Microfractures in metal-ceramic and all-ceramic implant-supported fixed dental prostheses caused by superstructure fixation

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The effect of ceramic veneering on the passivity of fit of cast metal and CAD/CAM-fabricated zirconia ceramic implant-supported three-unit cement-retained restorations was investigated, as well as the effect of misfit stress on the marginal integrity of ceramic veneers. Superstructures were fabricated using cast metal or by CAD/CAM milling of presintered or HIP zirconia ceramic ($n=10$). Before and after veneering, strain gages were used to measure *in vitro* the strain developed in all the restorations as a result of superstructure fixation. Fluorescent penetrant method was used to detect microcracks developed in ceramic veneers. Cast frameworks showed significantly higher strain values than CAD/CAM frameworks ($p=0.000$). Veneering significantly increased strain development in all CAD/CAM frameworks ($p=0.000$). Compared to zirconia ceramic restorations, significantly more microcracks were observed in cast restorations ($p=0.000$) both before and after superstructure fixation.

Keywords: Fluorescent penetrant method, Microfracture, Passive fit, Zirconia ceramic, Ceramic veneer

INTRODUCTION

Nonpassive-fitting implant-supported fixed dental prostheses (FDPs) can lead to both technical and biological complications, such as abutment fracture, connecting screw breakage, and bone loss¹. It has been pointed out that superstructures fabricated by conventional methods such as casting failed to achieve a passive fit^{2–4}. When multi-unit fixed restorations were fabricated using the computer-aided design/computer-aided manufacturing (CAD/CAM) technique, greater accuracy was achieved^{5–9}. The attractiveness of CAD/CAM fabrication procedures is further boosted with the use of high-strength ceramic materials such as zirconia ceramic¹⁰.

For both conventionally cast metal restorations and CAD/CAM-fabricated restorations made from zirconia ceramic, ceramic veneers would be bonded onto their frameworks. Ceramic veneering was reported to negatively affect the precision of fit of cast implant-supported FDPs¹¹. For zirconia ceramic restorations, contradicting results were reported. Dittmer *et al.*¹² and Kohorst *et al.*¹³ showed that ceramic veneering negatively affected the marginal and internal fit of four-unit zirconia restorations. Balkaya *et al.*¹⁴ found that only the porcelain firing cycle affected the marginal fit of all-ceramic single crowns, but not so with the glaze firing cycle. On the other hand, Vigolo and Fonzi¹⁵ found that neither the porcelain firing cycle nor the glaze cycle affected the marginal fit of four-unit CAD/CAM-fabricated zirconia restorations.

Fixation of ceramic-veneered superstructures that lack passive fit results in strain development. Strain induced by misfit causes microfractures in the ceramic veneer¹¹. For this reason, chipping/fracture of the veneer is one of the most common causes of veneer failure in

zirconia-supported all-ceramic restorations¹⁶. In a 5-year clinical study by Sailer *et al.*¹⁷, chipping of the veneering ceramic was cited as the second most common reason for failure of zirconia frameworks for posterior fixed partial dentures. Fractographic analyses of clinically failed zirconia-based FDPs by Taskonak *et al.*¹⁸ showed that primary fractures initiated from the veneer surfaces, whereas interfacial delamination in glass veneer/zirconia core bilayer structures controlled the secondary fracture initiation sites.

Numerous studies have reported on the incidence of veneer chipping in zirconia restorations. Kreissl *et al.*¹⁹ found that fracture of the veneering porcelain occurred in 5.7% of the implant-supported FDPs after an average observation period of 5 years. Kollar *et al.*²⁰ reported that tooth- or implant-supported zirconia crowns in the posterior region exhibited porcelain veneer chipping after a follow-up period of up to 30 months. Raigrodski *et al.*²¹ also reported on minor chipping of veneering porcelain in zirconia-based posterior three-unit restorations after short-term service. As for Edelhoff *et al.*²², a low incidence of veneer chipping, but no framework fractures, was observed in zirconia fixed partial dentures after a mean clinical observation period of over 39 months.

The goal of this study was to investigate a possible correlation between the passivity of fit of implant-supported zirconia FDPs and the fracture or chipping of ceramic veneers. First, the effect of ceramic veneering on the passivity of fit of cast metal and CAD/CAM-fabricated zirconia ceramic implant-supported restorations was quantified. The effect of misfit stress on the occurrence of microcracks in the ceramic veneer was subsequently examined using the fluorescent penetrant method^{11,23,24}.

MATERIALS AND METHODS

A patient situation with two implants in the lower left mandible (Standard Plus Implants, Straumann AG, Basel, Switzerland; 4.1 mm diameter, 10 mm bone sink depth) was transferred to an *in vitro* resin model (Acryline clear, anaxdent, Stuttgart, Germany) suitable for strain gage measurements (Fig. 1).

Fabrication of FDP frameworks

1. Fabrication of master casts

A total of 30 pick-up impressions were made from the *in vitro* resin model using the implant manufacturer's transfer copings, custom-made impression trays (Palatray XL, Heraeus Kulzer, Hanau, Germany), and polyether impression material (Impregum, 3M ESPE AG, Seefeld, Germany). Based on these impressions, 30 master casts with individual dies containing the respective implant analogs were poured in type IV stone (Fujirock, GC Corp., Tokyo, Japan). Abutments 5.5 mm in height for cement-retained restorations (synOcta abutment "cement retained", Straumann AG, Basel, Switzerland) were then attached to the implants on the *in vitro* model and on the master casts.

Both CAD/CAM-fabricated and cast FDP frameworks had an identical design: lower first premolar and first molar as retainers and a lower second premolar as pontic.

2. Fabrication of FDP frameworks with CAD/CAM

Twenty of the master casts were used for CAD/CAM fabrication of cement-retained FDP frameworks. Half of these master casts were used to fabricate frameworks milled from presintered zirconia ceramic (Zerion, Straumann CAD/CAM, Gräfelfing, Germany), and the other 10 master casts were used for milling from HIP zirconia ceramic (Denzir, Straumann CAD/CAM GmbH, Gräfelfing, Germany). The entire CAD/CAM process from scanning the master casts to fabricating the zirconia ceramic frameworks was undertaken by Straumann CAD/CAM (Gräfelfing, Germany) (Fig. 2a).

3. Fabrication of FDP frameworks by casting

Based on the CAD/CAM restorations, a silicone mold (Silaplast, Detax GmbH & Co KG, Ettlingen, Germany) was made for the fabrication of 10 cast frameworks. Using a pattern resin (Pattern Resin LS, GC Germany, Bad Homburg, Germany) and the implant manufacturer's burn-out plastic copings for cement-retained restorations, patterns resembling the design of the CAD/CAM restorations were manufactured on the remaining 10 master casts. These patterns were subsequently invested and cast with a high noble alloy for porcelain-fused-to-metal restorations (Jensen Expert, Jensen Industries Inc., North Haven, CT, USA) (Fig. 2a).

Strain gage measurement setup

Visual and tactile evaluations of all restorations ($n=10$ per group) were performed on the *in vitro* resin model to ensure a clinically acceptable fit with no visible marginal gaps. In the case of an obvious misfit, the space between implant abutment and FDP retainer was visualized

Fig. 1 *In vitro* model of an existing patient situation with two implants in a straight line configuration. A total of four strain gages attached mesially and distally adjacent to the implants captured the strains developed as a result of superstructure fixation. Here, a cast framework is cemented onto implant abutments with a force of 10 N exerted on the pontic through a universal testing machine.

using a light-body silicone (VOCO Fit Test C & B, VOCO, Cuxhaven, Germany). Areas showing insufficient cement space were selectively ground until the cement space achieved a uniform thickness.

Four strain gages with a nominal resistance of 120 Ω each (LY11-0.6/120, Hottinger Baldwin Messtechnik, Darmstadt, Germany) were mounted on the *in vitro* model mesially and distally adjacent to the implants (Fig. 1). The strain gages were abbreviated as "SG" and named according to their positions: Am —mesial SG at anterior implant; Ad —distal SG at anterior implant; Pm —mesial SG at posterior implant; Pd —distal SG at posterior implant^{4,11}. The strains developed around the implants were recorded using a measurement amplifier (Spider 8, Hottinger Baldwin Messtechnik, Darmstadt, Germany) and an analysis software (BEAM for Spider 8, AMS Gesellschaft für Angewandte Mess-und Systemtechnik, Flöha, Germany).

Strain measurement before ceramic veneering

A temporary cement (Temp Bond, Kerr Italia S.r.l., Scafati, Italy) was used for the fixation of all frameworks. It was mixed according to the manufacturer's recommendations. When the mixed cement was applied to the abutment cylinders, the SGs were set to zero. With the frameworks placed on the implant abutments, a force of 10 N was exerted on the pontic for 6 min using a universal testing machine (Inspekt mini 3kN, Hegewald & Peschke, Nossen, Germany). The load was removed, and the cement was allowed to set for a further 1 min. After a total of 7 min, the strain values before ceramic veneering at all strain gage positions of each restoration were recorded.

Fig. 2 a) FDP frameworks fabricated to fit the *in vitro* model. From top to bottom: conventionally cast FDP (high noble alloy); CAD/CAM FDP milled from HIP zirconia ceramic (Denzir); CAD/CAM FDP milled from presintered zirconia ceramic (Zerion).
b) CAD/CAM frameworks (Denzir and Zerion) were ceramic-veneered by overpressing (left) and cast frameworks by layering (right).

Ceramic veneering

All frameworks were carefully retrieved from the implant abutments using a crown and bridge remover (Safe Remover, Anthogyr, Sallanches, France). The retainers were manually cleaned of cement remnants and then immersed in ethanol before veneering.

To standardize the veneering thickness of all restorations, one CAD/CAM-fabricated framework was veneered with overpressed ceramic (Cercon ceram press, DeguDent, Hanau, Germany) and used for obtaining a silicon mold (Silaplast, Detax GmbH & Co KG, Ettlingen, Germany) prior to veneering the remaining CAD/CAM frameworks (Zerion and Denzir). For cast frameworks, they were veneered with the layering technique in strict adherence to the manufacturer's guidelines (Wegold Evolution, Wegold Edelmetalle AG, Wendelstein, Germany) (Fig. 2b). The firing protocol applied comprised one oxide bake (820°C), opaque bake I and II (820°C), dentin bake I and II (770°C), and one polishing bake (760°C). After firing, no additional treatments were applied to compensate for porcelain shrinkage.

1. Microfracture evaluation before superstructure fixation

After ceramic veneering, all frameworks were cleaned using isopropanol (MET-L-CHEK Spezialreiniger NPU, Helling, Heidgraben, Germany) and then immersed in a bath of fluorescent penetrant (MET-L-CHEK FP 97A(M), Helling GmbH, Heidgraben, Germany) for 24 h. After drying under ambient conditions, the ceramic-veneered frameworks were inspected under a fluorescent lamp (HBO 100, Zeiss, Oberkochen, Germany) and a microscope (20× magnification; Axio Imager A.1, Zeiss GmbH, Oberkochen, Germany). All visible microcracks (Fig. 3) detected on both FDP retainers of each veneered framework were recorded using a digital camera (AxioCam MRc5, Zeiss, Oberkochen, Germany) mounted on the microscope and an image acquisition software (Imaging Software AxioVision 4.6.3, Zeiss, Oberkochen, Germany)^{11,23,24}.

2. Strain measurement and microfracture evaluation after superstructure fixation

After cementing all the veneered frameworks on the *in vitro* model, the strains developed around the implants were recorded using the four strain gages—as per the strain measurement done for superstructure fixation before ceramic veneering.

After the frameworks were removed from the *in vitro* model, they were again inspected for microcracks using the fluorescent penetrant method.

Statistical analysis

Statistical analysis on the absolute strain values was performed using multivariate analysis of variance with FDP type (Cast/Denzir/Zerion) and veneering status (veneered/not veneered) as fixed factors (SPSS version 19, IBM Inc., Somers, NY, USA).

Statistical analysis on the number of microcracks detected was performed with a generalized linear model using Poisson distribution. FDP type (Cast/Denzir/Zerion) and fixation status (before cementation/after

Fig. 3 Typical view of a FDP retainer under fluorescent light showing multiple radial cracks extending into the ceramic veneer.

cementation) were the fixed factors (R, The R Foundation for Statistical Computing, Vienna, Austria; www.R-project.org).

For all statistical comparisons, level of significance was set at $\alpha=0.05$.

RESULTS

Strain development

For all the unveneered FDP frameworks, their mean strain values at the four different strain gage positions ranged from 64.32 $\mu\text{m/m}$ to 326.83 $\mu\text{m/m}$. For the veneered restorations, the range was 69.19 $\mu\text{m/m}$ –319.15 $\mu\text{m/m}$ (Fig. 4). In general across all the four different strain gage positions, cast frameworks exhibited higher strain values than Denzir and Zerion frameworks ($p=0.000$). In both unveneered and veneered conditions, cast frameworks also exhibited considerably higher values for the mean of standard deviations (which indicated the dispersion of developed strains) than Denzir and Zerion, which showed comparable values in both veneering conditions (Table 1). Nonetheless, all FDP frameworks (Cast/Denzir/Zerion) showed comparable mean strain values after ceramic veneering (Table 1).

Between the two types of CAD/CAM-fabricated FDP frameworks milled from HIP zirconia ceramic or presintered zirconia ceramic, no significant differences in strain development were detected ($p=0.165$) (Table 2). In contrast, cast frameworks showed significantly higher strain values than Zerion ($p=0.000$) and Denzir ($p=0.000$) (Table 2). For both Denzir and Zerion frameworks, ceramic veneering resulted in a significant increase in strain development ($p=0.000$). For cast frameworks, the effect of ceramic veneering on strain development was

Fig. 4 Mean strain values at the four different strain gage positions for all types of FDP frameworks before and after ceramic veneering.

not significant (Table 2). After ceramic veneering, there were no significant differences in the strain values among the three FDP types.

Microfracture evaluation

After ceramic veneering, the mean numbers of microcracks detected in FDP retainers were as follows:

Table 1 Mean strain values and means of standard deviations of all strain gage positions for all types of FDP frameworks

FDP type		Not veneered	Veneered
Cast	Mean strain value	208.920	218.634
	Mean of standard deviations	141.662	158.355
Denzir	Mean strain values	128.700	205.098
	Mean of standard deviations	67.304	92.746
Zerion	Mean strain values	135.715	220.218
	Mean of standard deviations	71.570	91.399

Table 2 Pairwise comparisons of FDP types based on strain development (MANOVA with Pillai's trace, level of significance $\alpha=0.05$); significant effects are given in bold

	Value	F	Hypothesis df	Error df	p-value
Zerion vs. Denzir					
FDP type	0.174	1.740	4.000	33.000	0.165
Veneering status	0.801	33.306	4.000	33.000	0.000
FDP type : Veneering status	0.256	2.843	4.000	33.000	0.039
Cast vs. Zerion					
FDP type	0.496	8.104	4.000	33.000	0.000
Veneering status	0.517	8.842	4.000	33.000	0.000
FDP type : Veneering status	0.258	2.873	4.000	33.000	0.038
Cast vs. Denzir					
FDP type	0.448	6.691	4.000	33.000	0.000
Veneering status	0.651	15.379	4.000	33.000	0.000
FDP type : Veneering status	0.277	3.162	4.000	33.000	0.026

Table 3 Analysis of deviance on the effects of FDP type (Cast/Denzir/Zerion) and fixation status (before cementation/after cementation) on the number of detectable microcracks; level of significance $\alpha=0.05$; significant effects are given in bold

	Df	Deviance	Residual Df	Residual Deviance	p-value
Null			59	152.975	
FDP type	2	87.267	57	65.707	0.000
Fixation status	1	14.150	56	51.558	0.000
FDP type : Fixation status	2	0.842	54	50.715	0.656

0.1 in both Denzir and Zerion frameworks, and 1.6 in cast frameworks. After cementation, the mean numbers of detectable microcracks were as follows: 0.1 in Zerion, 0.5 in Denzir, and 4.2 in cast frameworks.

An analysis of deviance (Table 3) revealed a significant influence of the fixed factors, FDP type (Cast/Denzir/Zerion) and fixation status (before cementation/after cementation), on the number of detectable microcracks ($p=0.000$). Based on coefficients for contrasts (Table 4), there were significant differences when comparing between Denzir and Cast groups ($p=0.000$) and between Zerion and Cast groups ($p=0.000$). In addition, there was a significant difference in the mean number of microcracks before and after cementation

($p=0.001$).

In an analysis of deviance comparing Zerion and Denzir frameworks (Table 5), neither the fixed factors of FDP type ($p=0.148$) and fixation status ($p=0.148$) nor the interaction of both factors ($p=0.366$) had a significant influence on the number of detectable microcracks.

Based on the mean strain development in all FDP types ($p=0.548$), no significant correlation between strain development and the number of microcracks could be established. However, a significant correlation between misfit strain dispersion and the number of microcracks was found ($p=0.041$).

Table 4 Contrast coefficients based on number of detectable microcracks; level of significance $\alpha=0.05$; significant effects are given in bold

	Estimate	Standard error	z-value	p-value
Denzir-Cast	-2.128	0.473	-4.499	0.000
Zerion-Cast	-3.738	1.012	-3.694	0.000
Before cementation-after cementation	-0.965	0.294	-3.285	0.001

Table 5 Analysis of deviance comparing Zerion and Denzir frameworks with fixed factors FDP type (Cast/Denzir/Zerion) and fixation status (before cementation/after cementation); level of significance $\alpha=0.05$; significant effects are given in bold

	Df	Deviance	Residual Df	Residual Deviance	p-value
Null			39	28.524	
FDP type	1	2.093	38	26.431	0.148
Fixation status	1	2.093	37	24.338	0.148
FDP type : Fixation status	1	0.818	36	23.520	0.366

DISCUSSION

Strain development

Results of this study showed that cast frameworks exhibited greater strain values than CAD/CAM-fabricated ones. This result agreed with previous studies which showed that the CAD/CAM fabrication method produced restorations with better accuracy of fit than conventional casting^{3,5-9}.

The choice of zirconia material in this study, *i.e.*, HIP zirconia ceramic *versus* presintered zirconia ceramic, had no effect on strain development in the all-ceramic frameworks. This result contradicted a study conducted by Kohorst *et al.*²⁵ and a review published by Abduo *et al.*², which claimed that restorations made from fully sintered zirconia showed better fitting accuracy.

This study also showed that ceramic veneering of implant-supported superstructures resulted in an increase in strain development. This finding is supported by several studies on the effect of porcelain veneering on the accuracy of fit of zirconia restorations^{12-14,26}. An exception was found with a study by Vigolo and Fonzi¹⁵, who reported that veneering did not affect the fitting accuracy of zirconia restorations.

The contradicting results by Kohorst *et al.*²⁵ as well as Vigolo and Fonzi¹⁵ might be explained by the different study designs. In the current study, assessment was based on strain development, and hence fitting accuracy, using strain gage measurements¹¹. In the aforementioned studies^{15,25}, assessment was based on marginal fit using gap measurements. As shown by Hegde *et al.*⁴, microgap measurements had no correlation with increasing misfit and that the presence or absence of a microgap was not necessarily indicative of passivity.

For cast frameworks, the effect of ceramic veneering was not as pronounced as that noted for CAD/CAM-fabricated zirconia ceramic frameworks. In the present study, all FDP types showed comparable levels of misfit after veneering. It might be argued that the cast

frameworks already reached maximum misfit in the as-cast condition, such that adding a ceramic veneer would not further aggravate the extent of misfit.

Microfracture development

After ceramic veneering, only two cracks were detected in both groups of zirconia ceramic frameworks. These microcracks could have resulted from residual stresses developed during the preparation of these all-ceramic implant superstructures²⁷. In contrast, a significantly greater number of microcracks was detected at the cervical margins of both FDP retainers in cast restorations.

After cementation, there was no significant increase in the number of microcracks in both groups of zirconia-based restorations—which did not differ significantly from each other. In contrast, the detectable microcracks in cast restorations significantly increased—an observation consistent with that in our previous experiment¹¹. Extremely high strain values were recorded at the midstanding strain gage positions (Ad, Pm) for cast restorations, which explained why there was a significant increase in the number of microcracks at the cervical margins of both FDP retainers. These high strain values were probably related to the hoop stresses which were developed when the superstructure was seated on conical abutments.

It is noteworthy that all veneered restorations exhibited comparable levels of total strain (averaged strain development at all strain gage positions). Based on the significant correlation between the number of microcracks and the dispersion of misfit strains ($p=0.041$), it appeared that the distribution of strains was a greater deciding factor in microcrack formation than the total strain level of a restoration.

Limitations of the study

A few limitations need to be acknowledged regarding the present study. Besides the limited sample size and *in*

vitro setting, one noteworthy limitation was the strain measurement method used. Strain gages could not be positioned directly at the implant shoulder. Therefore, strains were captured at an area away from the simulated bone-implant interface. Although the strain gages were positioned in the mesial-distal direction to capture the strains occurring in the direction of maximum principal stress, they failed to capture all the three-dimensional distortions which occurred. These distortions which are inherent in each implant-supported superstructure are inconsistent given their three-dimensional nature³⁾, and would thus result in positive and negative strain values at the sensors. In this study, absolute strain values were used for analysis, hence resulting in large standard deviations in all FDP groups.

To simulate current clinical practice, all zirconia-based frameworks were veneered with the overpressing technique and the cast restorations with the layering technique. Although the dental ceramic products chosen in this study were apt choices to represent the fully sintered and presintered zirconia types, the choice of zirconia-based dental ceramic for all-ceramic restorations could be a confounding variable itself. The cement type chosen might have also affected the experimental results. In most clinical implant cases, temporary cements are used for fixation of restorations, because definitive or adhesive resin cements would not allow access to the implant components at a later stage. Coupled with the need to remove all restorations from the *in vitro* model without damaging the model or the restoration, a temporary cement was used in this study.

The fluorescent penetrant method is currently considered as being sensitive enough for detecting surface microcracks in dental restorations. Although it has been shown that this technique is equally or better suited for microcrack detection than methods such as transillumination or scanning electron microscopy^{23,24)}, it has not been clarified whether it could efficiently detect all cracks present. It also remains to be asked if the cracks identified by this method would ultimately lead to a clinical problem such as ceramic veneer chipping.

CONCLUSION

Within the limitations of this study, it was concluded that the addition of a ceramic veneer to a cast metal or milled zirconia ceramic FDP framework caused a decrease in passivity of fit. The veneering process itself might have already resulted in microcrack formation at the cervical margins of FDP retainers. Cementation of implant-supported restorations led to a general increase in the number of detectable microcracks, which was more pronounced in cast restorations than CAD/CAM-fabricated zirconia-based restorations.

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