Load-bearing capacity of all-ceramic three-unit fixed partial dentures with different computer-aided design (CAD)/computer-aided manufacturing (CAM) fabricated framework materials


The purpose of this in vitro study was to compare the load-bearing capacity of posterior three-unit fixed dental prostheses (FDP) produced with three different all-ceramic framework materials: glass-infiltrated alumina (ICA), glass-infiltrated alumina strengthened with zirconia (ICZ), and yttria-stabilized polycrystalline zirconia (YZ). Additionally, the influence on aging of mechanical cyclic fatigue loading and thermal cycling in water were evaluated. A total of 20 frameworks each were fabricated from ICA, ICZ, and YZ by a computer-aided design (CAD)/computer-aided manufacturing (CAM) system. The framework designs were identical for all specimens. All frameworks were veneered with porcelain and cemented with glass–ionomer. Prior to fracture testing, 10 FDP of each experimental group were subjected to thermal and mechanical cycling. Additionally, fractographic analysis was performed. Statistical analysis showed that FDP made from YZ had significantly higher load to failure, whereas no difference was found between the other two materials. Aging did not have a significant effect on the fracture load.

All-ceramic fixed prosthodontics have become more widely used in clinical practice as a result of their high aesthetic potential and their excellent biocompatibility properties (1–9). In attempts to improve strength and fracture toughness, several new ceramic materials and techniques have been developed since the 1980s. The use of high-performance zirconium oxide ceramics in computer-aided design (CAD)/computer-aided manufacturing (CAM) systems, which were previously used for single tooth restorations in chairside procedures, expanded usage to dental laboratories. Many fixed prosthetic substructures are now fabricated using CAD/CAM systems, demonstrating that a major part of the working sequence is carried out by industrial milling machines (1, 10–13). Use of milling blocks fabricated under industrial quality standards has a great impact on ceramic materials. Every void and imperfection is a potential origin of cracks and thus clinical failure of ceramic restorations.

The In-Ceram system (Vita, Bad Säckingen, Germany) is a metal-free restorative system with a long research history. In the 1990s, three-unit fixed dental prostheses (FDP) made of glass-infiltrated alumina ceramics were introduced for the replacement of anterior teeth. The core was fabricated by a slip cast technique before CAD/CAM technology and milling blocks were introduced to the dental laboratory. A porous network of partially sintered alumina results from the slip casting process (14, 15). This technique exhibits a broad strength distribution related to the fabrication process, resulting in a low Weibull modulus (16). More recently, the framework has been milled from a porously sintered alumina blank [In-Ceram Alumina (ICA); Vita] by means of a CAD/CAM system followed by the obligatory glass-infiltration. This fabrication technique increased the Weibull modulus of these ceramics and thus their reliability (16).

The recommended cross-sectional dimension of the connector is 12 mm² for this ceramic system, strictly limited to anterior three-unit FDP (17). Zirconia-reinforced glass-infiltrated alumina [In-Ceram Zirconia (ICZ); Vita] is recommended for posterior three-unit FDP with a span of 10 mm or less between abutment teeth, if the connector cross-section is 16 mm² (18).

Yttria-stabilized zirconia ceramic is available for various indications, including posterior four-unit FDP,
with a recommended 7 mm² cross-section of the connectors (19). On the basis of the literature and manufacturer's recommendations, zirconia ceramics and glass-infiltrated alumina reinforced with zirconia can be used for posterior FDP. No literature is available on the in vitro testing of anatomically correct posterior FDP made from different framework materials milled using the same CAD/CAM system. It is expected that FDP made from lower-strength framework materials will have lower load-bearing capacity and that cyclic fatigue will lead to a significant reduction in the fracture load.

**Material and methods**

**Preparation**

A mandibular typodont model was used (Frascos UK 119, A-3 T; Franz Sachs & Co., Tettnang, Germany) and the right second premolar and second molar were prepared for a three-unit all-ceramic FDP. A 1.2 mm, 360-degree chamfer preparation was made with 1.5–2 mm of occlusal reduction. To standardize the amount of reduction, a silicone index (Optosil; Heraeus Kulzer, Hanau, Germany) was fabricated prior to tooth preparation. Additionally, the thickness of the provisional crown (Protemp 3 Garant; 3M ESPE, Seefeld, Germany) was used to verify the tooth structure removal. The preparation was completed with a surveyor (F1; DeguDent, Hanau, Germany) using a carbide bur (Komet H 356 RGE 103.031; Gebr. Brasseler, Lemgo, Germany) to ensure a total occlusal convergence angle of 8°. The FDP were cemented on metal duplicates. Duplicates of the original abutment teeth were made of chrome-cobalt alloy (CCA) (Remanium 2000; Dentaurum, Ispringen, Germany). Periodontal ligament resilience was simulated by coating the roots of the abutment teeth with polyether material (Impregum; 3M ESPE) and the alveolus in the resin base. The artificial alveolus was filled with polyether material (Impregum; 3M ESPE) and the walls of the abutment teeth, and 1.2 mm at all occlusal surfaces and at all surfaces of the pontics. One major goal of the study was to fabricate exact duplicates of the veneered FDP using alternative framework materials. Therefore, an impression of each FDP fixed onto the testing model (fit checker; GC-Germany, Munich, Germany) was made using a putty silicone material (Optosil; Heraeus Kulzer). The impressions were cut from mesial to distal to function as a guide for veneering the other substructures. Twenty frameworks were fabricated by the same CAM system using porously sintered alumina reinforced with zirconia (ICZ). Glass infiltration, removal of glass, and veneering were performed as described above.

After designing the framework, the data were enlarged by 20%. Twenty frameworks were fabricated using semi-sintered zirconia (YZ) (In-Ceram YZ; Vita) milled using the same CAM system. The enlarged frameworks were sintered to full density at a temperature of 1,500°C, resulting in 20% shrinkage. Frameworks were checked for fit and adapted. The system's veneering porcelain for zirconia frameworks (VM 9; Vita) was used to build the restorations to full contour.

**Manufacture of FDP**

All casts were digitized using an optical scanner (InEos; Sirona, Bensheim, Germany). The data were imported into a CAD program (Cerec 3D; Sirona). A substructure retainer thickness of 0.5 mm, and a connector size of 12 mm², were selected. Twenty substructures were fabricated in porously sintered alumina (ICA) by a CAM milling machine (InLab; Sirona). Glass-infiltration was carried out in a special furnace (Vita InCeramat 2; Vita) according to the manufacturer's directions. The excess glass was removed using a coarse diamond, paying particular attention that the substructure was not exposed. The fit of the FDP framework was checked on the master cast and adjusted if necessary. Additionally, residual alumina glass was removed in the sandblasting unit at a pressure of 600 kPa (cervical 300 kPa), according to the manufacturer's instructions. A dentin–enamel veneering process was carried out using the system's veneering porcelain (VM 7; Vita) with the powder build-up technique. The thickness of the veneering porcelain was checked, at 30 defined points, to be 0.8 mm at the axial walls of the abutment teeth, and 1.2 mm at all occlusal surfaces and at all surfaces of the pontics. One major goal of the study was to fabricate exact duplicates of the veneered FDP using alternative framework materials. Therefore, an impression of each FDP fixed onto the testing model (fit checker; GC-Germany, Munich, Germany) was made using a putty silicone material (Optosil; Heraeus Kulzer). The impressions were cut from mesial to distal to function as a guide for veneering the other substructures. Twenty frameworks were fabricated by the same CAM system using porously sintered alumina reinforced with zirconia (ICZ). Glass infiltration, removal of glass, and veneering were performed as described above.

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**Aging**

The FDP were cemented onto the CCA abutments with glass-ionomer (Ketac-Cem Aplicap; 3M ESPE). During their storage in distilled water at 36°C, 10 FDP from each experimental group were subjected to thermal and mechanical cycling (TMC). A total of 10⁶ thermal cycles, between 5 and 55°C (30 s dwell time at each temperature), during 1.2 × 10⁶ cycles of mechanical loading with 50 N (load frequency 2.5 Hz), were applied in the chewing simulator machine (Willytec; Graefelfing, Germany). The descending speed of the chewing simulator was 20 mm s⁻¹. The specimens were loaded with a tungsten ball [6 mm diameter, coated with a shrink fit tube (EAP, Dornhan, Germany)] in a vertical direction. The force was transferred to the central fossa of the occlusal surface of the pontic with the tungsten ball. Particular attention was paid that all specimens were loaded identically.

**Determination of load-bearing capacity**

All specimens were loaded until failure in a universal testing machine (Zwick, Ulm, Germany) at a crosshead...
speed of 0.5 mm min⁻¹ (26–28). The force was transferred to the central fossa of the occlusal surface of the pontic via a tungsten ball (10.0 mm diameter) on an interposed polyethylene foil (1.0 mm thickness) (Fig. 1). A sudden decrease in force of more than 15 N was regarded as an indication of failure, and the maximum force up to this point was recorded as force at fracture. Using visual examination, crack location and fragmentation of core and veneering materials were assessed. Selected fracture surfaces were analysed further by scanning electron microscopy (SEM).

Statistical analysis

The force at fracture data were imported into a statistical program (SPSS, 15.0; SPSS Software, Munich, Germany). To compare the results of the different framework materials, a two-way analysis of variance (ANOVA) and a post-hoc test (Student–Newman–Keuls) were performed. Weibull parameters, characteristic force at failure ($F_0$) and the Weibull modulus ($m$), were determined for each test group by fitting a Weibull distribution to each respective data set. The parameter $F_0$ is associated with 63.2 % probability of failure, whereas the modulus, $m$, is a measure of the scatter in the force at failure and of the reliability of the material investigated. The greater the value of $m$, the steeper the transition from survival to failure for the probability distribution against force at failure.

Results

All FDP tested survived $1.2 \times 10^6$ cycles of dynamic loading and $10^6$ thermal cycles in the artificial oral environment. Figure 2 shows the results of load-bearing capacity testing. While the effect of the framework material on force at fracture was found to be statistically significant ($P = 0.003$), the effect of fatigue failed to show statistical significance ($P = 0.283$). Compared with the corresponding forces at fracture, Weibull characteristic forces were 8–12% higher, but exhibited the same tendencies (Table 1).

Visual inspection of the specimens after fracture showed that all cracks ran through the connector area either between the second premolar and the first molar (34 specimens) or between the first molar and the second molar (26 specimens).

Fig. 1. Fracture test set up. PE, polyether simulating the resilience; F, polyethylene foil, TB, tungsten ball.

Scanning electron microscopy analysis revealed similar fracture patterns for all FDP. The origin of the fracture was located in the framework material, close to its surface at the gingival embrasure (the tensile surface). Typical hackle patterns could be followed back to the origin of the crack. A fracture mirror extended around the fracture origin (Fig. 3). Moreover, the glass-infiltrated frameworks showed a higher pore density than those made of presintered zirconia (Fig. 4A,B).

Discussion

In the present study, the fracture resistance of three-unit FDP was investigated in vitro. Compared with clinical studies, in vitro investigations are less expensive, easier to reproduce, and less vulnerable to unpredictable influences. To be able to carry out the testing of three-unit FDP, it is of paramount importance to design a test set up producing a failure mode similar to that occurring clinically. Model materials and testing conditions were chosen carefully to imitate clinical reality as much as possible. However, the abutment teeth were made of CCA, which has an elastic modulus of 200 GPa; the elastic modulus of CCA is superior to that of dentin, which has an elastic modulus of 12 GPa (29). According to Scherrer & de Rijk (29), increasing the elastic modulus of the supporting material results in increased fracture strength. Therefore, fracture forces evaluated in the present study might have been higher than in clinical practice. However, studies using resin material for the abutment teeth reported similar fracture forces for zirconia-based FDP (20).

Analysis using immobile retainers produced a much higher failure load than found when testing with mobile posts. The polyether layer around the abutment roots...
simulated a periodontal resilience of 50–120 µm at forces between 10 and 50 N in the horizontal direction (19, 25). Finally, the FDP were cemented using a conventional luting protocol, according to clinical use (30). The abutment teeth were prepared using an optimal design, and the FDP were produced according to the manufacturer’s instructions, in terms of milling, glass infiltration, and veneering. The design of the restorations was carried out using an experimental approach, not taking into account that the manufacturer does not recommend the use of glass-infiltrated alumina for posterior FDP. Additionally, the recommendations in terms of minimum wall thickness of the abutment tooth and the connector cross-section were not followed for groups ICA and ICZ. For comparison solely of the framework material, identical dimensions for all frameworks were employed. The clinical relevance of the present experimental set up appears in daily dental work, when recommendations are not followed because of limited space or inadequate preparations. However, it has to be taken into account that specimens, which would have been fabricated according to the manufacturer’s directions in groups ICA and ICZ, might have performed better in terms of load-bearing capacity.

Clinical fractures of all-ceramic restorations have rarely been identified. The majority of failures originated at the gingival side of the connector, the area of highest tension. Studies using finite-element analysis showed that during cyclic loading the highest stress within the FDP was located at the gingival side of the connector area (31–33).

All specimens tested in the present study showed this typical fracture pattern of failure in the connector area, which indicates that the design and manufacturing process of the FDP might have been suboptimal. A potential improvement could be achieved by carefully following the manufacturer’s recommendations for both framework and connector design.

### Table 1

<table>
<thead>
<tr>
<th>Framework material</th>
<th>Mean force at fracture</th>
<th>Minimum force at fracture</th>
<th>Maximum force at fracture</th>
<th>(F_0)</th>
<th>(m)</th>
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<tr>
<td>In-Ceram Alumina*</td>
<td>851 (331)(^a)</td>
<td>469</td>
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<td>1,078</td>
<td>4.5</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>In-Ceram YZ#</td>
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<td>822</td>
<td>1,376</td>
<td>1,122</td>
<td>5.7</td>
</tr>
</tbody>
</table>

\(^a\)No aging.  
\(^b\)Aging.  
Values marked with the same superscript letter are not statistically different (two-factor analysis of variance, \(P > 0.05\)).

**Fig. 3.** Scanning electron microscopy (SEM) image, at a magnification of 80, of a typical fracture surface of a failed specimen from the YZ group; the origin of the fracture is found in the zirconia framework, with a surrounding smooth mirror region (indicated by white arrows) and hackle patterns in the periphery. Zirconia framework material is located at the bottom, and veneering material is located above.

**Fig. 4.** Scanning electron microscopy imagines of fracture surfaces at higher magnification. The specimens made from presintered zirconia (YZ) (A) show fewer pores than the specimens made from glass-infiltrated ceramic (ICZ) (B).
which is also found in clinical failure of FDP (34). In contrast to comparable studies, no influence of the aging process was identified in the present study (20, 25). It has to be questioned if the aging process performed in this study was reliable and reflected the clinical situation. To simulate aging, three main factors have to be present.

(i) Water from the oral cavity, which propagates subcritical crack growth in ceramic materials.
(ii) Thermal stressing, which leads to a decrease in the mechanical stability of dental restorations.
(iii) The mechanical force applied for simulating the chewing process. This was simulated by 50 N, while a comparable study used 100 N as the maximum load (20). However, according to the literature, the chewing forces seldom exceed 50 N. The descending speed of the chewing simulator was reported to influence the impact of the applied force (35). Heinze (35) suggested a descending speed of 40 mm s⁻¹, while a descending speed of 20 mm s⁻¹ was employed in this study, which might explain why no effect of aging was observed. However, comparable studies did not report the descending speed (20, 21, 23, 35).

Weibull moduli in the range of 6.1–8 for zirconia-based FDP (20) and in the range of 7 for zirconia frameworks (19) have been reported, while the present study exhibited Weibull moduli in the range of 4.5–5.7. This might be caused by the material, by the fabrication process, or by the small number of specimens. However, a study investigating glass-infiltrated alumina enforced with zirconia four-unit FDP substructures showed a Weibull modulus of 4.5 (19) compared with 3.9 in the present study, whereas crowns exhibited values of 3.9–4.9 (36). The results of this study concur with the literature, where an increase of the Weibull modulus was reported after fatigue (37).

Although the manufacturer differentiates between glass-infiltrated alumina, which is not recommended for use as a posterior FDP framework, and glass-infiltrated alumina enforced with zirconia, which is recommended as a posterior framework, no differences between these two materials were found in the present study. The superiority of the strength of ICZ strength over the strength of ICA is well established and has been reported by several authors (38, 39). It is obvious that the veneering of ICZ has masked its strength over ICA. Chong & Chai (40) reported a similar effect in their study and found two factors explaining this phenomenon. First, the weaker veneering porcelain might have been responsible for the absence of differences between the two materials. Subjecting the veneering porcelain to tensile load during the fracture test might have resulted in crack initiation in the veneering porcelain at lower load (40). This might have propagated through the substructure materials and led to catastrophic failure.

The second factor stated was that during the veneering process residual stress built up in the specimens at the material interface (40). It has been proposed that this residual stress results from the apposition of materials of different elastic moduli and occurs during temperature changes as a result of porcelain firing (16, 40). However, it is uncertain to what extent the residual stress affected the masking of the superior strength of ICZ because no delamination of the veneering porcelain from the substructure material was observed.

In all ceramic systems, the flaw population (size, number and distribution) can be related to the material, or may be affected by the fabrication process (41, 42). According to SEM analysis, the sintering to density of YZ induced fewer flaws compared with the glass-infiltration process, resulting in better strength properties and a higher Weibull modulus.

For all six groups of FDP tested in the present study, the mean forces at fracture were approximately 30–105% higher than the 500 N benchmark, which is considered to be the lower limit of static load-bearing capacity for clinically acceptable FDP in the posterior region (43). However, it has to be taken into account that the minimum fracture load of groups ICA and ICZ were below or slightly (8–17%) above 500 N. The minimum fracture loads of YZ were at least 40% above 500 N. In long-term clinical studies, posterior FDP showed a survival probability of 82.5% after 3 yr (9) when fabricated from ICA and a survival probability of 94.4% after 3 yr (44) when fabricated from ICZ. However, posterior FDP fabricated with ytria-stabilized polycrystalline zirconia exhibited a 100% survival probability in several studies after 2–3 yr (30, 45, 46).

As a clinical implication of this study, the glass-infiltrated alumina reinforced with zirconia should not be used as a substructure for posterior FDP as it exhibited no significant increase of load-bearing capacity compared with glass-infiltrated alumina. Instead, yttria-stabilized polycrystalline zirconia should be used because of its superior strength.

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References


