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Research Paper

Load-bearing capacity of soldered and subsequently veneered 4-unit zirconia FDPs

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ABSTRACT

Objectives: This study evaluated and compared the impact of soldering on fracture resistance of veneered 4-unit fixed dental prostheses (FDPs).

Materials and methods: Forty-eight 4-unit zirconia frameworks were milled and randomly divided in four groups ($n=12$). Untreated frameworks served as control, one group underwent thermal treatment, one group was sectioned and soldered in the connector between both pontics and one group was sectioned and soldered centrally in the mesial pontic. All frameworks were veneered with glass-ceramic material in powder build-up technique. The fracture load was determined on two different failure types, namely on chipping of the veneering ceramic and on total fracture of the FDP. Data were analysed using descriptive statistics, one-way ANOVA together with the Scheffé post-hoc test and Weibull statistics ($p<0.05$).

Results: The mean range of fracture load of chipped FDPs was determined between 655 N and 789 N; no differences between the tested groups were found ($p=0.587$). The mean fracture load until total fracture ranged in all tested groups from 768 N to 1261 N. Sound FDPs and soldered FDPs in the connector area presented lower mean total fracture load compared to soldered FDPs in the pontic ($p<0.001$).

Conclusions: Soldered zirconia frameworks showed similar in-vitro performance compared to sound frameworks.

1. Introduction

Zirconia based restorations exhibit high biocompatibility (Piconi and Maccauro, 1999), good aesthetics and similar mechanical properties compared to those of metal-ceramics (Filser et al., 2001). Therefore, zirconia is suitable to substitute metal-ceramic for fixed dental prostheses (FDPs). The clinical applicability of yttria-stabilized zirconia (Y-TZP) for posterior FDPs has been presented in several studies (Vult von Steyern et al., 2005; Edelhoff et al., 2008; Sax et al., 2011). Zirconia restorations can be produced from prefabricated blanks by Computer Aided Design (CAD)/Computer Aided Manufacturing (CAM) milling technique. Dependent on the type of blank used, there are two different strategies for processing zirconia. First, milling can be performed in a full-sintered stage. As no further sintering is needed the fit of these frameworks is very good (Tinschert et al., 2001; Vult von Steyern et al., 2005). However, this approach is associated with shortcomings,

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such as high wear of the milling instruments and an extended milling time because of slower feed (Tinschert et al., 2001; Vult von Steyern et al., 2005). With the aim of eliminating these technical difficulties, another technique for manufacturing zirconia was developed which allowed the frameworks to be fabricated from pre-sintered zirconia (Beuer et al., 2009b). For achieving optimal mechanical properties these pre-sintered restorations have to be sintered to full density. This post-milling heat treatment is attended by a high sintering shrinkage ranging from 15% to 30% (Reich et al., 2005; Sax et al., 2011) thus demanding the correction of the resultant changes in framework dimensions. Both the mechanical properties of the material and the specified fabrication process can considerably affect the long-term clinical performance. The fit of restorations milled from pre-sintered blocks might be inferior due to inaccuracies resulting from the sintering shrinkage, the scanning procedure, compensatory software design, and milling process. In-vitro investigations have failed to show the superiority of CAD/CAM zirconia frameworks over cast alloy frameworks regarding fit (Reich et al., 2005; Wettstein et al., 2008). Moreover, the sintering shrinkage of the pontic and distortion of the zirconia framework during post-milling sintering of 3- and 4-unit FDPs has been shown to affect marginal and internal fit (Kunii et al., 2007). Clinical studies also reported poor marginal fit for zirconia frameworks associated with biological problems (Sailer et al., 2006; Sax et al., 2011). Poorly fitting restorations may accelerate mechanical failure, due to abutment caries or screw failure in the case of implant abutments (Felton et al., 1991). Furthermore, the advent of implants in dentistry necessitated passive fit of complex restorations (Abduo et al., 2011). In tooth-supported restorations, the periodontal ligament and the cement layer can compensate inaccuracies to a certain extent. However, for FDPs on rigid implants, a higher precision is required. CAD/CAM milling of pre-sintered zirconia was reported to lead to a magnitude of distortion similar to that after casting frameworks with CoCr alloys (Abduo et al., 2011). Soldering might be the answer for trying to overcome deficient fit. It may improve dimensional precision or reduce the distortion. For metal cast alloys, soldering has been applied for many years. In soldering alloys, an intermediate alloy or solder is employed to unite the parts to be joined (Byrne, 2011). For zirconia, zirconhotbond, a silica-based ceramic solder, is available on the market for the joining of zirconia understructures in dentistry. To our best knowledge, there are no studies evaluating the influence of soldering of zirconia restorations on fracture load results. Therefore, the purpose of this study was to examine the influence of soldering on the fracture load of 4-unit FDPs. The hypothesis tested was that soldered FDPs show lower fracture load values compared to non-soldered ones.

2. Material and methods

This study tested the fracture load of zirconia FDPs soldered with zirconhotbond DD Bio ZS. The list of materials used in this study, the manufacturers and their lot numbers are presented in Table 1.

2.1. *Master model*

In order to produce standardized frameworks, a steel model with two abutments simulating an FDP between a canine and a first molar was used. Abutments of this model had flat occlusal surfaces and a ball end. They were cylindrical (height: 5 mm; diameter canine: 7 mm; molar: 8 mm) with a 1 mm circular shoulder and 6° taper and were surrounded by a 0.75 mm layer of plastic cover that allowed for simulation of the periodontium (Rosentritt et al., 2011). The holder of the test set-up was made of aluminium alloy having cylindrical holes in a distance of 23.2 mm.

2.2. *Fabrication of the zirconia frameworks*

The shape of the steel model was digitised (inEos Blue, Sirona, Bensheim, Germany) and an anatomically supported zirconia framework was designed (Cerec 3D, software version 3.10, Sirona). 48 identically-shaped 4-unit frameworks were milled from pre-sintered zirconia (DD Bio ZS blanks, Dental Direkt, Bielefeld, Germany) using a labside CAD/CAM-system (Cerec MC XL, Sirona). The connectors had a cross-sectional area of 13.7 mm^2, an occluso-gingival height of 3.5 mm, and a buccolingual width of 5.0 mm.

After milling, the zirconia frameworks were randomly divided into four groups ($N=48$, $n=12$ per group). Group 1 was left sound; group 2 was submitted to thermal treatment (Table 2). The frameworks of group 3 and 4 were separated each at one point using a diamond separating disc (Dynex Separating discs Brillant, Renfert, Hilzingen, Germany). In group 3, the frameworks were separated perpendicularly at the mesial pontic, in group 4 in the connector area between the first premolar and the second premolar. The gap width amounted to 0.7 to 1.0 mm. In order to achieve neat cutting surfaces, they were reworked with a water-cooled air-turbine (KaVo, EXPERTtorque E680 L, Biberach/Ri, Germany). Subsequently, the enlarged frameworks were sintered to full density according to the manufacturer's instructions (Vita ZYromat, Vita Zahnfabrik, Bad Säckingen). The surfaces to be joined were air-abraded (CEMAT NT4, Wassermann Hamburg, Germany) using alumina powder (10 s, 2 bar, distance: 10 mm) with a mean particle size of 50 μm (Renfert, Hilzingen, Germany). Then, the separated frameworks were soldered with a ceramic solder (zirconhotbond, DCM GmbH, Rostock, Germany). A silicone key (dentona 1:1 gum, Dentona AG, Dortmund, Germany) was made by using of a sound FDP to achieve standardized fixation of the separated frameworks on the plaster model. The zirconia surfaces to be soldered were evenly covered with the zirconhotbond (DCM GmbH) material. The two parts of the framework were assembled on the plaster model, the fit was verified by means of the silicon key, and additional solder material was applied. Subsequently, the solder material was solidified by applying heat from a high power hair dryer. In order to avoid any movement of the segments during the sintering process, liquid firing cotton (zirconhotbond fix, DCM GmbH) was used to create a custom firing tray. The FDP was placed on a regular firing tray (Vita Zahnfabrik, Bad Säckingen, Germany) and the solder was sintered according to the manufacturer's instructions (Vita Vacumat 40 T, Vita Zahnfabrik). After cooling to room temperature (20 °C) finishing was performed with diamond burs under water-cooling on the outside.

2.3. *Veneering of the zirconia frameworks*

Veneering ceramic for dentin (Vita VM9, Vita Zahnfabrik) was applied on the zirconia framework using a silicone key (dentona 1:1 gum) to achieve standardized shape and size of the FDPs. In a second firing, dentin was added in order to compensate for the sintering shrinkage. Finally, glaze paste was applied on the FDPs and fired (Table 2). Firings were performed according to the instructions of the manufacturer using the recommended prior calibrated ceramic furnace (Vita Vacumat 40 T, Vita Zahnfabrik). After veneering the connectors had a cross-sectional area of 41.7 mm^2, an occluso-gingival height of 6.4 mm, and a buccolingual width of 8.3 mm. Both pontics showed a cavity in their middle congruent to the loading stainless steel ball (diameter 5 mm) ensuring a 3-point-contact between the steel ball and the occlusal surface at loading.

2.4. *Fracture load measurement*

The non-cemented veneered FDP was loaded at a cross-head speed of 1 mm/min with two balls (diameter 5 mm) placed on the centres of the pontics in a universal testing machine (Zwick/Roell Z010, Zwick, Ulm, Germany). The fracture load was determined on two different failure types, namely on chipping of the veneering ceramic and on total fracture of the FDP. In order to prevent force peak and to achieve homogeneous load distribution on the pontics a piece of 0.2 mm Teflon foil (Angst+Pfister, Zürich, Switzerland) was placed between the ball and the pontics. The design of the 4-point fracture load test is shown in Fig. 1.

2.5. *Statistical analysis*

The descriptive statistics such as means, standard deviation (SD) and the corresponding 95% confidence intervals (95% CI) were calculated for the failure types total fracture and chipping for each group separately. One-way ANOVA together with the Scheffé post-hoc test was applied in order to investigate the differences of fracture load between the groups. Additionally, the Weibull statistics (shape, scale) were

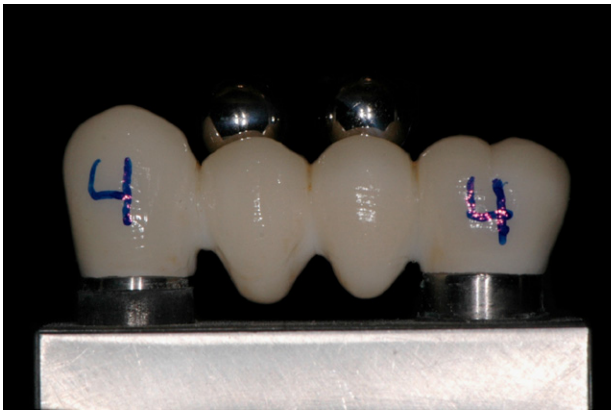

Fig. 1 – Design of the 4-point fracture load test.

Table 1 – Summary of products used.

Materials	Name	Manufacturers	Lot. no.
Framework zirconia	DD Bio ZS	Dental Direkt, Bielefeld, Germany	50,400,745
Veneering ceramic	Vita VM9	Vita Zahnfabrik, Bad Säckingen, Germany	136,010
Ceramic solder	zirconhotbond	DCM GmbH, Rostock, Germany	060,801

Table 2 – Firing schedules of thermal treatment, veneering ceramic and solder.

	Vacuum		Heating rate (°C/min)	Firing temperature (°C)	Holding time (min)
	On at temperature (°C)	Off at temperature (°C)			
Thermal treatment					
	450	1000	30	1000	3
	Pre drying		Heating rate (°C/min)	Firing temperature (°C)	Holding time (min)
	Temperature (°C)	Time (min)			
VITA VM 9					
Dentin 1	500	6	55	910	1
Dentin 2	500	6	55	910	1
Glaze firing	500	–	80	900	1
	Vacuum		Heating rate (°C/min)	Firing temperature (°C)	Holding time (min)
	On at temperature (°C)	Off at temperature (°C)			
zirconhotbond					
Solder firing	450	1000	30	1000	3

computed. In all tests p-values smaller than 5% were considered statistically significant. The data were analysed using SPSS Version 20 (SPSS INC, Chicago, IL, USA).

3. Results

Descriptive statistics (mean, SD, 95% CI) of the measured results of each tested group for fracture load until chipping and fracture load until total fracture (fracture of veneering together with zirconia framework) are presented in Table 3.

The mean range of total load of chipped FDPs was determined between 655 N and 789 N. No differences between the tested groups were found ($p=0.587$).

The mean fracture load until failure type total fracture ranged in all tested groups from 768 N to 1261 N. Sound FDPs and soldered FDPs in the connector area presented lower mean fracture load compared to soldered FDPs in the pontic ($p=0.001$).

Among chipping groups, the highest Weibull modulus was observed for sound FDPs ($m=4.4$), followed by both soldered FPD groups ($m=3.2$). The lowest value was found for thermally treated FDPs ($m=1.6$). Within the total fracture groups sound FPDs showed the highest Weibull moduli ($m=6.6$), followed by the thermally treated FDPs ($m=5.0$) and soldered FDPs in the connector area ($m=3.2$).The lowest value was found for the soldered FDPs in the pontic ($m=2.5$) (Table 4).

4. Discussion

The results of this study showed no differences in the mean load of chipped FDPs in all groups. Concerning mean fracture load until total fracture no differences were found between sound FDPs and FDPs soldered in the connector area. The FDPs soldered in the pontic even exhibited higher load-bearing capacities than sound FDPs and FDPs soldered in the connector area. Thus, the hypothesis that soldered FDPs show lower fracture load values compared to non-soldered ones is rejected. The ceramic solder employed in the present study was a silica based glass ceramic material. Pursuant to the manufacturer the material is not approved for the soldering of parallel surfaces of separated or fractured FDPs. Bond strength between silica based ceramic and zirconia has been investigated in numerous studies to assess the reliability of veneered zirconia restorations as failures of such restorations are mainly attributable to chipping of the veneering ceramic (Sailer et al., 2006). This fracture behaviour is related to several factors, such as residual stresses caused by the thermal history of the ceramics (Swain, 2009; Belli et al., 2013), the mismatch in the coefficient of thermal expansion between framework and veneering ceramic (Belli et al., 2013), geometry of the restoration (Sundh and Sjogren, 2004; Swain, 2009), and bond of the veneering ceramic to the zirconia framework (Aboushelib et al., 2006). The thickness of the veneering ceramic layer plays an important role in the occurrence of stresses in the restoration. Crack incidence was reported to increase with thicker veneering (Guazzato et al., 2010). In the present study, the gap for the solder was kept small (0.7 to 1.0 mm). Thereby stresses were probably kept within a certain critical limit. Moreover, it was reported that the convection on the surfaces and corners of core layer lead to a higher thermal gradient, thus generating higher residual stresses (Zhang et al., 2012; Belli et al., 2013). When soldering, the effective surface is significantly smaller compared to veneering sound zirconia frameworks. This factor also might have been a reason for encouraging performance of the soldered areas in this study. Additionally, chemical bonds between both materials were suggested to develop during firing (Fischer et al., 2008a). Yet, it should be considered that the present test set-up did not include thermal and mechanical ageing. Water exposure in the oral cavity may cause hydrolysis of the Si–O–Si bonds which might affect the mechanical properties of the ceramic (Fischer et al., 2008b). Likewise chewing stress during mastication can cause

Table 4 – Weibull statistics of fracture load.

	Shape	Scale(N)
Chipping		
Sound FDPs	4.4	827.6
Thermal treatment	1.6	954.6
Soldered FDPs in the pontic	3.2	731.8
Soldered FDPs in the connector area	3.2	847.0
Total fracture		
Sound FDPs	6.6	871.8
Thermal treatment	5.0	1375.2
Soldered FDPs in the pontic	2.5	1279.2
Soldered FDPs in the connector area	3.3	858.8

Table 3 – Descriptive statistic of fracture load (N) with 95% confidence intervals for all tested groups.

	Mean	95%CI	SD
Chipping			
Sound FDP	751^{a}	648; 853	160
Thermal treatment	789^{a}	581; 996	324
Soldered FDPs in the pontic	655^{a}	507; 802	230
Soldered FDPs in the connector area	757^{a}	597; 915	249
Total fracture			
Sound FDP	814^{a}	728; 899	133
Thermal treatment	1261^{b}	1073; 1448	294
Soldered FDPs in the pontic	1132^{ab}	819; 1443	490
Soldered FDPs in the connector area	768^{a}	615; 921	239

Different superscript letters (a, b) represent a significant difference according to post hoc test between the groups.

damage of the surface leading to fatigue failure. Thus, further investigations concerning performance of soldered FDPs under simulated clinical conditions are necessary.

The FDPs soldered in the connector area exhibited lower fracture load values than those soldered in the pontic. The reason for this outcome might be the smaller joining surface of the FDPs soldered in the connector area compared to that of the FDPs soldered in the pontic. Moreover, load application was conducted at the centres of both pontics probably creating higher stresses at the intermediate connector. In a FEM study investigating a 4-unit FDP with a similar load application maximum stresses appeared in the framework close to its surface at the gingival embrasure of the connector between the two pontics (Dittmer et al., 2010). The stress gradient was reported to run almost vertically from the basal to the occlusal side. In-vitro studies also described the crack to run through the connector area between the two pontics (Kohorst et al., 2007; Larsson et al., 2007; Sarafidou et al., 2012). However, these studies utilised the load with a 3-point test.

Fracture of the sound and soldered FDPs occurred between the pontics with one exception for the sound FDPs and two exceptions for the FDPs soldered in the pontic (Table 5). This fracture pattern is in accordance with the results of the studies cited above (Kohorst et al., 2007, 2008; Larsson et al., 2007; Sarafidou et al., 2012). In case of the FDPs soldered in the connector area the fracture line ran through the soldered region. The thermally treated FDPs fractured mostly at the distal connector (Table 5). This fracture pattern is inconsistent with that of the studies cited above (Kohorst et al., 2007, 2008; Larsson et al., 2007; Sarafidou et al., 2012). Yet in those investigations thermal treatment of FDPs was not considered. However, mode and direction of loading can vary significantly among individuals and within the same individual. In the present study load was applied perpendicular at the centres of both pontics to achieve a maximum of reproducibility. Clinical contact areas on the pontic and the abutments may cause differing fracture load values and modes of failure. Consequently, the results obtained in this study may not be translated directly into the clinical situation.

In a survey of the literature, a small number of studies were found that address the fracture load of 4-unit veneered zirconia FDPs. The reported mean fracture load values for 4-unit all-ceramic FDPs range between 904 and 2009 N (Kohorst et al., 2007, 2008; Sarafidou et al., 2012). For sound FDPs in the present study a mean fracture load of 751 N for chipping and 814 N for total fracture were registered. Comparison of these values with the cited results is difficult because the investigations have been carried out utilising different test set-ups. For example, the localisation and direction of load application, the dimensions and shapes of the specimens and the connectors varied. The cited studies applied the load in a 3-point test. Moreover, static or dynamic loading in dry or wet environments had been used. In the current study, the FDPs were loaded on rigid steel abutments. It has been shown that the values obtained on immobile abutments are higher compared to those on mobile ones (Rosentritt et al., 2011), and that abutments with a higher elastic modulus lead to increased fracture load values (Sarafidou et al., 2012). Another weak point in the present test design is that no thermal and mechanical cyclic loading was carried out. Furthermore, the FDPs were not cemented on the abutments. The lack of cement might have caused lower bending forces and less damping effect. Thus, possible influences of cement application should be investigated in further studies, together with the influence of thermal and mechanical cycling.

The load-bearing capacity of dental restorations should exceed maximum bite forces to be able to remain in service in the long term. Maximum chewing forces were reported to be approximately 400 N in the molar region (Helkimo et al., 1977). In the present study, fracture loads of all four groups exceeded this value by far. Therefore, performance of soldered FDPs may be promising, although further studies with thermal and mechanical cycling and prospective clinical trials are required to prove their suitability for clinical use. However, it has to be taken into account that fatigue effects were not included in the present study. Some authors suggested a decrease of initial fracture loads by 50% caused by fatigue (Kohorst et al., 2007; Tinschert et al., 2007). Taking this decrease into account the measured fracture loads of this study are reduced to values that might be critical in clinical use explaining the occurrence of chipping.

The thermally treated FDPs exhibited higher total fracture loads than the sound FDPs and the FDPs soldered in the connector area. Y-TZP has been reported to be unstable over time, due to the spontaneous transformation of the tetragonal into the monoclinic phase. Amongst others, micro and macro cracking of the zirconia can cause this transformation leading to mechanical property degradation (Piconi and Maccauro, 1999). Cracks can develop as a consequence of grinding of zirconia (Kosmac et al., 1999). Crazes might be a result from processing steps such as sintering as well. Additionally, it has been proposed that grinding by machining with diamond burs can introduce residual compressive stresses on the surface, which influence the

Table 5 – Relative frequencies (%) with 95% confidence intervals of failure type after fracture load test.

	Failure at the pontic	Failure at the connector between the 2 pontics	Failure at the mesial connector	Failure at the distal connector
Sound FDPs	–	91.7% (61.5; 99.8)	–	8.33% (0.2; 38.5)
Soldered FDPs in the pontic	8.33% (0.2;38.5)	83.3% (51.6; 97.9)	–	8.33% (0.2; 38.5)
Soldered FDPs in the connector area	–	100% (73.5; 100)	–	–
Thermal treatment	–	–	25.0 (5.5; 57.2)	75.0 (42.8; 94.5)

mechanical properties of the material (Kosmac et al., 1999). Subsequent heat treatment was suggested to relax these residual stresses. Therefore, the thermal treatment carried out in the present study might have effected the higher fracture load values.

In this study, the fracture load data were supported with Weibull statistics in which failure probability can be predicted at any level of stress. The Weibull statistic has two parameters: (a) characteristic fracture load (scale, s) and (b) Weibull modulus (shape, m). High estimate of Weibull modulus indicates that the spread of the distribution is small and the material has higher structural reliability. In the used SPSS 20 software only the absolute estimates could be obtained but information on the 95% CI and the post-hoc test for the Weibull parameter was not possible to calculate. Therefore, no statistical comparison of the experimental groups was performed. However, for both failure types, the highest Weibull moduli were found for the sound FDPs supporting the thesis that CAD/CAM-fabrication without manual treatment leads to higher predictability (Beuer et al., 2009a).

5. Conclusions

Within the limitations of this in-vitro study, it can be concluded that:

- Soldering of zirconia frameworks had no influence on the chipping behaviour of 4-unit zirconia based veneered FDPs.
- Thermal treatment improved the load-bearing capacity of 4-unit zirconia based FDPs.
- Additional treatment of the zirconia frameworks (thermal treatment and soldering) reduced the reliability of 4-unit zirconia based FDPs.

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