A focus on zirconia: an in-vitro lifetime prediction of zirconia dental restorations

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Fracture performance of computer aided manufactured zirconia and alloy crowns.

Keywords: all-ceramic, zirconia, CAD/CAM, fracture force, fractography
7.1 Abstract

Objective. The aim of this in-vitro study was to compare the fracture resistance and fracture performance of CAD/CAM zirconia and alloy crowns.

Materials and Methods. One electrophoresis alumina ceramic (Wolceram) and four zirconia-based systems (ce.novation, Cercon/Cercon Ceram Kiss, Digison/GC Initial and Lava/Lava Ceram) were investigated. A porcelain-fused-to-metal method (Academy/Vita Omega) was used either in the conventional casting technique or in laser sintering. Sixteen crowns of each material were fabricated and veneered with the corresponding ceramic. Crown and root dimensions were measured. Eight crowns of each system were adhesively bonded or conventionally cemented. After artificial aging, the fracture resistance and fracture pattern were determined. Defect sizes were analyzed and investigated by fractographic means (SEM).

Results. The fracture force of the tested systems after aging varied between 1111 N and 2038 N with conventional cementation and 1181 N and 2295 N with adhesive bonding. No significant differences were found between adhesive or conventional cementation. Fracture patterns were in most cases a chipping of the veneering ceramic and, in single cases, a fracture of the core. Only in one case could a fracture of the tooth be determined.

Conclusion. Fractographic analysis revealed that the fracture origin was located on the occlusal surface. Conventional cementation showed no disadvantages in respect to the fracture behaviour.
7.2 Introduction

Long-term experience, as well as high aesthetics and good biological compatibility recommend press ceramics for clinical application as adhesively bonded posterior crowns. With the promise of new and faster technologies (computer-aided design/manufacturing: CAD/CAM), as well as easier handling (no adhesive cementation required) and strength increase, new materials try to capture the market. Standardized computer-controlled ceramic fabrication processes such as milling (Lava, Cercon), ceramic built-up (Ce.novation) or computerized slip casting/electrophoresis (Alumina-ceramic Wolceram) are discussed for optimized quality in contrast to technician-made restorations. High-strength hot isostatic pressed (hip) or partly stabilized zirconia ceramics have a high fracture strength with a small range of strength variation and a high structural reliability compared to conventional dental glass-ceramics [1, 2]. Metal-based restorations can be fabricated conventionally via casting techniques or alternatively with Laser-sintering (Bego Medical, G). There should be only small differences in composition and final structure of the alloys, independent of whether they are laser-sintered or conventionally melted.

The computer-based fabrication process is started by digitizing the clinical situation with a 3-D scanner, and then the cores of the restorations are then CAD-designed and finally fabricated in the particular CAM process. One system allows for the alternative scanning of wax-up-models (Cercon). A weak point in view of processing and strength may be that the CAD/CAM cores had to be veneered with comparable low-strength conventional glass-ceramics in press- or layering technique. Chipping of the veneering ceramic has already been reported in the past with porcelain fused to metal (PFM) restorations [3], but especially chipping of veneering ceramic from zirconia is widely discussed [4-6] with the rise of the actual zirconia systems. Basic effects of the veneering on the interface core/veneering [7] as well as on fracture performance of two- or three-layer specimens are reported and help in understanding the failure mechanisms [8-10]. Laboratory results allow for predicting the combination of different material layers, but failure type and pattern may vary for clinically relevant restorations. A main reason may be found in the individual design and dimension of a special restoration where, for example, the compliance of veneering thickness is difficult to achieve. On the other side, the in-vivo conditions may differ from loadings in the laboratory. For investigating the performance of new materials, fracture benchmark tests were performed. However, these static test on dental restorations may reveal a different failure pattern in comparison to the in-vivo situation [11, 12]. Beyond this, the influence of improper, alternative tooth abutment material (e.g. steel) [13-15] may falsify the results. Simulation procedures with dynamic loading and thermal cycling with clinically relevant chewing forces and bath temperatures may help for aging the specimens and cause a clinical-approximated
performance of the restorations [16, 17]. Failures, which appear during simulation can be compared to failures during oral application and may help to estimate the lifetime of new materials. If no failure occurs during simulation, a subsequent static fracture test may allow for locating initiated weak points or at least compare the tested materials to clinically well-known systems. Basic fractographic information [18, 19] that describes ceramic failures as initiated by flaws or damages from the marginal side or occlusal surface [12] contribute to valuating the results.

The aim of this investigation was to evaluate the failure force and fracture performance of different all-ceramic- and metal-based crowns after simulation of oral service. The influence of the crown dimension and type of cementation on the fracture should be determined.

### 7.3 Materials and Methods

The roots of the human molars (n=96) were coated with a 1 mm thick layer of polyether material (Impregum, 3M Espe, Germany) to simulate human periodontium, and inserted into PMMA resin (Palapress Vario, Kulzer, Wehrheim, Germany). This layer allows a maximum mobility of the tooth in axial and vertical directions of 0.1 mm at a load of 50 N. Human molars were used to ensure a clinically relevant modulus of elasticity of the abutments and to simulate a relevant bonding between crowns and tooth. All teeth were prepared according to the directives for ceramic restoration techniques, using a 1 mm deep circular shoulder crown preparation. Sixteen crowns of each material group listed in Table 7.1 were fabricated according to the manufacturer’s instructions. All frameworks were veneered with the corresponding veneering ceramics.
Table 7.1: Materials, manufacturer and type of cementation.

<table>
<thead>
<tr>
<th>Core/ Veneering</th>
<th>Manufacturer</th>
<th>Conventional Cementation</th>
<th>Adhesive Bonding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biopont/Vita Omega</td>
<td>Bego, G/Vita Zahnfarbik, G</td>
<td>Harvard, Richter &amp; Hoffmann, G</td>
<td>Syntac classic/ Variolink2, Ivoclar- Vivadent, FL</td>
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<td>Lasersintering</td>
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<td>Cenovation</td>
<td>ce.novation, G</td>
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<td>Cercon/Cercon Ceram Kiss</td>
<td>DeguDent, G</td>
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<td>Digizon/GC Initial</td>
<td>Girrbach, G/ GC, USA</td>
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<td>Lava/Lava Ceram</td>
<td>3M Espe, USA</td>
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<tr>
<td>Inceram (Wolceram)/Vita Alpha</td>
<td>Wolceram, G/Zahnfarbik, G</td>
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</table>

For comparing the type of cementation, eight crowns of each group were adhesively luted with dual-curing composite (Variolink2, Syntac classic, Ivoclar-Vivadent, FL), and eight crowns were cemented with conventional zinc-oxide-phosphate cement (Harvard, Hoffman & Richter, Germany). The dimensions of the investigated teeth and crowns were determined for the adhesive/conventional cementation: height of the crown [mm]: 6.8 ± 1.1 / 6.9 ± 1.0; length of the root [mm]: 11.5 ± 2.2 / 10.9 ± 2.0; length distal-mesial [mm] 9.4 ± 1.4 / 9.0 ± 1.6; and length palatinal-buccal [mm]: 9.9 ± 1.0 / 9.9 ± 1.1.

An artificial aging was performed to simulate a 5-year period of oral service. The loading parameters were [16]: 1 200 000 mechanical loads with 50 N and a simultaneous thermal cycling with distilled water between 5°C and 55°C (3,000 times with 2min each cycle). A human molar was adjusted as antagonist in a dental articulator (Girrbach, G) and tooth and crown were transferred to the simulator. Antagonist-tooth relation was controlled with an occlusal foil. Aging was interrupted each 100,000 mechanical loadings and the crowns were optically investigated for failures (fracture, chipping).

Fracture testing: After aging, all crowns were loaded until failure using a testing machine (Zwick, Ulm, Germany, v=1 mm/min). The force was applied using a steel ball (d=12 mm) while a tin foil (1 mm) between crown and antagonist was used to prevent force peaks. The
crowns were optically examined before and after fracture testing. Failure mode was divided into initial crack, chipping in the veneering ceramic, chipping down to the framework and fracture of the core or the tooth (Fig. 7.1). The location and the size of failure were analyzed in mesial, distal, buccal or lingual direction.

Fig. 7.1: Type of failure

Medians and 25%/75% of the fracture resistance (N) were calculated. Statistical analysis was performed using One-way ANOVA and Kruskal Wallis test (α=0.05) (15).

7.4 Results

The mean fracture resistance of the tested systems varied between 1111 N and 2118 N with the conventional cementation and 1181 N and 2295 N with adhesive bonding. All tested systems showed no significant different fracture force after either conventional or adhesive cementation. The fracture force with adhesive bonding was lower for the systems Biopont laser, Digizion and Lava compared to conventional cementation, whereas the other systems revealed higher fracture strength with adhesive bonding (Fig. 7.2).

Main failure types were chippings of the veneering ceramic. For Cercon and Wolceram, one fracture of the framework could be found with both types of cementation. For Cennovation, one core fracture could be determined with conventional cementation and two core fractures with adhesive bonding. In only one case of the Cercon group with conventional cementation was a tooth fractured observed. The detailed fracture pattern is shown in Table 7.2.
Fracture performance of computer aided manufactured zirconia and allow crowns.

**Fig. 7.2:** Fracture force [N] after TCML (mean, standard deviation std).

![Fracture force graph](image)

**Table 7.2:** Number [n] and type of failure (defect type see Fig. 7.2.).

<table>
<thead>
<tr>
<th></th>
<th>adhesive / conventional</th>
<th>tooth</th>
<th>core</th>
<th>chipping</th>
<th>crack</th>
<th>fracture in the veneering</th>
<th>fracture between framework and veneering</th>
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<tr>
<td>Digizon</td>
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<td>8</td>
<td>3</td>
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<td>Lava</td>
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<td>Cenovation</td>
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<td>7</td>
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<td>Cercon Kiss</td>
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<td>Wolceram</td>
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<td>Biopont</td>
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<td>Biopont laser</td>
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The share of the failed veneering was related to the surface of the whole crown. Here we found failures between 5% and 32% (Fig. 7.3).

**Fig. 7.3:** Crown area [%], which was affected by failure (mean, std).

PFM restorations and Cercon Kiss (adhesive) provided the lowest share of failed veneering with values of about 10% or lower. No significant differences in the propagation of the defects could be determined whether adhesive bonding or conventional cementation was used. The defects in tendency were broader on mesial and distal tooth-sides compared to labial or palatinal sides (Fig. 7.4a/b).
Fig. 7.4a: Crown area [%], which was affected by failure (mean, std; distal / mesial side)

Fig. 7.4b: Crown area [%], which was affected by failure (mean, std; palatal / labial side)
7.5 Discussion

Neither the fracture force nor the fracture pattern revealed significant differences between the adhesive and conventional cementation of the tested crowns. Assuming that the strength of the tested ceramic crowns was reduced by cycling loading [20, 21], which in our case was supposed to simulate oral service of about five years [17] the fracture loading of the tested systems after TCML was high enough to resist chewing forces in posterior applications. The results exceed postulated requirements of 500N for replacing posterior teeth [22].

All results showed that a broad distribution of the fracture values restricts the significance of the investigation, indicating the high individuality of the restorations. On the other hand, the measured dimensions of the crowns had no significant influence on the fracture results, as described for crown material or thickness [14]. The wide distribution of the results may be explained by the Weibull distribution for ceramic materials in combination with individual veneering dimensions of the crowns. This means that the distribution of the results already starts at low values, increases to a maximum and finally shows a steep decrease [23]. Beyond this, the fracture behaviour of a ceramic is strongly influenced by fabrication and defect size (density, severity, flaws, voids or cracks) [24]. Improper finishing of the abutment or occlusal surface may cause additional microstructure damages.

The hipped sintered zirconia (Digizon) showed no strength advantages compared to the other systems that were milled in a pre-sintered state (and sintered to the final dimensions after milling) or fabricated in a grow-up process. The electrophoretically manufactured alumina crowns and one zirconia system provided lower fracture values between 1180 N and 1310 N, but they were not statistically different from the PFM crowns [25]. Comparing the two PFM crown types with each other, there was also no statistically significant difference.

Contrary to expectations the fracture results were comparable to adhesively bonded glass- or leucit-reinforced all-ceramic systems [15, 26, 27]. In contrast to results for ceramics with a lower modulus of elasticity (~100GPa) [14], different cement properties with differences of Young’s modulus or compression strength did not contribute to the fracture resistance. It can be argued that the fracture strength depended on the strength of the weakest part of the crown.

Whereas glass-ceramic is reported to fracture, the tested systems with higher strength core ceramic provided chipping of the comparable low-strength veneering ceramic in most cases in contrast to the fracture of the high-strength core. This confirms laboratory bonding results where reduced bond strength is described as related to the veneering ceramic [7].

The SEM fractographic analysis showed that the fracture origin was located on the occlusal surface in most cases. Here, the antagonist caused wear or superficial flaws during TCML, which in the following fracture test was the origin of the fracture or chipping (Fig. 7.5).
These results are partly in agreement with investigations on in-vivo failures on glass-ceramic systems where a failure pattern from occlusal and marginal areas was described [12]. SEM pictures also demonstrated that chipping may be divided into two different types: on one side, chipping was interfacial between cores and veneering ceramic. On the other side, the crack ran in the veneering itself. In this case, a thin layer of the veneering ceramic remained on the core material. It is supposed that the fracture strength of these high-strength restorations is therefore influenced by the strength of the veneering material itself and the veneering-core bonding. Both failure patterns are described in laboratory investigations on specimens [9, 10], but some authors describe mainly interfacial [7] or inter-veneering failures [26]. The results underline the requirement for a core design that supports the occlusal veneering ceramic [28, 29]. Insufficiently performed occlusal adaptation of the veneering may cause superficial defects that may cause chipping damage in long term [30]. Among others, the survival of a high-strength zirconia restoration is therefore dependent on the quality and the handling of the low-strength veneering.

It can be concluded that adhesive bonding, as required for other non-zirconia ceramic systems, seems unnecessary for high-strength ceramics and may therefore allow an easier application even under subgingival or moist conditions. The described failure modes indicate a high strength of the core materials as well as the sufficient bonding between the zirconia and veneering. Summarizing the results, all tested systems showed good to sufficient fracture resistance and no influence of the type of cementation on the fracture resistance or fracture pattern. For reducing chipping and increasing fracture resistance, an occlusal supporting framework design should be guaranteed.
7.6 References
