Validation procedures in computerized dentistry
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Citation for published version (APA):

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CHAPTER 7

Effect of design parameters on the failure strength of PRIMERO crowns

Keywords: CAD/CAM, zirconia; high-strength crowns; digital veneering.
7.1 Abstract

Objective: With this in vitro study the fracture strength of zirconia-based crown copings with different design veneered with a CADVeneer porcelain layer are compared.

Methods: A 1.2 mm, 360° chamfer preparation was performed on a first central incisor was duplicated in gypsum for scanning, and in a cobalt–chromium-alloy for testing. A crown with dentin layer was designed with the CYRTINA CAD/CAM system (Oratio, NL-Zwaag). A sample of 5 zirconia copings [N=5] was produced in five different designs and divided into five groups of five. The five designs consisted of zirconia copings with a uniform thickness of 0.6 mm (G1), with an anatomically reduced shape (G2), with a porcelain shoulder of 0.7 mm (G3), a uniform thickness of 0.6 mm with a lingual band (G4), and an anatomically reduced shape with a lingual band (G5). The coping was pressed over with Cyrtina Enamel porcelain, and the outer contour was milled and glazed. All crowns were cemented conventionally onto the metal die and tested in the universal testing machine until clinical failure. The fracture load data were compared by a one-way analysis of variance and a multiple comparison posthoc test ($P < 0.05$).

Results: Specimens from group G1 showed a mean (S.D.) fracture load of 6661.0 (1059.52) N, G2 7768.3 (660.02) N, G3 4625.5 (1241.64), G4 7301.6 (573.06) and G5 8009.5 (272.86) N. The difference between groups 1 and 4 was statistically significant ($P < 0.05$).

Significance: The new CAD/CAM-fabricated bilayered restorations with an anatomically designed coping were superior to the crowns with coping with uniform thickness in terms of fracture load and offer the possibility to produce cost-effective crowns and fixed partial dentures with a potential lower risk of chippings. A porcelain shoulder significantly reduces strength.
7.2 Introduction

Metal-free, all-ceramic restorations have become more widely distributed due to their high esthetic potential and their excellent biocompatible properties [1], [2], [3], [4], [5], [6], [7], [8] and [9]. Today, many framework structures for prosthetic restorations are fabricated in CAD/CAM procedures, which means that a major part in the working sequence is carried out by means of industrial machines [1], [10], [11], [12] and [13]. On the one hand, frameworks can be fabricated more efficiently. On the other hand, it is possible to achieve industrial quality standards, which are particularly important for ceramic materials. Every pore and imperfection is a potential starting point for cracks and thus for the clinical failure of ceramic restorations. The frameworks made of glass-infilt rated oxide ceramic fabricated in the slip technique exhibited large spectra of strength distribution related to the fabrication process resulting in a low-Weibull modulus [14]. Using the same ceramic material in the form of industrial prefabricated blocks and applying the milling technique, the Weibull modulus of oxide ceramics and thus the reliability of the restorations was significantly increased [14]. However, to-date the veneering material has been layered according to the well-known fabrication process of the metal-ceramic technique. According to ISO 6872 and 9693 standards a minimum flexural strength of 50 MPa for veneering glass-ceramics is required. The bond between veneering ceramic and zirconia framework is currently the subject of comprehensive investigations [15] and [16]. The typical failure pattern of a veneering material in the daily clinical practice is known as ceramic chipping [17] and [18]. This fracture pattern is associated with a thin layer of glass-ceramic that remains on the zirconia framework [11], [12], [17] and [18]. This indicates a reliable bond of veneering ceramics to the framework, but also reveals a weakness of the veneering porcelain. A possible reason for the incidence of chippings may be found in the former limited CAD-software options by which crown and fixed dental prosthesis (FDP) frameworks could not be machined to an anatomically reduced form, offering adequate support to the veneering material. In contrast many systems could offer only uni-thickness copings for crowns as well as bar-shaped connectors for FDPs. Therefore with these systems, veneering ceramic had to be applied in thick layers to accomplish functional and esthetic demands without any cusp support [11] and [19]. For metal-ceramic restorations, it was reported, that inadequate framework design represents one important reason for an unfavorable failure rate of the veneering material [20]. Modern CAD/CAM-systems are able to provide a considerably better anatomically cut back framework design, thus future clinical long-term results may be more favorable [11] and [19].
From an economical point of view, the esthetic and functional completion of crown and FDP frameworks involving traditional methods, such as the powder layering technique, appears to be inefficient. One possibility for increasing the cost-effectiveness involves the industrial fabrication of veneered crowns by machining of the entire restoration by means of CAD/CAM technologies [21]. Restorations made out of mono-blocks of either leucite-reinforced glass-ceramics with a flexural strength of around 100–150 MPa with mandatory adhesive cementation, or lithium-disilicate reinforced glass-ceramics exhibiting a flexural strength of 350–400 MPa, with the option of conventional cementation. Therefore, the indication range is strongly limited to single crowns and small FDPs [8], [12], [14], [22], [23] and [24]. The combination of a CAD/CAM-fabricated framework with CAD/CAM-fabricated veneering would be of major interest.

The authors introduced a new procedure for veneered all-ceramic crown restorations using a CAD/CAM-fabricated high-strength zirconia coping and a layer of porcelain veneering material. It can be assumed that the new procedure of producing a core with veneer layer by the PRIMERO CADVeneer method leads to an increase in mechanical strength compared to traditional techniques enabling a lower clinical chipping rate of the veneering material.

### 7.3 Materials and methods

A 1.2 mm, 360° chamfer preparation was used on a central first incisor (Fig. 7.1a). The chrome-cobalt die was duplicated with a silicon impression (Optosil, Heraeus Kulzer, Hanau, Germany) material and the cast gypsum die was scanned with a “D250” (3Shape A/S, Copenhagen, Denmark). Different core shapes were designed designs incisor was designed using Cyrtina®CAD software (Fig. 7.1).

![Figure 7.1: The die and two coping designs used (G1 and G5).](image)
For the coping a minimum wall thickness of 0.6 mm and a virtual spacer layer of 20 μm were chosen. After the milling procedure the enlarged copings were removed from the CAM-machine and final sintering was performed in a special sinter furnace (Nabertherm) at 1460°C for 2 hours. The frameworks were examined for debris, corrected if necessary and cleaned by air abrasion with 50 μm aluminium oxide at 0.5 bar pressure. The frameworks were evaluated on the dies by visual inspection under a microscope with a magnification of eight (Stemi DV 4, Zeiss) for marginal discrepancy. Copings were rejected if the margin was rated visually unacceptable by two investigators. Undercontoured frameworks and frameworks which could be rotated on the definitive die under finger pressure were also rejected. New copings were fabricated on the same dies to replace the rejected specimens. Twenty-five acceptable frameworks were achieved and adapted until the best possible fit was achieved. The adaptation was made by an experienced dental technician with a magnification of eight (Stemi DV 4, Zeiss) according to the literature [25].

As the result of the framework fabrication three copings for each of the 15 testing models were available. The sample of 45 copings was divided into three groups so that for each of the 15 testing models one adapted coping existed.

**Veneering technique**

The layering technique was applied to veneer the copings of the five groups using the PRIMERO technique.

*Figure 7.2: Veneered crown after CAD/CAM-fabrication process.*

The coping was fabricated, pressed over with veneer material and milled back to the outer contour. Finally, the restorations were completed with one stain and glaze firing cycle at a
temperature of 750°C. A calibrated dental technician who was experienced in veneering ceramic frameworks inspected the specimens.

*Cementation of the crowns*

After glaze firing, each crown was fixed on the cobalt-chrome die with Harvard zinc phosphate cement (Richter und Hoffman). The internal walls of the crowns were aluminium oxide abraded (50 μm particle size, 0.5 bar pressure) prior to cementation. The retainer was set back onto the definitive die with finger pressure, and the excess cement was removed. A special cementing device was used to ensure that the crown was loaded centrally at a force of 50 N for 10 min. All cementations were done by the same team of an experienced dental technician, who sat the crowns onto the die. All restorations were stored in distilled water at a temperature of 37 °C for at least 48 h until they were loaded for the fracture test.

*Load until fracture*

All crowns were put into the universal testing machine (Testometric 350-10CT, Hartech, Netherlands) and finally loaded until fracture occurred. Before the load was applied, the specimens were ground flat at the top to ensure a plane-contact between the top of the crown and the pressure plate. The load was applied with an 8 mm diameter stainless steel ball placed on the occlusal surface of the crowns and a crosshead speed of 0.5 mm min\(^{-1}\) [27], [28] and [29]. To distribute the applied force over a larger area and avoid loading stress peaks on the veneering material, a 1 mm thin piece of aluminium was placed between the pressure plate and the crown (Fig. 7.3).

*Figure 7.3: Testing setup in the universal testing machine.*

Fracture was defined as occurrence of visible cracks in combination with load drops and acoustic events or by chipping which made the crown clinically unusable.

The loads at fracture were registered, and differences between the groups were calculated using a one-way analysis of variance test (ANOVA) at a significance level of 5%.
Additionally a multiple comparison posthoc test (Student–Newman–Keuls) was performed to evaluate differences between the experimental groups.

<table>
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<tr>
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<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error</th>
<th>95% Confidence Interval for Mean</th>
<th>Minimum</th>
<th>Maximum</th>
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<td>Lower Bound</td>
<td>Upper Bound</td>
<td>Lower Bound</td>
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<td>291,19562</td>
<td>6272,2338</td>
<td>7474,2302</td>
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</table>

Table 7.1: Mean, standard deviation, maximum and minimum of fracture loads from five experimental groups.

Figure 7.5: Fracture load of different experimental groups.
7.4 Results

The mean and standard deviation of fracture strength values for the five experimental groups are shown in Table 7.1 and Fig. 7.5.

Two failure types were observed: total fracture, through both core and veneer and partial fracture through the veneer only (chipping). Total fractures were more frequent in the ST group (six) while four total fractures occurred in the OT group and no total fracture was observed in group VT. In all instances of partial fracture, the fracture was cohesive within the veneer material (Fig.’s 7.6-7.7).

![Figure 7.6: Cohesive fracture of a specimen from group 1.](image1)

![Figure 7.7: Cohesive failure in the porcelain (V=200x)](image2)

![Figure 7.8: Section through zirconia (r) and Cyrtina Enamel (V=500x)](image3)

Crowns of group 2 and 5 showed significantly (P < 0.05) higher fracture strengths compared to crowns of group 1 and 4 (Table 7.2). The Student–Newman–Keuls test indicated two subgroups, which exhibited statistically significant differences (Table 7.3).

<table>
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<tr>
<th>Group/Design of coping</th>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
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<td>X</td>
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<td>0.00101</td>
<td>0.240332</td>
<td>0.019187</td>
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<td>G2: Anatomical coping</td>
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<td>8.32E-06</td>
<td>0.388468</td>
<td>0.653606</td>
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<td>G3: Porcelain shoulder</td>
<td>0.00101</td>
<td>8.32E-06</td>
<td>X</td>
<td>6.05E-05</td>
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<td>G4: G1 mit Lingualem Band</td>
<td>0.240332</td>
<td>0.388468</td>
<td>6.05E-05</td>
<td>X</td>
<td>0.196179</td>
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<td>G5: G2 mit Lingualem Band</td>
<td>0.019187</td>
<td>0.653606</td>
<td>3.09E-06</td>
<td>0.196179</td>
<td>X</td>
</tr>
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</table>

Table 7.2: ANOVA (P=0,05)-Analysis: Green indicates significant difference between two groups.
<table>
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<th>(I) crown type</th>
<th>(J) crown type</th>
<th>Mean Difference (I-J)</th>
<th>Std. Error</th>
<th>Sig.</th>
<th>95% Confidence Interval</th>
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*Table 7.3: Multi-comparison posthoc test (Student–Newman–Keuls) indicating two statistically different (P < 0.05) homogeneous subgroup.*
7.5 Discussion

It has been suggested that test specimens should have the same critical flaws as crowns made for clinical use and the environmental influences should be reflected in the laboratory settings [32]. The approach chosen in the present study was considered justified as the study design took aspects regarding test specimens, environmental influences and test mode into account.

The recommendations concerning tooth preparation design, dimensions, and shape of the zirconia core are identical for crowns veneered with porcelain. The approach for the new way of veneering was to produce identical restorations concerning dimension and core design. In all five groups, the cores were accomplished as if they were intended for clinical use. The veneer application and milling were performed according to a proprietary method, with appropriate dimensions and identical for all five groups. Cementations were made according to the manufacturer's recommendations, with zinc phosphate cement on metal-dies. According to Scherrer, increasing elastic modulus of the supporting material results in increased fracture strength [30]. The elastic modulus of the supporting die was 200 GPa, superior to that of dentin which is 12 GPa [30]. If natural teeth were used as the supporting model, the fracture strength of the crowns might have been lower [31]. However, natural teeth would have been destroyed during the testing at the high fracture loads [32]. Loading conditions and cementation were identical for all specimens.

Ceramic structures tend to fail because of surface tension, where cracks and flaws propagate by slow crack growth leading to the catastrophic failure [33]. In all-ceramic systems, the flaw population (size, number and distribution) can be related to the material, or be affected by the fabrication process. Thus, it might be expected that the heat pressing introduces fewer flaws than layering, resulting in better strength properties, as it is a more controlled procedure. By comparison, the layering technique is more sensitive and subject to variability due to the individual building and firing procedures. Nevertheless, no statistically significant differences were found in the fracture loads between group G1 and G4 and between G2 and G5. A study which compared fatigue of veneered and heat pressed zirconia crown systems also found no statistical difference between veneering by layering and by heat pressing in terms of mechanical stability [34]. The homogeneity and the distribution of flaws may be similar between test groups. It is reasonable that the failure mode of zirconia-based all-ceramic restorations veneered with a relatively weak porcelain – assuming a good bond – tends more to cohesive chipping of the porcelain. Thus, the relatively weak veneering porcelain (90 MPa) of the specimens led to cohesive fractures, where a thin porcelain layer still remained on the
zirconia coping. This type of failure indicates the good interfacial bond between the core and the veneer material that is critical for the success of these composite structures [35].

The fracture strength of specimens with a shoulder of veneering porcelain was significantly lower (\(P < 0.05\)) than that of the other groups tested. The main reason is probably due to the non-supporting shoulder, initiating a crack. The number of total fractures also expresses the stability of the zirconia-based crowns. Fifteen of the 25 specimens failed catastrophically at a very high fracture load. Second the CAD/CAM-process uses high quality material with a minimum of flaws compared to the manual procedures of veneering. The fact that ten cohesive fractures were observed also indicates that a good interfacial bond is achieved using the PRIMERO technique.

Catastrophic failure as a result of contact loading has made it difficult to identify whether cone cracking or subsurface damage was responsible. It is supposed that both processes may occur at the failure site as reported by previous studies [35].

The specimens were fabricated merely by the CAD/CAM technique, which leads to a significant reduction in the fabrication time for such restorations. The increase in the strength of such systems may result in greater clinical reliability of restorations.

All groups evaluated showed greater fracture loads than most available literature and exceeded the maximum chewing forces [13], [22] and [34]. However, clinical failure of zirconia-based restorations was reported [18], [19], [36] and [37]. It is supposed that fatigue has a major effect on the mechanical stability and explains the high values compared to similar studies, such as fatigue, not taken into account in this study [13] and [34]. The abutment material, as mentioned above, has a significant influence and increased the fracture load in this study [30] and [31]. Similar fracture loads have been reported with titanium abutments [28]. The diameter of the loading piston can also influence the fracture strength of all-ceramic restorations [38]. One of the possible reasons for the relatively high strength values are a consequence the automated way of production without manual processing, resulting low defect restoration (Fig. 7.8). This study also used a piston with a larger diameter than comparable studies to ensure the three-point-contact of the piston to the occlusal surface of the specimen. Increasing the loading angle can lead to lower fracture strength [38]. However, comparable studies did not mention the angle of the loading direction [34] or showed similar angles [13] and [22].

The standard deviation of up to 36% was in the same range [22] or higher compared to similar studies [13] and [34]. This can be explained by the design of the specimens as they were
designed as crowns for clinical use in this study. Other studies reporting lower standard deviations used more simplified shapes of the occlusal surface [13] and [34].

**7.6 Conclusion**

According to the results of this study layering porcelain on different designs of zirconia copings showed significant differences in the fracture resistance of zirconia-based single crowns, although different fracture patterns considering partial or total fracture could be observed. However, the sintering of a CAD/CAM-milled veneer layer on anatomicallly designed copings leads to a significant increase of mechanical stability. This enhances the clinical reliability of zirconia-based restorations. Additionally this technique leads to an extremely cost-effective fabrication of all-ceramic veneered crowns merely using CAD/CAM facilities for the production of the crowns.
7.7 References


