingen, Germany), IPS e.max CAD for 30 s and IPS Empress CAD for 60 s. The etched surfaces were rinsed with water for 30 s and air dried, followed by silanization with 3M ESPE Sil (3M ESPE, Seefeld, Germany) for 5 min. Lava Ultimate CAD/CAM (3M ESPE, Seefeld, Germany) restorations were basally tribochemically silicated with the CoJet System (50 μm, 1.2 bar; 3M ESPE, Seefeld, Germany) for 15 s. Teeth surfaces were etched with a total etch technique (enamel 30 s, dentin 15 s) with 37% phosphoric acid (Total Etch, Ivoclar Vivadent, Schaan, Liechtenstein) and rinsed with water for 30 s. According to the manufacturer’s instructions, the surfaces were conditioned with Syntac Primer, Adhesive and Heliobond (Ivoclar Vivadent, Schaan, Liechtenstein).

All restorations and platelets were adhesively bonded with a dual-curing composite (Variolink II, Ivoclar Vivadent, Schaan, Liechtenstein). The base and catalyst paste (low viscosity) were mixed in equal parts and applied to the basal surface of the restoration or platelet. Restoration and platelets were seated with finger pressure and light cured with Elipar FreeLight 2 (430–480 nm, 1190 mW/cm^2, 3M ESPE, Seefeld, Germany) for 20 s, each from the occlusal, buccal and lingual sites. All samples were stored for 24 h in 37 °C warm, double distilled water.

2.4. *Fatigue*

Fatigue simulations were conducted in a computer-controlled chewing simulator (MUC 2; Willytec GmbH, Gräfelfing, Germany) that allows vertical and horizontal movements. The chewing simulator type MUC 2 is the predecessor of the Willytec chewing simulators. The movement cycle is not controlled by ball spindles and stepper motors, but by compressed air cylinders. As a result, some parameters are different. For example, the sinking speed (45–50 mm/s) and the horizontal speed (6–12 mm/s) are slightly higher. The samples were mounted in closed chambers, which were filled with double distilled water.

As antagonistic specimens, 5 mm Degussit-balls (highly compacted oxide ceramic; FRIALIT, Mannheim, Germany) were used to perform a natural mastication cycle at 1 Hz, including 0.5 mm sliding horizontal motions while in contact. Due to the hardness, the contact surface of the antagonist changed only slightly during the tests.

In the first test series with a loading force of 50 N, the number of load cycles increased logarithmically from 10 to 1 million. IPS e.max CAD specimens did not fracture within 1 million cycles at a 50 N load. Therefore, the test conditions were tightened in a second test series. All IPS e.max CAD specimens were tested for an additional million masticatory cycles with a loading force of 100 N.

After 10^1, 10^2, 10^3, 10^4, 10^5 and 10^6 load cycles, all specimens were examined by lateral illumination with a light emitting diode (LED) lamp (LED-Lenser V12 with fibre optic light guide, Syndicad Ingenieurbüro, Munich) to detect the visible cracks of the restoration, which were classified as failure. The specimens were left in their chambers for examination

Table 1 – Materials and product information.

Restoration material	Type	Manufacturer	Batch no.	Composition
IPS e.max CAD (LT, A3)	Lithium disilicate ceramic	Ivoclar Vivadent, Schaan, Liechtenstein	605275	57–80% SiO_2, 11–19% Li_2O, 0–13% K_2O, 0–11% P_2O_5, 0–8% ZrO_2, 0–8% ZnO, 0–5% Al_2O_3, 0–5% MgO
IPS Empress CAD (LT, A3)	Leucite-reinforced glass ceramic	Ivoclar Vivadent, Schaan, Liechtenstein	574514	60–65% SiO_2, 16–20% Al_2O_3, 10–14% K_2O, 3.5–6.5% Na_2O, 0.5–7.0 other oxides, 0.2–1.0% pigments
Lava Ultimate CAD/CAM (LT, A3)	Resin nanoceramic	3M ESPE, Seefeld, Germany	3312A3LT	80% nano ceramic, 20% resin matrix
Luting system				
Material	Components	Manufacturer	Batch no.	Composition
Syntac	Etchant	Ivoclar Vivadent, Schaan, Liechtenstein	G07234	35% phosphoric acid
	Primer	Ivoclar Vivadent, Schaan, Liechtenstein	G19483	Maleic acid 4%, triethylene glycol dimethacrylate (TEGDMA), water, acetone
	Adhesive	Ivoclar Vivadent, Schaan, Liechtenstein	J0076	Water, poly(ethylene glycol) dimethacrylate (PEGDMA), glutaraldehyde
	Heliobond	Ivoclar Vivadent, Schaan, Liechtenstein	H14837	bisphenol A-glycidyl methacrylate (bisGMA), urethane dimethacrylate (UDMA), TEGDMA
Variolink II	Base and catalyst	Ivoclar Vivadent, Schaan, Liechtenstein	H28532	bisGMA, TEGDMA, UDMA, fillers, ytterbium trifluoride, stabilizer, pigments, benzoyl peroxide

between cycles to avoid changing the position of the specimens and thus the point of incidence of the antagonist, as this could distort the results.

2.5. *Statistical analysis*

Statistical analyses were performed using the computing environment R (R Development Core Team, 2017). Survival curves were created by the Kaplan–Meier method, and a log-rank test was conducted to compare the survival distributions.

3. Results

3.1. *Highly standardized specimens*

All highly standardized IPS Empress CAD (0.3 mm and 0.5 mm) and IPS e.max CAD (0.3 mm) specimens survived one million masticatory cycles at a loading force of 50 N without observable cracks or fractures.

3.2. *Clinically relevant specimens*

All IPS e.max CAD restorations survived one million masticatory cycles with a loading force of 50 N as well as 100 N. Ten out of twenty IPS Empress CAD occlusal veneers cracked, 8 veneers cracked after 10,000 cycles and another 2 cracked after 100,000 cycles. One occlusal Lava Ultimate CAD/CAM veneer failed after 100,000 cycles. Cracks always occurred in the area of the contact point of the antagonist (Fig. 1). Significant differences in the survival between the materials could be found (log-rank $p < 0.001$), as shown in the Kaplan–Meier survival graph (Fig. 2). The cumulative survival probability for IPS Empress CAD after 10,000 cycles was 60.0%, with a further decrease to 50.0% after 100,000 cycles. The Lava Ultimate CAD/CAM veneer achieved a survival probability of 95.0% after 100,000 and one million cycles compared to 100% survival for the IPS e.max CAD veneer. These results suggest a significantly poorer survival for the IPS Empress CAD specimens compared to the IPS e.max CAD ($p < 0.001$) or even the Lava Ultimate CAD/CAM ($p = 0.001$) specimens. In contrast, there was no significant difference between the IPS e.max CAD and Lava Ultimate CAD/CAM ($p = 0.317$) veneers.

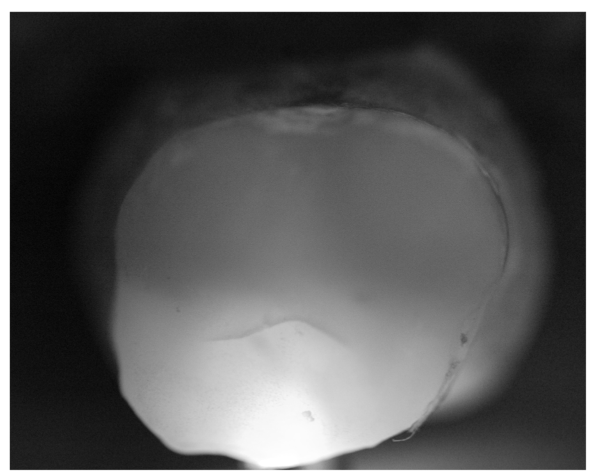

Fig. 1 – IPS Empress CAD with a crack.

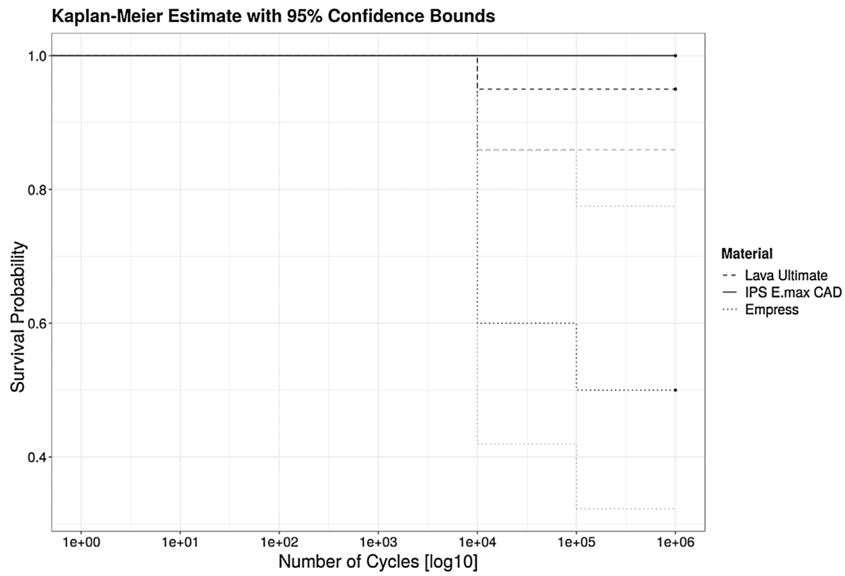

Fig. 2 – Kaplan–Meier estimate with 95% confidence bounds (log-rank $p < 0.001$) of anatomical specimens at a loading force of 50 N.

4. Discussion

There is little information regarding the reliability and longevity of current CAD/CAM materials adhesively bonded as ultrathin occlusal veneers on a combined enamel and dentin surface [22–25]. The aim of this study was therefore to determine whether ceramics or nanoceramic composites with an ultrathin layer thickness of 0.3–0.5 mm could be used to restore pressure-loaded occlusal dentin and enamel defects.

This question was investigated in our case with the aid of a mechanical fatigue simulation in which one million subcritical load cycles were applied to the specimens. Three different and commonly used materials, namely, a leucite glass ceramic (IPS Empress CAD), a lithium disilicate ceramic (IPS e.max CAD) and a nanoceramic composite material (Lava Ultimate CAD/CAM), were tested in a chewing simulator. The number of masticatory cycles was set logarithmically to one million, and a loading force of 50 N was used. The loading force of 50 N was selected to represent the nominal occlusal force due to the variability among individuals, which range between 10 and 120 N during mastication [26–29]. When preparing the samples, no cusps were modelled, but only uniform anatomical restorations, since the chewing load exerted on the thin ceramic and cusps would have impaired access to the thin areas.

In this study, the worst-case scenario for an occlusal veneer restoration was investigated, i.e., an enamel ring with a high elastic modulus (e-modulus) and a dentin centre with a low e-modulus. The difference in the e-moduli between the restoration and tooth substance determines the critical load for crack initiation [30]. The lower e-modulus of dentin allows the development of increased flexural stresses at the adhesive joint, which exposes the ceramic to a higher risk of cracking. Previous studies have shown that minimally invasive occlusal onlay ceramic restorations, which have been bonded only to the enamel, are far more fracture resistant than those bonded to dentin and even revealed a fracture resistance comparable to that of thick occlusal veneers when bonded to dentin [22,31,32]. Furthermore, ceramics tolerate pressure loads fairly well but are less tolerate to tensile stresses. Our study design is therefore favourable for ceramics since mainly pressure loads are induced. However, the lateral movement in the chewing simulator presents a rather small tensile stress.

In the first part of this study, the minimum thickness for the ceramic test specimen was determined. Therefore, sawed and ground ceramic platelets were produced since they allow a more accurate thickness determination and a more uniform thickness than the anatomically formed specimens. The first tests were conducted with bovine anterior teeth ground from buccal. Due to the large pulp cavity, however, almost all samples cracked since the thin buccal wall of the tooth deflected considerably under load. Therefore, further tests were performed with human teeth. The plan was to increase the ceramic thickness starting from a 0.3 mm layer thickness until the samples could survive one million masticatory cycles. Surprisingly, the 0.3 mm IPS e.max CAD and IPS Empress CAD specimens already survived this load. Therefore, we did not have to increase the specimen thickness any further. For the preparation of the clinically relevant test specimens, a layer thickness between 0.3 and 0.5 mm was chosen since thinner platelets could not be produced due to a high fracture rate during the manufacturing process.

All IPS e.max CAD samples survived one million cycles in the chewing simulator at a loading force of 50 N. Additionally, further testing of the same samples with a force of 100 N for an additional one million cycles did not result in any cracking. Guess et al. also described a 100% survival of IPS e.max Press partial coverages on premolars in the chewing simulator with thermocycling at 1.2 million cycles and 50 N, regardless of the restoration thickness (0.4 mm–2 mm) or preparation design.

The teeth in the group of occlusal ultrathin veneers were only reduced 0.5 mm occlusally in a sound tooth structure; therefore, an adhesive bond only to the enamel is likely for this group, which was accomplished by enamel etching with 37% phosphoric acid for 30 s and using an etch and rinse adhesive system [22]. A 100% survival was also confirmed in a study by Al-Akhali in which all occlusal 0.5–0.8 mm IPS e.max CAD veneers, adhesively bonded to only the enamel with a total etch adhesive system, survived thermodynamic loading with 98 N [33]. In contrast, a study by Sasse et al. determined that a minimum veneer thickness of 0.7–1 mm should not be altered. In this study, various thicknesses of IPS e.max CAD veneers were tested in a chewing simulator for 600,000 cycles with a loading force of 100 N. The veneers were bonded with a self-etching primer to the enamel, the enamel and dentin or the enamel and composite [23]. A recent study by Al-Akhali et al. also found that the use of a self-etch adhesive system reduces the survival of ultrathin occlusal veneers and cannot be recommended for bonding. Occlusal IPS e.max CAD veneers with a thickness of 0.5–0.8 mm, which were bonded to the enamel using a self-etching primer, were tested under thermodynamic loading of 98 N for 1.2 million cycles. Only 50% of the specimens survived the load showing no cracks [34]. However, self-etching primers have a lower ability to etch enamel than adhesive systems with separate phosphoric acid enamel etching, and many studies have proven the importance of adequate enamel etching for a good adhesive bond [35–37]. Yazigi et al. also confirmed this finding for ultrathin occlusal veneers, which treat a combined enamel–dentin defect, in which the self-etching adhesive with selective pre-etching of the enamel margins performed as efficiently as the traditional etch and rinse protocol [24]. In our study, the etch and rinse adhesive system Syntac classic was used, as it has been the gold standard in our student education since 1992 with many documented clinical cases. Therefore, the study design is comparable to our clinical experiences. The good adhesive bond to dentin and enamel using an etch and rinse system likely contributed to the high survival rate of the IPS e.max CAD veneer in our study.

During the chewing simulation, one Lava Ultimate CAD/CAM sample cracked after 10,000 cycles, and no additional specimens failed up to one million cycles. Additionally, Ioannidis et al. found a 100% survival rate of occlusal 0.5 and 1 mm thick lava Ultimate CAD/CAM veneers under thermocycling in the chewing simulator at 1.2 million cycles and 49 N. However, only an adhesive attachment to enamel and not to a combined enamel–dentin defect was performed [38]. The good performance of the Lava Ultimate CAD/CAM veneer in our study can be explained by its viscoelastic properties. Lava Ultimate CAD/CAM is a highly cross-linked particle reinforced composite consisting of monodispersed, nonaggregated and nonagglomerated silica and zirconia nanoparticles that form nanoclusters with high structural integrity [39]. The higher filler content, the proprietary silane coupling agent treatment for chemical bonding with the resin matrix during block manufacturing, and the advanced heat treatment of the resin matrix result in a higher strength of the Lava Ultimate CAD/CAM restoration, which is also reflected in the reported flexural strengths of 205 MPa [39,40]. Furthermore, the polymeric matrix is more damage-tolerant than the brittle glassy matrix of all-ceramic restorations [41].

The IPS Empress CAD restorations performed significantly worse than the other materials since 10 out of the 20 specimens cracked during fatigue testing. The first 8 specimens cracked after 10,000 cycles and another 2 after 100,000 cycles. Occlusal ultrathin IPS Empress veneers were investigated by Schlichting et al. under accelerated fatigue, revealing a significantly higher failure rate for the 0.6 mm thick IPS Empress restorations than for the 1.2 mm thick restorations [42].

The fracture resistance of ultrathin CAD/CAM-produced lithium disilicate and nanoceramic restorations under fatigue appears to as good as the restorations with the minimum layer thickness recommended by the manufacturer. With regard to the ease of fabrication at lower costs compared to laboratory-fabricated restorations and the possibility of using them without further sacrificing hard tooth tissue, a reduction in the minimum layer thickness should be considered for these materials in clinical use.

All observed failures were limited to the restorative material and did not involve the tooth itself. The evaluation of cracks as a failure criterion is a very hard criterion since the fragments can remain in situ for a long time under clinical conditions and protect the tooth However, our aim was to investigate the long-term stability of the materials. Even if cracks in the material have no clinical consequences, the occurrence of a crack means the failure of the restoration. Yazigi et al. found in their research that cracks in ultrathin occlusal veneers made of lithium disilicate ceramic did not affect the performance and were not associated with a decreasing fracture strength. Although the mode of failure was affected by the cracks [25].

Fractographic examination of the crack surface would have been desirable. In our experiments, however, no fragments were detached from the tooth surface, so that the crack surface was not directly accessible. Since the fractured specimens still adhered to the tooth surface, they could only have been prepared for fractographic analysis by grinding the tooth from the back of the occlusal veneer. However, this process could have led to the undesirable formation of further cracks or to the alteration of the existing cracks. For this reason, the fractographic analysis was omitted.

Both wear and fatigue are not pure material properties, but the properties of the test system in combination with the tested materials, which means that similar systems achieve comparable results. However, these are not exactly comparable due to numerous minimal differences in the test system. One should therefore only compare data generated in the same test system with identical test parameters.

Lava Ultimate CAD/CAM and IPS e.max CAD restorations performed similarly well. However, the IPS e.max CAD veneers showed no crack formation even at a loading force of 100 N. The hypothesis that ultrathin ceramics or nanoceramic composites attached to dentin and a circular enamel margin can be considered a treatment option that is accepted for IPS e.max CAD and Lava Ultimate CAD/CAM restorations. However, this option must be rejected for IPS Empress CAD ceramics due to its high cracking rate under fatigue testing.

5. Conclusion

Ultrathin occlusal veneers made of glass-ceramic IPS Empress CAD proved to be less durable than those made of lithium disilicate ceramic IPS e.max CAD. It is also noteworthy that Lava Ultimate CAD/CAM showed just as few cracks as IPS e.max CAD and was therefore superior to IPS Empress CAD in terms of fatigue loading. Whether this result is due to the viscoelastic properties of the composite material must be investigated further. IPS e.max CAD and Lava Ultimate CAD/CAM should be preferred to IPS Empress CAD for the treatment of occlusal tooth loss with ultrathin veneers.

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REFERENCES

[1] Lussi A, Carvalho TS. Erosive tooth wear: a multifactorial condition of growing concern and increasing knowledge. Monogr Oral Sci 2014;25:1–15, http://dx.doi.org/10.1159/000360380.
[2] Zero DT, Lussi A. Erosion–chemical and biological factors of importance to the dental practitioner. Int Dent J 2005;55:285–90.
[3] Lussi A, Schaffner M, Hotz P, Suter P. Dental erosion in a population of Swiss adults. Community Dent Oral Epidemiol 1991;19:286–90.
[4] Khan F, Young WG, Law V, Priest J, Daley TJ. Cupped lesions of early onset dental erosion in young southeast Queensland adults. Aust Dent J 2001;46: 100–7.
[5] Jaeggi T, Lussi A. Prevalence, incidence and distribution of erosion. Monogr Oral Sci 2014;25:55–73, http://dx.doi.org/10.1159/000360973.
[6] Cavadini C, Siega-Riz AM, Popkin BM. US adolescent food intake trends from 1965 to 1996. Arch Dis Child 2000;83:18–24.
[7] O'Sullivan EA, Curzon ME. A comparison of acidic dietary factors in children with and without dental erosion. ASDC J Dent Child 2000;67:186–92, 60.
[8] Loomans B, Opdam N, Attin T, Bartlett D, Edelhoff D, Frankenberger R, et al. Severe tooth wear: European consensus statement on management guidelines. J Adhes Dent 2017;19:111–9, http://dx.doi.org/10.3290/j.jad.a38102.
[9] Johansson A, Johansson AK, Omar R, Carlsson GE. Rehabilitation of the worn dentition. J Oral Rehabil 2008;35:548–66, http://dx.doi.org/10.1111/j.1365-2842.2008.01897.x.
[10] Attin T, Filli T, Imfeld C, Schmidlin PR. Composite vertical bite reconstructions in eroded dentitions after 5.5 years: a case series. J Oral Rehabil 2012;39:73–9, http://dx.doi.org/10.1111/j.1365-2842.2011.02240.x.
[11] Manhart J. Temporäre Anhebung der Vertikaldimension mit Komposit in einem vereinfachten direkten Spritzgussverfahren. Swiss Dent J 2017;127:413–44.
[12] Fasbinder DJ. Materials for chairside CAD/CAM restorations. Compend Contin Educ Dent 2010;31:702–4, 6, 8-9.
[13] Ivoclar Vivadent. IPS e.max scientific report vol. 02 2001–2013; 2012 [Accessed 01 February 2019] http://www.ivoclarvivadent.com/zoolu-website/media/document/12839/IPS+e-max+Scientific+Report+Vol-+02+-+2001-2013.
[14] Ivoclar Vivadent. IPS Empress CAD monolithic solutions LABSIDE instruction for use; 2012 [Accessed 01 February 2019] http://downloads.ivoclarvivadent.com/zoolu-website/media/document/40221/IPS+Empress+CAD+Monolithic+Solutions+Labside?_ga=2.236083842.207199041.1524734917-1046276998.1522054706.
[15] Federlin M, Krifka S, Herpich M, Hiller KA, Schmalz G. Partial ceramic crowns: influence of ceramic thickness, preparation design and luting material on fracture resistance and marginal integrity in vitro. Oper Dent 2007;32:251–60, http://dx.doi.org/10.2341/06-70.
[16] Magne P, Schlichting LH, Maia HP, Baratieri LN. In vitro fatigue resistance of CAD/CAM composite resin and ceramic posterior occlusal veneers. J Prosthet Dent 2010;104:149–57, http://dx.doi.org/10.1016/S0022-3913(10)60111-4.
[17] Ozturk E, Bolay S, Hickel R, Ilie N. Shear bond strength of porcelain laminate veneers to enamel, dentine and enamel-dentine complex bonded with different adhesive luting systems. J Dent 2013;41:97–105, http://dx.doi.org/10.1016/j.jdent.2012.04.005.
[18] Bowen RL, Cobb EN. A method for bonding to dentin and enamel. J Am Dent Assoc 1983;107:734–6.
[19] Stawarczyk B, Liebermann A, Eichberger M, Güth J-F. Evaluation of mechanical and optical behavior of current esthetic dental restorative CAD/CAM composites. J Mech Behav Biomed Mater 2016;55:1–11, http://dx.doi.org/10.1016/j.jmbbm.2015.10.004.
[20] Wendler M, Belli R, Valladares D, Petschelt A, Lohbauer U. Chairside CAD/CAM materials. Part 3: cyclic fatigue parameters and lifetime predictions. Dent Mater 2018;34:910–21, http://dx.doi.org/10.1016/j.dental.2018.03.024.
[21] Bartlett D, Ganss C, Lussi A. Basic Erosive Wear Examination (BEWE): a new scoring system for scientific and clinical needs. Clin Oral Investig 2008;1(12 Suppl):S65–8, http://dx.doi.org/10.1007/s00784-007-0181-5.
[22] Guess PC, Schultheis S, Wolkewitz M, Zhang Y, Strub JR. Influence of preparation design and ceramic thicknesses on fracture resistance and failure modes of premolar partial coverage restorations. J Prosthet Dent 2013;110:264–73, http://dx.doi.org/10.1016/S0022-3913(13)60374-1.
[23] Sasse M, Krummel A, Klosa K, Kern M. Influence of restoration thickness and dental bonding surface on the fracture resistance of full-coverage occlusal veneers made from lithium disilicate ceramic. Dent Mater 2015;31:907–15, http://dx.doi.org/10.1016/j.dental.2015.04.017.
[24] Yazigi C, Kern M, Chaar MS. Influence of various bonding techniques on the fracture strength of thin CAD/CAM-fabricated occlusal glass-ceramic veneers. J Mech Behav Biomed Mater 2017;75:504–11, http://dx.doi.org/10.1016/j.jmbbm.2017.08.016.
[25] Yazigi C, Schneider H, Chaar MS, Ruger C, Haak R, Kern M. Effects of artificial aging and progression of cracks on thin occlusal veneers using SD-OCT. J Mech Behav Biomed Mater 2018;88:231–7, http://dx.doi.org/10.1016/j.jmbbm.2018.08.017.
[26] Bates JF, Stafford GD, Harrison A. Masticatory function — a review of the literature. III. Masticatory performance and efficiency. J Oral Rehabil 1976;3:57–67.
[27] De Boever JA, McCall Jr WD, Holden S, Ash Jr MM. Functional occlusal forces: an investigation by telemetry. J Prosthet Dent 1978;40:326–33.
[28] Gibbs CH, Mahan PE, Lundeen HC, Brehnan K, Walsh EK, Holbrook WB. Occlusal forces during chewing and

swallowing as measured by sound transmission. J Prosthet Dent 1981;46:443–9.
[29] Kikuchi M, Korioth TW, Hannam AG. The association among occlusal contacts, clenching effort, and bite force distribution in man. J Dent Res 1997;76:1316–25, http://dx.doi.org/10.1177/00220345970760061201.
[30] Lawn BR, Deng Y, Miranda P, Pajares A, Chai H, Kim DK. Overview: damage in brittle layer structures from concentrated loads. J Mater Res 2002;17:3019–36, http://dx.doi.org/10.1557/JMR.2002.0440.
[31] Piemjai M, Arksornnukit M. Compressive fracture resistance of porcelain laminates bonded to enamel or dentin with four adhesive systems. J Prosthodont 2007;16:457–64, http://dx.doi.org/10.1111/j.1532-849X.2007.00227.x.
[32] Clausen J-O, Abou Tara M, Kern M. Dynamic fatigue and fracture resistance of non-retentive all-ceramic full-coverage molar restorations. Influence of ceramic material and preparation design. Dent Mater 2010;26:533–8, http://dx.doi.org/10.1016/j.dental.2010.01.011.
[33] Al-Akhali M, Chaar MS, Elsayed A, Samran A, Kern M. Fracture resistance of ceramic and polymer-based occlusal veneer restorations. J Mech Behav Biomed Mater 2017;74:245–50, http://dx.doi.org/10.1016/j.jmbbm.2017.06.013.
[34] Al-Akhali M, Kern M, Elsayed A, Samran A, Chaar MS. Influence of thermomechanical fatigue on the fracture strength of CAD-CAM-fabricated occlusal veneers. J Prosthet Dent 2019;121:644–50, http://dx.doi.org/10.1016/j.prosdent.2018.07.019.
[35] Erickson RL, Barkmeier WW, Kimmes NS. Bond strength of self-etch adhesives to pre-etched enamel. Dent Mater 2009;25:1187–94, http://dx.doi.org/10.1016/j.dental.2009.04.004.
[36] da Rosa WLO, Piva E, da Silva AF. Bond strength of universal adhesives: a systematic review and meta-analysis. J Dent 2015;43:765–76, http://dx.doi.org/10.1016/j.jdent.2015.04.003.
[37] Van Landuyt KL, Kanumilli P, De Munck J, Peumans M, Lambrechts P, Van Meerbeek B. Bond strength of a mild self-etch adhesive with and without prior acid-etching. J Dent 2006;34:77–85, http://dx.doi.org/10.1016/j.jdent.2005.04.001.
[38] Ioannidis A, Muhlemann S, Ozcan M, Husler J, Hammerle CHF, Benic GI. Ultra-thin occlusal veneers bonded to enamel and made of ceramic or hybrid materials exhibit load-bearing capacities not different from conventional restorations. J Mech Behav Biomed Mater 2019;90:433–40, http://dx.doi.org/10.1016/j.jmbbm.2018.09.041.
[39] 3M ESPE. Lava Ultimate CAD/CAM restorative technical, product profile. http://www.d-way.cz/data/product/13/23/files/Lava_Ult_TPP.pdf. [Accessed 01 February 2019].
[40] Egbert JS, Johnson AC, Tantbirojn D, Versluis A. Fracture strength of ultrathin occlusal veneer restorations made from CAD/CAM composite or hybrid ceramic materials. Oral Sci Int 2015;12:53–8, http://dx.doi.org/10.1016/S1348-8643(15)00017-8.
[41] Aboushelib MN, Elsafi MH. Survival of resin infiltrated ceramics under influence of fatigue. Dent Mater 2016;32:529–34, http://dx.doi.org/10.1016/j.dental.2015.12.001.
[42] Schlichting LH, Maia HP, Baratieri LN, Magne P. Novel-design ultra-thin CAD/CAM composite resin and ceramic occlusal veneers for the treatment of severe dental erosion. J Prosthet Dent 2011;105:217–26, http://dx.doi.org/10.1016/S0022-3913(11)60035-8.